

Numerical Modelling of Tiered Retaining Walls

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ABSTRACT

Tiered retaining walls tend to be constructed on property boundaries to address planning requirements with respect to excavations on the boundary, and/or for aesthetics (e.g., improve sunlight, reduce mass, etc.), and may be constructed independently as adjacent sites are developed. The interaction between tiered cantilevered pole walls is not well researched. This paper summarises the finding of the author's masters research, which consisted of numerical analysis of tiered retaining walls using two finite element analysis software programmes, RocScience RS2 (finite element analysis software) and WALLAP (pseudo-finite element software). The numerical analysis was undertaken in three parts. Analysis of single retaining walls to establish baseline results, utilising both RS2 and WALLAP to calculate the internal forces (bending moments and shear forces) and associated deflections; analysis of the variation in internal forces and deflections with changes to the in-plane spacing between tiered retaining walls utilising RS2; and analysis of equivalent tiered walls loads using WALLAP. The results showed that the effective retained height of the lower wall approaches the combined retained height of the tiered retaining walls as the spacing between the walls approaches zero. This increase in the effective retained height can be detrimental to the stability of the walls, particularly in situations where the interaction has not been considered.

Keywords: tiered cantilever pole retaining walls, overlapping earth pressure wedges, numerical modelling.

1 INTRODUCTION

This paper summarises research into the interaction between closely spaced cantilever pole retaining walls with vertical offsets (tiered retaining walls). There is minimal guidance for the design of tiered retaining walls, and architects and civil/structural designers tend to overlook the potential interaction and associated loads in concept designs.

Tiered retaining walls are commonly used on boundaries to address planning requirements with respect to boundary excavations or constructed independently as adjacent sites are developed. The research reviewed relevant literature and undertook numerical analysis using two finite element analysis software programmes (RocScience RS2 and WALLAP), and assessed the interaction between tiered cantilever pole retaining walls.

2 BACKGROUND AND LITERATURE REVIEW

2.1 Types of Retaining Walls

Retaining walls are structural elements used to support ground that is either cut or filled. They tend to be linear structures that are assessed in terms of plain strain. Retaining walls are therefore visualised by an in-plane cross section through the wall, although some walls approach axisymmetric situations such as relatively localised excavations/shafts (Das, 2010). There are a range of different retaining wall types that are based on variations or combinations of the following three main types, gravity walls, cantilever walls, and tied-back/anchored walls (US Army Corps of Engineers, 1989).

Gravity retaining walls use the mass of the structural element to resist the overturning forces from the soil being supported (Das, 2010). Larger retained heights therefore require heavier walls to resist the applied forces. They transfer the lateral forces applied to the wall into vertical pressure and require the founding soil to have sufficient bearing capacity. Therefore, the bearing capacity of the founding soil can limit the retained height. Typical examples of gravity walls are gabion baskets walls, mass block walls, and crib walls.

Cantilever retaining walls are detailed to resist internal bending moments and shear forces and use soil mass to counteract the overturning forces applied (Derucher, et al., 1978). There are two main forms, pole walls and concrete cantilever walls. Pole retaining walls utilise closely spaced piles with or without rails to distribute the force between piles. The pile embedment is selected based on the soil mass required in front (downslope) of the wall to resist the forces behind (upslope) of the wall, and the pile dimensions are sized and detailed to resist the bending moments and shear forces generated by the lateral forces on the wall. Concrete cantilever walls (i.e., masonry block or tilt slab) utilise a shallow footing and transfer the lateral forces into bearing pressures similar to gravity walls. This method reduces the mass of the structural elements that are required for gravity walls systems. The stem (vertical member) and base of the wall are sized and detailed to resist the bending moment, and shear forces generated.

Anchored or tied-back walls use horizontal forces from anchors/reinforcement to resist some or all the pressure applied to the wall (Federal Highway Administration, 1999). They can take forms similar to either gravity or cantilever type walls, such as reinforced soil walls (mechanical stabilised earth wall or soil nailed walls), or pile walls with one or more rows of anchors (the anchors can be attached to deadmen, bulkheads, embedded piles, or a rod/tendon grout bonded into the soil/rock) (Federal Highway Administration, 1999). The anchor(s) provide support to the pile, stem or face of wall which reduces the maximum moment and the mass of soil required in front of the wall, and therefore can reduce the section size and embedment depth of the pile.

2.1 Tiered Retaining Walls

Tiered walls are defined in this paper as two or more walls that are parallel, or near parallel, with a vertical offset between the walls. These are also called terraced retaining walls, parallel retaining walls, or twin retaining walls (if a pair of walls).

