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Soil- structure interaction assessment for a high-rise building at Perth CBD

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ABSTRACT

This paper presents an application of the soil-structure interaction concept, a major issue for high-rise buildings supported on raft foundations, to a proposed 28 storey building within the Perth CBD, Western Australia. The subsoil conditions at the site comprised inter-bedded medium dense to dense sands and stiff to very stiff clays overlying weathered bedrock. The structural loads were designed to be imposed on the raft via isolated columns, walls, lift core and shear walls. The FEAR computer software was used to model the soil-raft interaction by incorporating the effects of increased soil stiffness, due to a reduction in the in-situ overburden pressure at the foundation level caused by excavation, for serviceability loads. Iteration of analyses was required to arrive at reasonable thickness of the raft. Two approaches were adopted to model the effect of reduction in the in-situ overburden stress and the results in terms of deflections are presented. The effect of serviceability loads from the proposed building on the adjacent buildings has been assessed in terms of predicting additional settlements outside the proposed building footprint at raft foundation level. The settlement contours, assessed from the finite element analysis, have been presented.

1 INTRODUCTION

A 28 storey apartment building is planned to be constructed within the Perth CBD. As schematically shown in Figure 1, the apartment building is bounded by Adelaide Terrace to the north, an 8 storey building to the west and south, and a 12 storey building to the east.

The site is generally flat and occupies an area of about 800m^2. From the south eastern boundary, the ground surface falls steeply towards the lower level of the 2 level basement car park of the existing 8 storey building.

The proposed 28 storey apartment building will abut to the adjacent existing buildings. The ground level will be at 11.5m AHD. The proposed building will have 2 basement levels at 8.3m AHD and 5.4m AHD, which will be linked to the basement levels of the 8 storey building to the south. The apartment building will also connect to the 8 storey building at above ground floor level 3 to the west. The 8 storey building is supported on conventional strip and pad footings. The proposed apartment building will be founded on similar level as the existing 8 storey building.

The adjacent 12 storey building to the east is founded on a large raft, which is located in the middle half of the total foundation area. The rest of the foundation area is supported on pad footings. The foundation level of the 12 storey building is about 7.8m AHD which is about 2.4m above the top of the raft foundation of the proposed building.

This paper presents the results of geotechnical studies carried out for the 28 storey apartment building. The field investigation and data interpretation undertaken to assess subsurface profile and geotechnical parameters for the studies are presented and discussed. Two approaches to modelling soil – structure interaction using Sydney University finite element software FEAR are presented and compared. The deflections obtained from FEAR analysis for the two approaches are graphically presented for comparison.

The effect of basement excavation for the proposed apartment building on the foundation of the adjacent 12 storey building is not within the scope of this paper.

