3D Modelling in Deep Excavations – Case Studies

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ABSTRACT: In 2D modelling computer programs which calculate in plain strain conditions, it is considered that modelled section contiunes infinitely with the same geometry through the axis perpandicular to the section. However, any variation in soil type, surcharge loads, topography or supporting conditions in this parpendicular axis effects the behaviour of the stress distribution in the soil. Therefore 3D modelling computer programs provide more realistic solution for the sections which contain variety of above mentioned conditions in parpendicular axis. In this paper, calculations in 2D and 3D modelling studies for two different shoring works are presented. Calculated plain strain ratio (PSR) values are compared with previously published studies.

1. INTRODUCTION

Urbanization brings lack of sufficient spaces for basement excavations in growing cities; therefore implication of retention structures for deep excavations is frequently encountered geotechnical engineering subject in big cities. It is clear that dimensioning of the retention structures is important for a reliable and cost effective solution and this brings the necessity of a realistic calculation approach. There are variable computer programs for modelling retention structures and most of these programs are based on two-dimensional modelling. Plain strain condition is the strain representation of two-dimensional models and it is considered that section continues with same geometry infinitely through the axis perpendicular to the section which is calculated. With the advancements of the technology more capable computers are provided which enable three dimensional modelling and new computer programs are released for this purpose.

With three dimensional modelling of infrastructures a more realistic calculation approach can be provided considering the variations of the soil type, surcharge loads, topography and supporting conditions on the axis which is perpendicular to the calculated section. Three dimensional modelling of deep excavations provides significant effects which will be encountered from lateral arching of the retained soil and lateral flexure of the support systems between corners (Lee et al., 1998). A general background for three dimensional modelling is given below;

In 1975 St. John studied a square shaped unsupported excavation in stiff London Clay. Both 2D plain strain, 2D axisymmetric and 3D models are analyzed. According to the results good agreement was obtained between 2D axisymmetric and 3D models however 2D plain strain analysis significantly overpredicted horizontal movements.

In 1979 Burland et al. also recommended axial symmetry instead of plain strain in square excavations, further if the excavation supported with diaphragm walls large compressive hoop stresses are arisen along diaphragm walls which does not represent a realistic consequence (Lee et al., 1998).

In 1992 Simpson indicated that axisymmetric and plain strain models have negligible differences and attributed this to the shallow depth to a relatively rigid stratum.

In 1993 Wong and Patron pointed the significantly arising corner effects in some several deep excavation projects in Taipei.

Also in 1993 Ou and Chiou reported that 3D calculation is required for a realistic prediction of wall behavior in excavation with short sides.

In 1995 Lee et al. reported that in soft soils corner effect is getting stronger and this showed that 2D models to be much more sensitive to soil parameters than the 3D models.

In 1995 Liu reported that in deep excavations which are strutted densely corner effects are suppressed above the excavation level but under the excavation level it is again possible to see the corner effect preventing high wall deflection.

Also in 1996 Ou et all. have described "PSR" plain strain ratio as the maximum movement in the center of an excavation wall computed by 3D analyses divided by that computed by plain strain model. Ou et al. originally defined PSR in terms of the ratio of width to length of the wall and distance from the corner.

In 1998 Lee et al. reported a comparison between field data and 2D - 3D analysis. The results of the 3D analysis are mostly in agreement with field data, some differences are also obtained due to the construction delay and over-excavation.

In 2000 Ou et al. published a case study about Taipei National Enterprise Centre Project and it is reported that plain strain condition could be occurred 34.4 m away from the corner, excavation depth was 19.7 m and construction method was top-down.

In 2002 Beadman and Cheng utilized results of four case studies to calibrate an empirical method for calculation of displacements around corners which was developed by Arup Geotechnics in London. Then in 2010 Fuentes and Devriendt developed a new empirical method for calculation of displacements around corners.

In 2007 Finno et al. reported that PSR is affected by the ratio of the length of wall to the excavation depth, the ratio of the plan dimensions of the excavation L/B, L being the side where displacements are computed, the wall system stiffness and factor of safety against basal heave.

In this paper numerical analysis of two deep excavations are summarized and discussed in terms of 2D and 3D modelling.