There are some design manuals for gravity-type tiered walls that discuss replicating the influence by utilising a surcharge equivalent to the weight of soil supported by the wall (NCMA, 2010). However, there was negligible literature on tiered cantilever pole retaining walls with vertical offsets identified during the research. The available information tended to be planning documents produced by local territorial authorities (LTAs), which were generally associated with planning limitations. The LTA documents did not tend to reference how to design for these walls or discuss potential for proximate walls to influence each other.

Research into closely spaced retaining walls is generally limited to parallel walls without a vertical offset, such as walls utilised for silos, wharfs, jetties, docks, and cut off walls such as those discussed by Onsa (2015) and others. These walls benefit from the reduced spacing between the walls, and these walls tend to move away from each other, and the overlapping active pressure wedges effectively share and reduce the active earth pressures acting on each wall.

2.1 Lateral Pressures

The forces on cantilever pole retaining walls are the result of the combination of several lateral (horizontal or near horizontal) pressures applied to the back of the wall, and these forces can also be partly or wholly resisted by lateral pressures applied to the front of a wall. The main lateral pressures comprise earth pressures, surcharge pressure, water pressure, and seismic pressure (Derucher, et al., 1978).

Lateral earth pressures are typically expressed as a triangular pressure distribution and is related to the vertical stress at a given depth within the soil and rock, soil parameters, stress history of the soil, shear stresses applied to the soil, slope and wall geometry, and wall friction (Das, 2010; Rankine, 1857; and Coulomb 1776). The lateral earth pressure in ground proximate to retaining wall (upslope and downslope) are dependent on and described by the relative movement of the wall as either at-rest (for no movement of wall), active (with movement of wall away from the soil), or passive (with movement of wall towards soil) pressure. Active and passive wedges are inferred to develop above and below the wall. The detrimental effects of overlapping passive pressure wedges are discussed for closely spaced piles by Broms (1964a; 1964b) and anchors FHWA (1999) and others. However, discussion of overlapping active and passive pressure wedges (which likely occur with closely spaced tiered retaining walls) was not identified during the literature review and is considered by the author to be a critical factor in the interaction of tiered retaining walls.

Surcharge pressures tend to be applied for an “infinite” width behind the retaining wall and treated as a rectangular pressure block (opposed to triangular soil pressure) to simplify the analysis (NCMA, 2010; and Derucher, et al., 1978). Alternatively, the stress from surcharge loads can be specifically calculated based on work by Boussinesq (1883).

Water can develop various pressures on retaining walls, which include hydrostatic, seepage, hydrodynamic, ice, and swelling pressures (Bellezza, et al., 2009; Derucher, et al., 1978; and NCMA, 2010).

Seismic accelerations from earthquake events can result in horizontal and vertical accelerations of the soil and wall (gravity wall), and the associated inertial forces can destabilise retaining walls. For rigid gravity walls the inertial force related to the weight of the wall is considerable and should be considered alongside soil seismic loads. Whereas, cantilever pole retaining walls tend to have relatively minimal mass and the acceleration of the soil wedge will be critical for the loading on the wall.

3 METHODOLOGY

To assess the potential interaction between tiered cantilever pole retaining walls, numerical modelling was undertaken in three stages:

1. Single Retaining Wall Modelling using RS2 and WALLAP
2. Tiered Retaining Wall Modelling Using RS2
3. Approximate Tiered Retaining Wall Modelling using WALLAP (not discussed in this paper)

3.1 Single Retaining Wall Modelling

A range of single retaining wall models (base and sensitivity scenarios) were set up to establish the baseline results for pole retaining walls for a range of soil and wall parameters and retained heights (between 1m and 4m heights). This enabled interaction to be assessed for the tiered retaining wall modelling which undertaken in the later stages, and allowed for comparisons to be made between modelling software. The base case and associated parameters are presented in Figure 1 (lower wall only).

The sensitivity models were set up by varying a single parameter from the base case. The following ten parameters were adjusted from the base model for the sensitivity scenarios: embedment depth, soil friction angle, cohesion, Youngs Modulus of soil, surcharge, ground slope, groundwater depth, and bending stiffness (EI) of wall.

The results of each software (RS2 vs WALLAP) and sensitivity cases (sensitivity vs base) were compared to establish a relative percentage difference for the maximum bending moments (BM), shear forces (SF), and deflections (Δ).

3.2 Tiered Retaining Wall Modelling

The tiered retaining wall models have been developed utilising the single wall base case parameters for a range of retained height and proximity combinations. A sketch of the tiered walls is presented in Figure 1. The base case parameters have been maintained from the single retaining wall analysis.