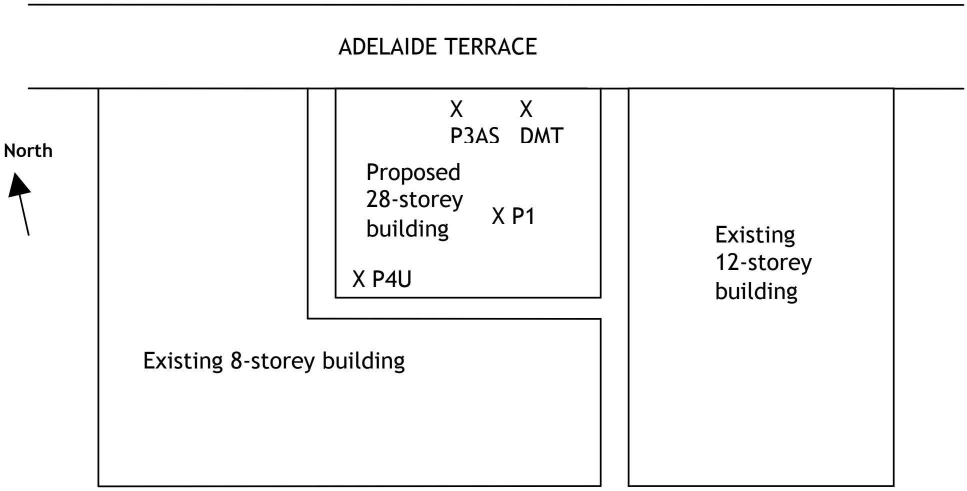


Figure 1: Location of Proposed Building and Investigation Test Sites

2 GEOTECHNICAL INVESTIGATION

2.1 Field Testing

The existing ground level of the building site is at 11.5m AHD. Locations of the field testing are shown in Figure 1 and comprised:

- 1 electric friction Cone Penetration Test (CPT) probe (P1) to a depth of 36.6m below the existing ground surface.
- 1 dilatometer test (DMT) carried out at depths of 2m, 5m, 8m, 11m, 15m, 20m, 26m and 27m below the existing ground surface.
- 1 CPT probe (P3AS) with 8 seismic cone tests carried out at depths of 2m, 8m, 14m, 19m, 25m, 30m, 34m and 35.3m below the existing ground surface.
- 1 CPT probe (P4U) with 4 pore pressure dissipation tests carried out at depths of 13m, 21m, 27m and 34.9m below the existing ground surface.
- Installation of one 32mm standpipe piezometer monitor groundwater level and collect groundwater sample for aggressivity test.

2.2 Subsurface Conditions

The CPT data obtained for the site are shown in Figure 2(a). Based on the results of the field investigation, the site has a generalised subsurface profile as summarised in Table 1. The soil layers interpreted from the CPT data for the site is shown in Table 1.

The groundwater level at the site during the time of field testing varied from approximately 5.8m AHD to 7.8m AHD. The Perth Groundwater Atlas, published by the Water & Rivers Commission of Western Australia (1997), indicates that the highest probable groundwater level at the site is about 7m AHD.

2.3 Interpretation of Soil Stiffness

Fahey *et al.* (2003) suggested an equation to represent the relationship between Young's Modulus (E) and cone resistance (q_C) initially provided by Baldi *et al.* (1989) for an axial strain of 0.1%

representative to actual footing settlement. The equation for aged normally consolidated sand is given below and the estimated Young's Modulus profile is shown in Figure 2(b).

$$E = (105 \pm 25) \times \sqrt[3]{q_c \times \sigma'_{vo} \times P_{atm}} \qquad (1)$$

where: σ'_{vo} = Effective overburden stress
P_{atm} = Atmospheric pressure

The stiffness of soils that can be assessed from seismic data is considered small strain shear modulus (G_0). It can be estimated using the following equation:

$$G_0 = \rho V^2 \qquad (2)$$

where: ρ = Soil density
V = Shear wave velocity

Figure 2 presents a comparison of soil stiffness interpreted from CPT, dilatometer and seismic tests. It has been found that the small strain soil stiffness is 1.5 to 4.5 times the soil stiffness derived from dilatometer tests, which is comparable with Fahey *et al.* (2003) results for Perth CBD soils.

The stiffness of the foundation soils was primarily interpreted from the dilatometer data with some considerations given to CPT and seismic test data. Fahey *et al.* (2003) demonstrated in their studies of high rise building foundations within the Perth CBD that the soil strain induced in the dilatometer testing is comparable with the degree of soil straining underneath building foundations.