2. CASE STUDIES

Numerical studies for two different projects with deep excavations are summarized in this section. These excavations are calculated both 2-D plain strain model and 3-D model. Site monitoring data couldn't be submitted within this paper, since monitoring studies are still being performed.

2.1. Water Intake Structure, Samsun

A deep excavation was planned for a water intake structure which was planned to be constructed in an industrial plant site in Samsun, Turkey.

Excavation for the water intake structure is planned to be torch shaped as illustrated in Figure 1. Excavation widths are variable which 23.80 m and 15.70 m. Total length of the excavation is approximately 44.50 m and excavation depths are -11.35 m and -8.30 m respectively.

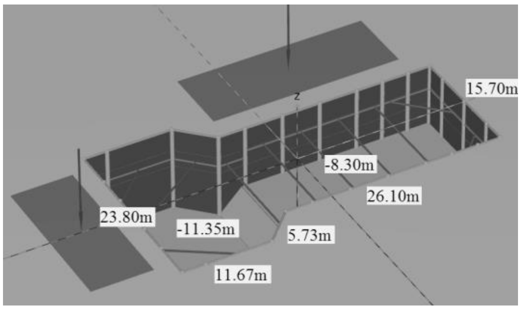


Figure 1. Water Intake Structure Dimensions

Soil profile is considered as given in the table below;

Table 1. Soil Profile for Water Intake Structure

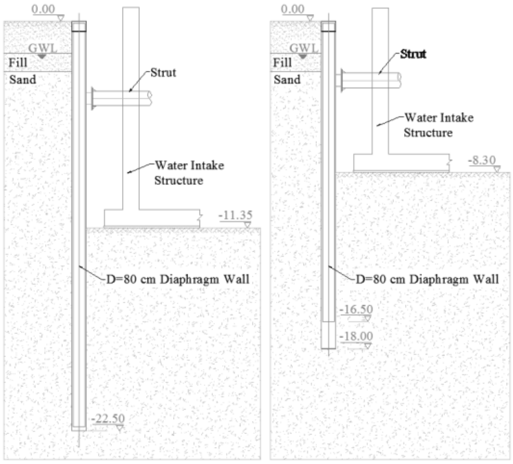
Soil	Depth	γ, kN/m³	Ø', °	c', kPa	E MN/m²
Fill	0-3m	17	30°	1	15
Sand	3m-	17.5	34°	1	25

Water level was observed approx. 2.0 m below the ground surface resulting hydrostatic pressures are considered in the calculations behind the shoring wall.

Since no building or heavy structure exist around the excavation only 15 kPa surcharge was considered as an estimated site operational surcharge.

To eliminate the excessive ground water infiltration into the excavation pit diaphragm wall shoring system is planned to be constructed. Diaphragm wall depth will be 22.50 m for the section with 11.35 m excavation depth, and 18 m for the section with 8.30 m excavation depth. In 18 m deep diaphragm wall reinforcement cage is considered to be installed in only first 16.50 m of the diaphragm wall.

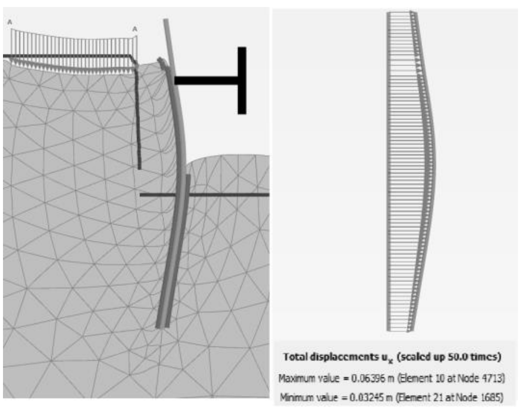
Diaphragm wall panels will be supported with steel struts which will be placed at elevations of -4.25m and -3.25m for the sections with excavation depths 11.35m and 8.30m respectively. Sections of the shoring wall are given in Figure 2a and 2b;