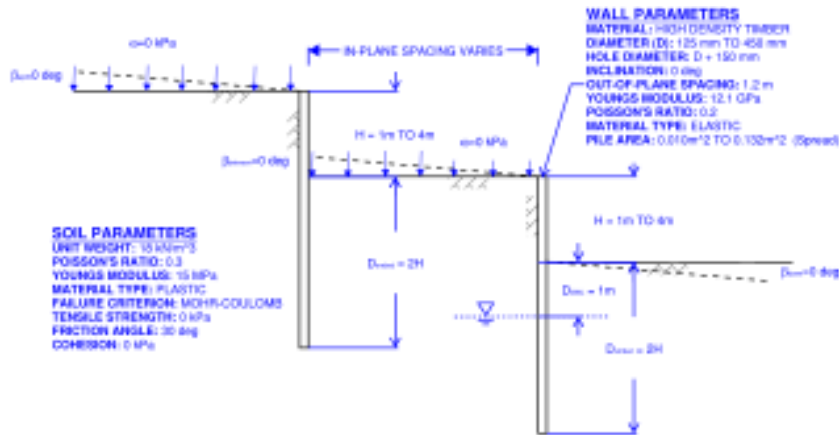


Figure 1: Tiered retaining wall base model and parameters

The retained height combinations have been developed based on 1 m retained height increments ranging between 1 m to 4 m. This enabled a six sets of various retaining wall combinations to be assessed. Each set was named based on the retained height of each wall (e.g., 2 m high upper wall and 3 m high lower wall was named 2-3).

Each set of retained height combinations has been modelled with six different in-plane spacings between the walls. The spacings range from remotely spaced (Model 1) to closely spaced (Model 6). The spacing between the walls are proportional to the retained height of the retaining walls being modelled. The in-plane retaining wall spacings for Models 1 to 6 are summarised below:

- **Model 1:** Developed so that lines projected at 45° and 60° from the bottom of each pole in the lower and upper wall (respectively) would touch (i.e., outside the influence if both walls were rotating about the base of the poles).
- **Model 2:** Developed as average spacing of Model 1 and Model 3
- **Model 3:** Developed so that an active wedge of the lower wall and a passive wedge of the upper wall, projected at 45° and 60° (respectively) from the retained height minus 0.5 m below the ground level at the toe would touch (i.e., rotation of each wall at the approximate depth of maximum moment).
- **Models 4, 5, 6:** Developed to be three-quarters, half, and quarter of the in-plane spacing of Model 3, respectively.

The results of each model were compared against the single wall and Model 1 results to establish a relative percentage difference for the maximum bending moments (BM), shear forces (SF), and deflections (Δ).

4 RESULTS

The maximum BM, SF, and Δ results for the single retaining wall base case has been presented in Figure 2, with 1%, 5% and 10% displacement of retained height for reference (dashed). The range of results for the lower walls has been presented based on the combined height for the tiered wall for comparison.

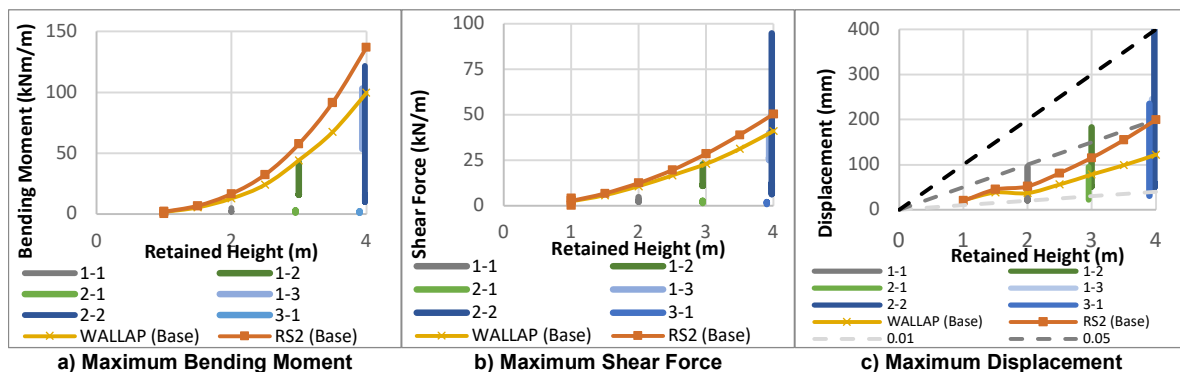


Figure 2: Comparison of Lower Wall results against the single wall baseline results for the lower tiered retaining wall

The selected total displacement outputs and variation of selected tiered wall model relative to Model 1 results have been presented below. The bending moment variations are presented on Figure 4, shear forces variations are presented on Figure 5, and displacement variations are presented on and Figure 6.