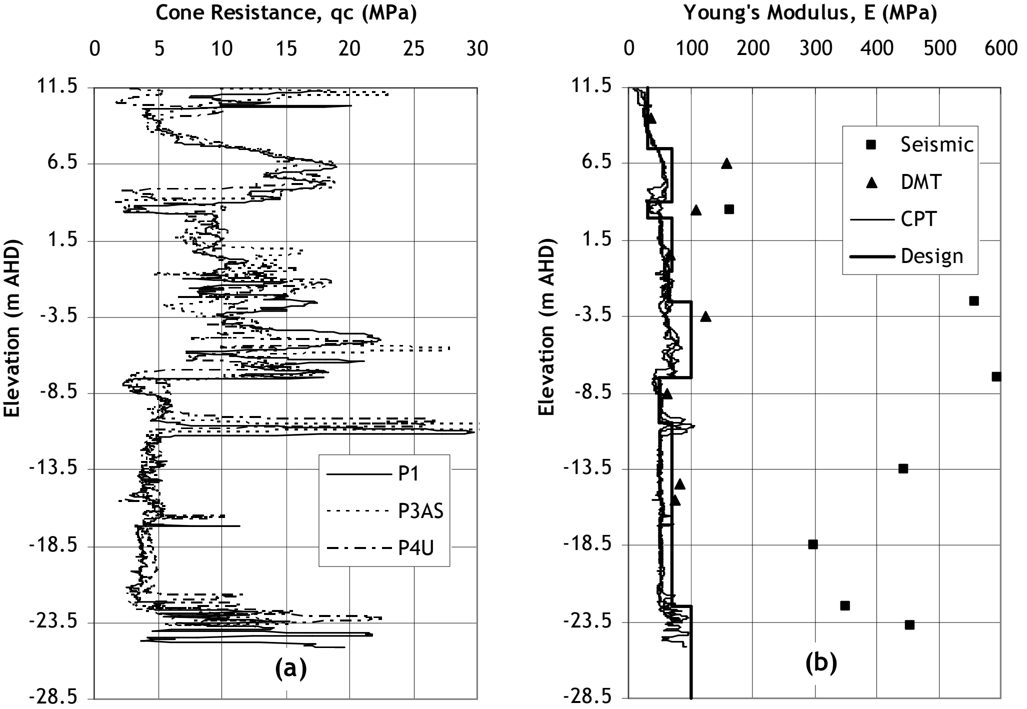


Figure 2: Interpreted Soil Stiffness

3 GEOTECHNICAL MODEL

The geotechnical model adopted for the analysis of raft foundation for the proposed 28 storey apartment building is presented in Table 1.

Table 1: Subsurface Profile and Geotechnical Model Adopted

Subsurface Profile			**Elevation (m, AHD)**	**Thickness (m)**	**Elastic Modulus, *E* (MPa)**	**Poisson's Ratio, *ν***
Layer	**Description**	**Geological Unit**				
1	Fill Sand (medium dense)	Recent Fill	11.5 to 10.0	1.5	30	0.3
2	Sand (medium dense)	Tamala Sand	10.0 to 7.5	2.5	30	0.3
	Sand (dense)		7.5 to 4.0	3.5	70	0.3
3a	Clay (stiff to very stiff)	Guildford Formation	4.0 to 3.0	1	30	0.3
	Sand (medium dense)		3.0 to -0.5	3.5	70	0.3
	Silty / Sandy Clay (very stiff)		-0.5 to -2.5	2	65	0.3
	Sand (medium dense to dense)		-2.5 to -7.5	5	100	0.3
	Clay (very stiff)		-7.5 to -10.5	3	50	0.3
3b	Clayey Sand (medium dense to dense)		-10.5 to -22.5	12	70	0.3
4	Weathered siltstone / shale.	Kings Park Formation	< -22.5	> 10	100	0.3

4 ANALYSIS

4.1 Design Loads

The performance of the raft foundation has been assessed for design using the Sydney University finite element software FEAR Version 7 for serviceability load (i.e. dead Load + 0.7 x live Load), ultimate load and wind load. In this paper, the results are presented in terms of settlement for the serviceability loads only. The raft is assumed to have a Young's modulus of 30GPa. The raft thickness analysed varies from 1.0m to 1.3m except at the location of the edge walls and shear walls. It should be noted that the FEAR program does not take into account superstructure rigidity. Since the edge walls and shear walls contribute to the foundation rigidity, the raft thickness at the edge and shear wall locations were appropriately increased to model the soil structure interaction. This modification provided reasonable bending moments and shear forces from the FEAR program that were comparable to the results from structural analysis undertaken by the project structural consultant.