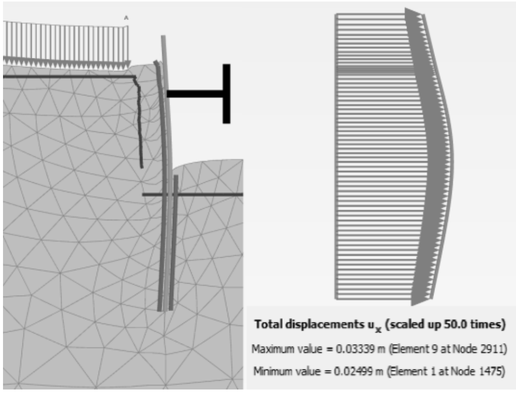
Figures 2a&2b. Diaphragm Wall Shoring Sections

Lateral displacements of the diaphragm walls with 2D plain strain model are calculated as 64mm and 33mm for sections with excavation depths 11.35m and 8.30m respectively. (Figures 3a&3b and Figures 4a&4b)

Surface settlement behind the shoring wall is estimated as 68 mm and 34 mm for the sections with excavation depths 11.35m and 8.30m respectively.



Figures 3a&3b. Diaphragm Wall Lateral Displacement (Exc. Depth is -11.35m)



Figures 4a&4b. Diaphragm Wall Lateral Displacement (Exc. Depth is -8.3m)

Lateral displacements of the diaphragm walls with 3D model are calculated as follows (Figure 5);

For 11.35 m Excavation depth, lateral displacements are 38mm and 30mm for the long and short sides respectively.

For 8.30 m Excavation depth, lateral displacements are 27mm and 18mm for the long and short sides respectively.

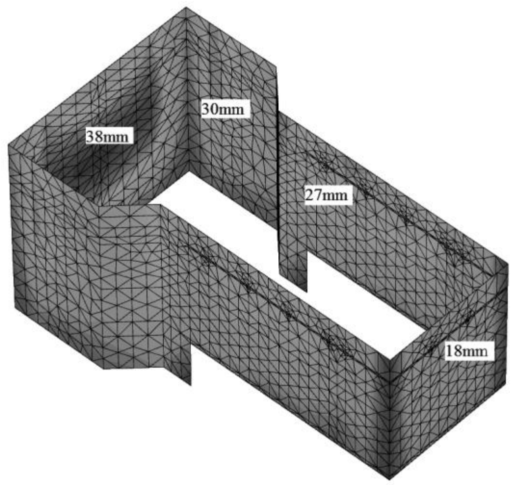


Figure 5. Diaphragm Wall Displacement With 3D Model Calculation

Surface settlements are estimated as follows (Figure 6); For 11.35 m Excavation depth, surface settlements are 34mm and 30mm for the long and short sides respectively.

For 8.30 m Excavation depth, surface settlements are 25mm and 18mm for the long and short sides respectively.

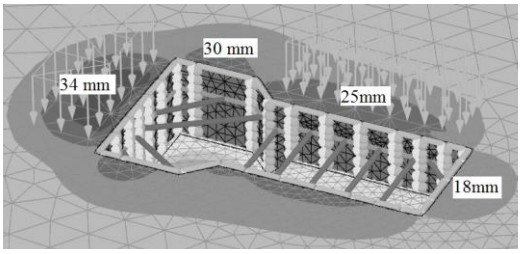


Figure 6. Surface Settlements With 3D Model Calculation

2.2. Hotel Project, Izmir

A hotel structure is planned to be constructed with 3 basement floors in Izmir, Turkey.

Excavation for the hotel basements is planned to be rectangular shaped as illustrated in Figure 7. Excavation plan dimensions are 34m by 22m. Excavation depth is 11.30 m.

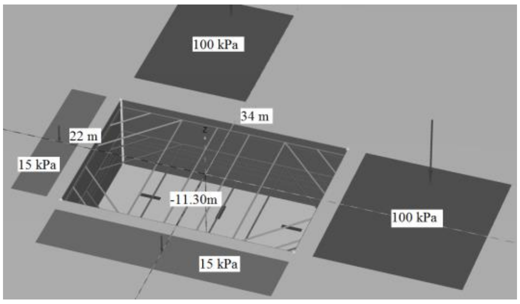


Figure 7. Hotel Basement Excavation Dimensions

Soil profile is considered as given in the table below;

Table 2. Soil Profile for Hotel Project, Izmir

Soil	Depth	γ, kN/m³	Ø', °	c',kPa	E,MN/m²
Fill	0-7m	19	34°	10	25
Sand	7-8m	18	30°	2	5
Clay 1	8-15	17	-	*	10
Clay 2	15-18	17	-	*	25
Gravel	18-19	18	32	5	20
Clay 3	19-21	18	-	*	30
Gravel	21-23	18	32	5	20
Clay 4	23-29	18	-	*	38

* Clay layers modelled with undrained parameters. 30, 50, 60 and 75 kPa cu values are considered for Clay 1, 2, 3 and 4 layers respectively.