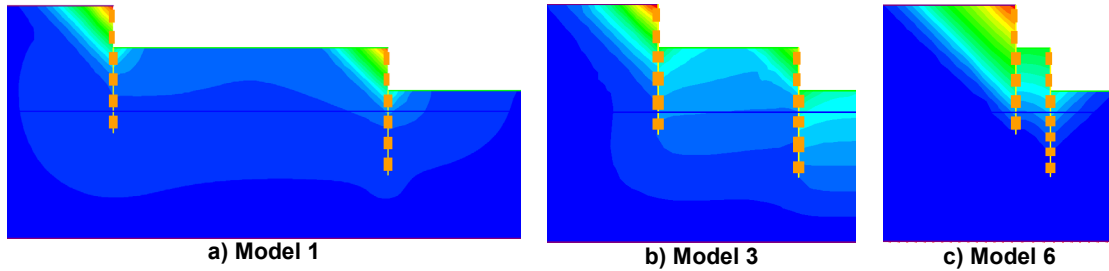


Figure 3: Selected RS2 total displacement outputs for Tiered Wall Scenario 2-2

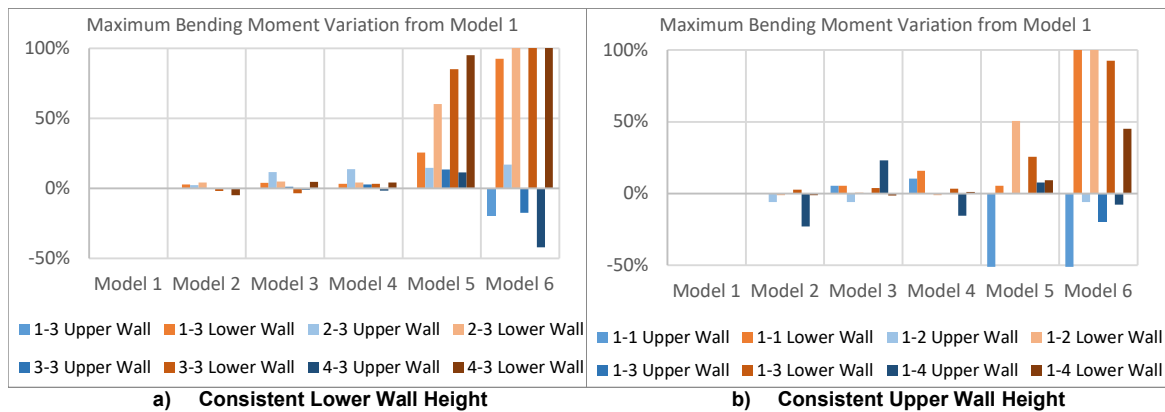


Figure 4: Selected tiered retaining wall bending moment variation relative to Model 1 with in-plane spacing

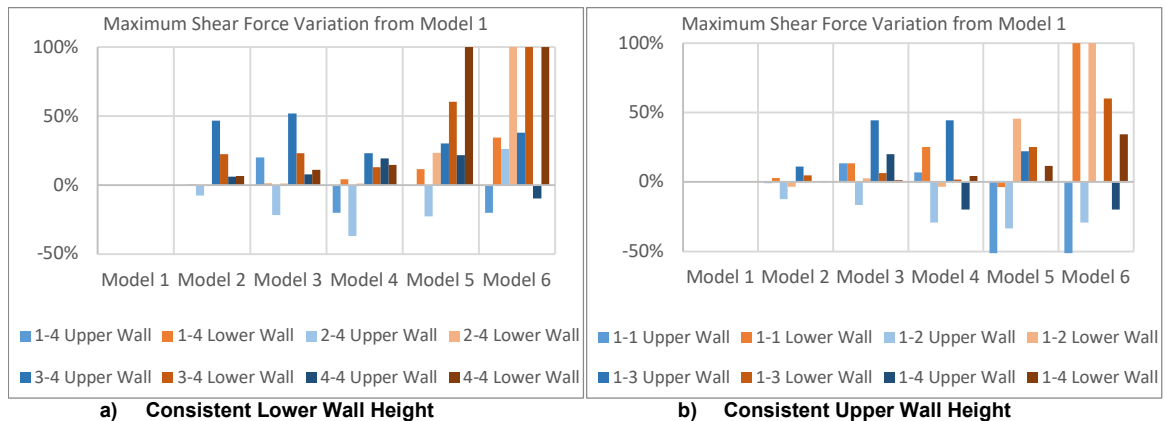


Figure 5: Selected tiered retaining wall shear force variation relative to Model 1 with in-plane spacing