4.2 Modelling Approaches

The 7.7m deep excavation for basement construction would have the effect of reducing the bearing pressure from the building on the foundation soil. The net bearing pressure on the foundation soil would be the bearing pressure due to building loads minus effective weight of the excavated soil. Hence, building settlements can be anticipated to be less than settlements without the basement excavation. Since building loads are transferred to the raft through shear walls and columns, it may be inappropriate to use net uniform bearing pressure to obtain bending moments, shear forces and contact stresses in the raft. To model the effect of excavation on the raft foundation behaviour under building loads, two modelling approaches have been employed as discussed below.

4.2.1 Approach 1

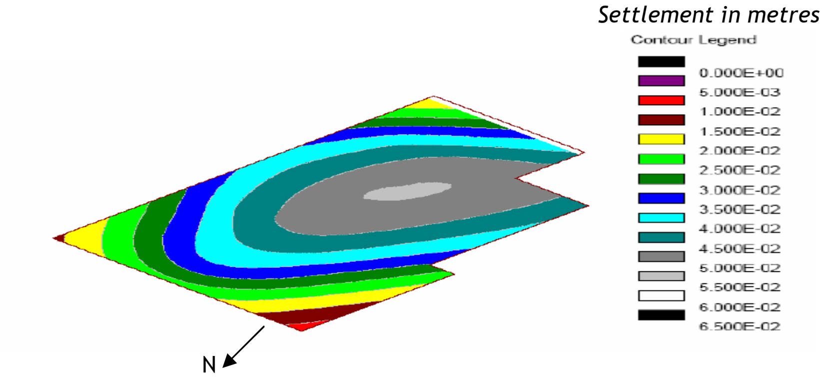
In this approach, the stiffness of the soils underneath the raft have been adjusted and increased to allow for reduction in raft settlement due to the effect of excavation. FEAR analysis was initially undertaken to assess settlements of raft subject to a uniform load equivalent to the net building pressure. The actual locations and magnitude of the building loads were then used, and FEAR analysis iteration with soil stiffness adjustment was carried out until the calculated raft settlements were reasonably similar to those calculated using the net building pressure. It was found that Layers 3a and 3b (the soil layers below the raft) would have to be adjusted to 1.5 times their stiffness values indicated in Table 2 to produce similar raft settlements. Since the foundation soil is unloaded during excavation and reloaded with the building structure past the present overburden stress level, an adjustment factor of 1.5 to the soil stiffness appears to be reasonable. Because the actual locations and magnitude of the building loads were used in the analysis, the calculated raft bending moments, shear forces and contact stresses were likely to be reasonable.

4.2.2 Approach 2

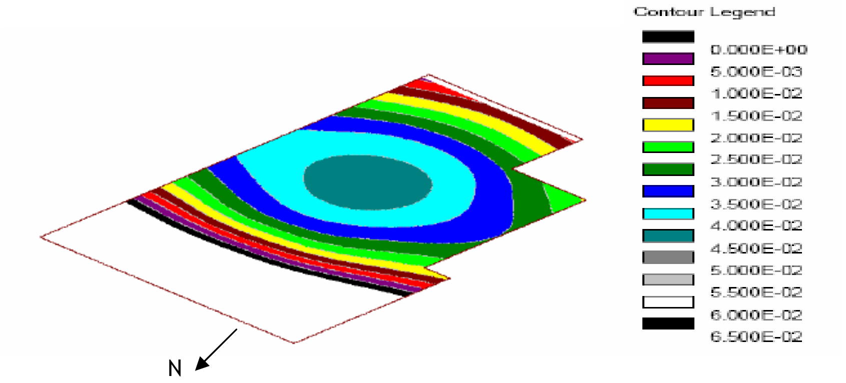
In this approach, the unadjusted soil stiffness values in Table 2 have been used directly in the raft analysis. The effect of excavation on raft settlements were modelled in FEAR by applying a negative (upward) uniform load of about 75kPa, which was equivalent to the net reduction of overburden stress due to excavation and raft construction. The second approach was undertaken primarily to compare with Approach 1.