Water level was observed at 1.0 m below the ground surface, resulting hydrostatic pressures are considered in the calculations behind the shoring wall.

There are two neighboring buildings which modelled with 100 kPa surcharge load. 15 kPa surcharge was considered as site operational loads for the other sides.

To eliminate the excessive ground water infiltration into the excavation pit diaphragm wall shoring system is planned to be constructed. Diaphragm wall length will be 20 m for 11.30 m excavation depth.

Diaphragm wall panels will be supported with two rows of steel struts which will be placed under -1.40m and -5.35m below the ground surface. Sections of the shoring wall are given in Figure 2a and 2b;

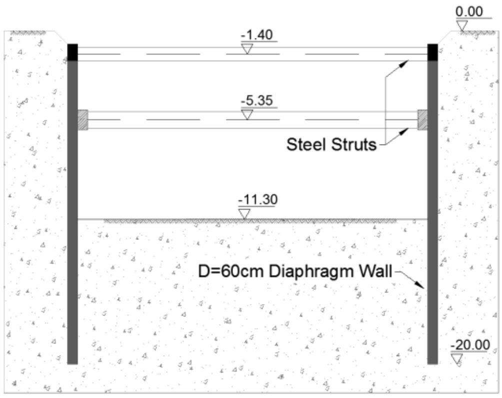


Figure 8. Diaphragm Wall Shoring Section

Also six numbers of barrettes were implemented under the foundation to eliminate the uplift risk. In deep shoring calculations these barrettes are also taken into account.

Lateral displacements of the diaphragm walls with 2D plain strain model are estimated as 147mm and 10mm for sections neighboring building and the street sides respectively (Figure 9).

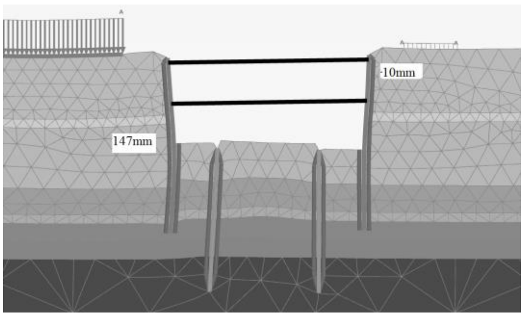


Figure 9. Diaphragm Wall Lateral Displacement

Surface settlement behind the shoring wall is calculated as 102mm and 12 mm for sections neighboring building and the street sides respectively.

Lateral displacements of the diaphragm walls with 3D model are estimated as follows;

For the sides neighboring the buildings, lateral displacements are 57mm and 54mm for the short and long sides respectively. The lateral displacement of the short side is smaller than the other because the building load effects to only the half of this side.

For the sides neighbouring to the streets, lateral displacements are 33 mm and 37 mm for the short and long sides respectively.

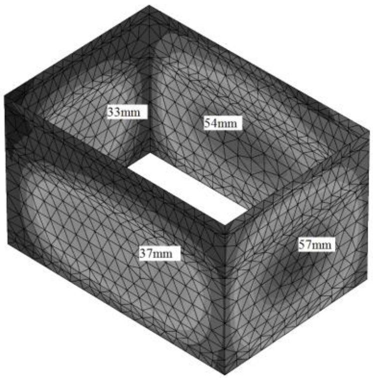


Figure 10. Displacements with 3D Model

Surface settlements are calculated as follows (Figure 11);

For the sides neighbouring the buildings, surface settlements are mm and 31 mm for both long and the short sides.

For the sides neighbouring the streets, surface settlements are 22mm and 16mm for the long and short sides respectively.