4.3 Results of FEAR Analysis

The primary settlement contours for the two modelling approaches under serviceability loading have been presented in Figure 4.



Approach 1



Approach 2

Figure 4 Computed raft settlements

Figure 4 shows that maximum raft settlements of 55mm (Approach 1) and 45mm (Approach 2) occur within the vicinity of the lift core where building loads are the largest. The shapes of the settlement contours for the two approaches are different, with Approach 2 indicating zero settlement within the northern third area of the raft, which may not be realistic.

4.4 Influence to Adjacent Buildings

The excavation (stress unloading) for the basement and building construction (stress loading) can cause distress to nearby buildings. The effect could be potentially severe and result in large differential settlements if basement excavation level is below foundation level of nearby existing buildings. The effect of structural loads from the proposed building on adjacent buildings has been assessed in terms of increase in settlements. The settlement contours beyond the proposed building footprint at the raft foundation level has been predicted using FEAR. The modeling assumes that the subsurface profile and geotechnical parameters underneath the adjacent buildings are the same as in Table 1. The soil layers underneath the adjacent buildings are assumed to be unaffected by basement construction. Hence, Approach 1 cannot be directly used to assess the settlements. The modeling adopted for the purpose involved using the geotechnical parameters in Table 1, and applying a net building pressure to the raft calculated as contact stresses estimated from Approach 1 minus the effective weight of the excavated soils. The predicted settlement contours (i.e. additional settlements for the nearby buildings due to the construction of the proposed building) are presented in Figure 5. The estimated primary settlements are the effects at the foundation level of the proposed building beyond the proposed building footprint due to serviceability load only and do not consider the effect of basement excavation and stiffness of foundation of adjacent buildings.

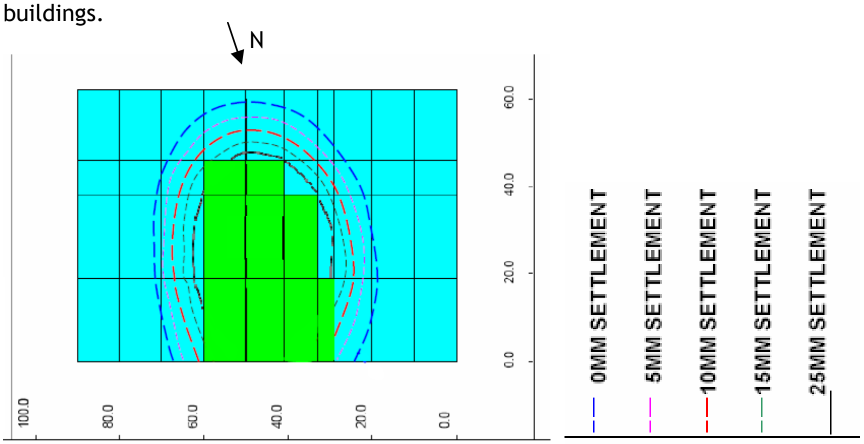


Figure 5 Predicted settlements contours underneath nearby buildings

5 CONCLUSIONS

The following conclusions can be drawn from the soil structure interaction analysis of the 28-storey building in Perth CBD.

- The maximum settlement calculated from the two different modelling approaches (Approach 1 and 2) are similar. However, the shapes of the settlement contours from the two approaches are different, with Approach 2 indicating zero settlement within the northern third area of the raft, which may not be realistic.
- The effect of superstructure rigidity on the raft foundation can be approximately modelled by increasing the raft thickness at the locations of the load bearing shear walls and edge walls.
- The construction of a new high rise building can affect the performance of nearby buildings due to increase in settlements. The increase in settlements for the nearby buildings can be estimated using FEAR.

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