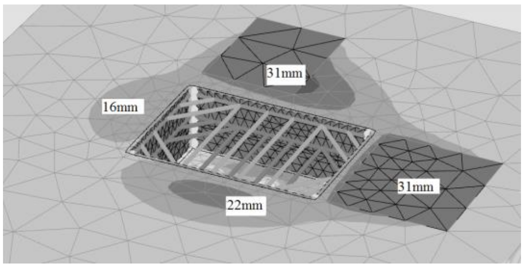


Figure 11. Settlements With 3D Model Calculation

Calculated lateral diaphragm wall displacements and surface settlements in two and three dimensional model analysis and also for both of two cases are summarized in the Table 3.

Table 3. Lateral Displacements and Settlements

Case/ Model	Exc. Depth m	Surc. Load kPa	Lateral Disp. mm	Settle-ments mm
1. / 2D	11.35	15	64	68
1. / 3D	11.35	15	38/30*	34/30*
1. / 2D	8.30	15	33	34
1. / 3D	8.30	15	27/18*	25/18*
2. / 2D	11.30	100	147	102
2. / 3D	11.30	100	54/57*	31/31*
2. / 2D	11.30	15	10	12
2. / 3D	11.30	15	37/33*	22/16*

* First value is for the long, second value is for the short side of the excavation.

3. PLAIN STRAIN RATIO (PSR)

As described in introduction part Finno et al. (2007) reported that plain strain ratio "PSR" is related with the ratios of the length of wall to the excavation depth, the ratio of the plan dimensions of the excavation L/B, L being the side where displacements are computed, the wall system stiffness and factor of safety against basal heave. According to Finno et al. (2007) PSR can be estimated with below formula;

$$PSR = (1 - e^{-kC(L/H_e)}) + 0.05(L/B - 1)\,, \qquad (1)$$

"k" is system stiffness factor and can be calculated as;

$$k=1-0.0001(S) \qquad (2)$$

Where "S" is support system stiffness and calculated as; (Clough et al. 1989)

$$S = \frac{EI}{\gamma_w h^4}\,, \qquad (3)$$

Where "EI" is bending stiffness of the wall, "γ_w" is unit weight of water and "h" is average vertical spacing of lateral support elements.

"C" is factor that depends of the factor of safety against basal heave.

$$C = 1 - \{0.5(1.8 - FS_{BH})\} \qquad (4)$$

L is being the side where movements are computed. B is the secondary length of the wall. H_e is the excavation depth.

PSR values are calculated for the sections both considering plaxis results and the method submitted by Finno et al. (2007) and summarized in the table below;

Table 4. Calculated PSR values

Case	Exc. Depth m	Surc. Load kPa	Lat. Disp. mm-2D	Lat. Disp. mm-3D	PSR, Plaxis Models	PSR, calc. with formula (1)
1	11.35	15	64	38	0.593	0.854
1	8.30	15	33	27	0.818	0.990
2	11.30	100	147	57	0.388	0.748
2	11.30	100	147	54	0.367	0.921

4. CONCLUSIONS

Numerical studies of two different deep excavation projects are summarized above. Two cases which have similar excavation depth but with different dimensions, surcharge loads, soil types and supporting systems have been studied.

Consequences of the calculated displacements and PSR calculations can be listed as;

- In both cases 3D model calculations resulted with less lateral displacements and settlements.
- Lateral displacements and settlements increased with the increase of excavation depth, surcharge loads and the length of the excavation side where displacements are calculated.
- As an exception, in the second case since building load does not affect to the whole of the long wall, smaller displacements are calculated when compared to the short side.
- PSR values which were calculated with Plaxis results are compared with the ones calculated with considering method submitted by Finno et al. (2007). It is seen that PSR values calculated with Plaxis models are below the values calculated with this method.
- In the first case excavation pit is not rectangular and has variable excavation depths. In the second there are heavy surcharge loads which are not a direct parameter of the calculation method submitted by Finno et al. (2007). Also surcharge load is not symmetric and there are barrettes which effects basal heave. All these reasons can be related with the incompatibility of calculated PSR values.
- In both cases since excavation phase will initiate shortly, no monitoring data could be provided for comparison, it is clear that with the results of comprehensive monitoring data in both cases the reasons of the incompatibility of PSR values could be evaluated.

These studies showed that with 3D calculations a more realistic approach could be provided for estimating displacements in problems that necessitate 3-D modeling.

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