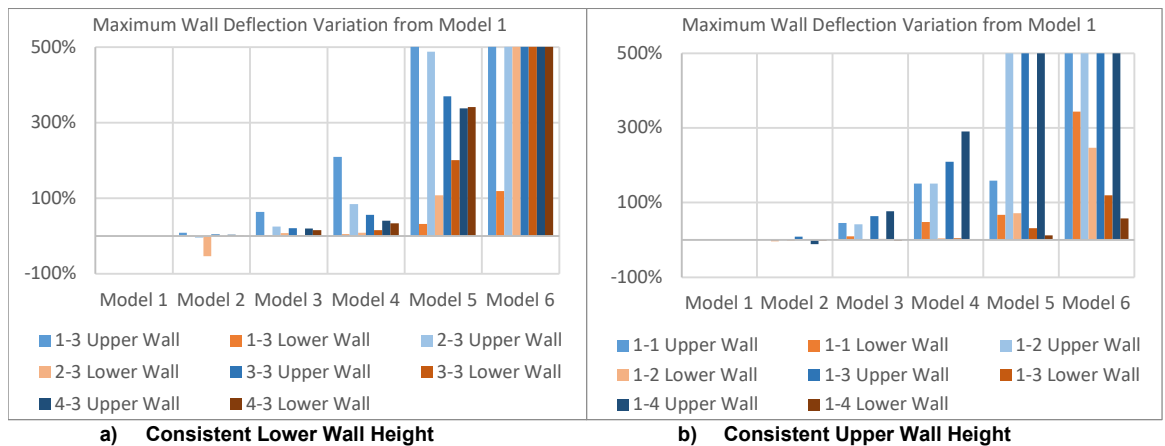


Figure 6: Selected tiered retaining wall displacement variation relative to Model 1 with in-plane spacing

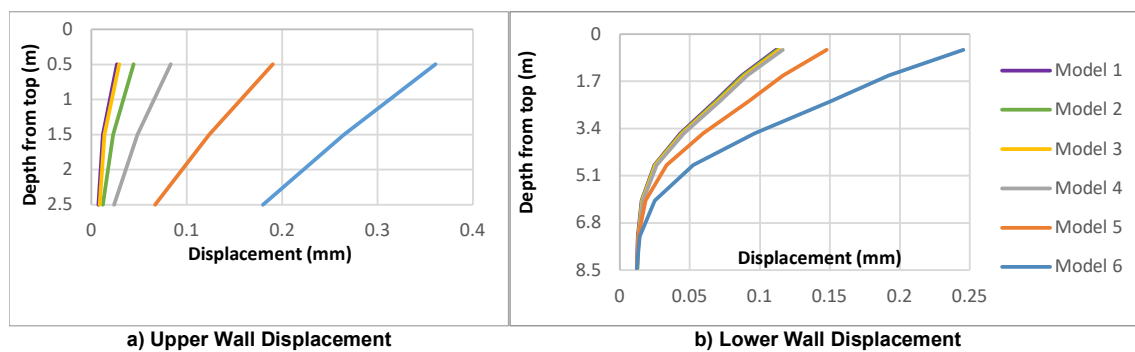


Figure 7: Deflection (Δ) results for Tiered Wall Scenario 1-3

5 DISCUSSION

5.1 Single Retaining Walls

The calculated BM, SF, and Δ results for the single wall modelling tended to be 22%, 15%, and 25% less respectively in WALLAP than RS2 (Figure 2). There was a similar trend for all of the sensitivity models (i.e., RS2 results were larger than WALLAP results), except for the models that included soil cohesion. The selection of the non-linear modulus (L_0) parameter in WALLAP appears to be the main parameter that results in the variation between the two software. Reduction to an L_0 to zero reversed the differences for BM and SF and resulted in the Δ calculated to be between 50% and 100% higher in WALLAP than RS2.

5.1 Tiered Retaining Walls

The graphical output from the modelling (Figure 3) showed most of the displacement of the soil occurred within apparent active and passive pressure wedges. These wedges approached in Models 1 to 3 and overlapped to varying degrees in Models 4 to 6. This overlap has resulted in additional load being transferred to the lower wall the displacement of the both walls. There was also slight displacement of the soil beyond these wedges, and this is attributed to the early displacement of the upper walls.

The overlap of lateral earth pressure wedges results in effective retained height of the lower wall approaching the combined height of both walls as in-plane spacing between the walls approaches zero. The embedment depth of each wall has been set as 2H for the height of the subject wall rather than the combined height of each wall, and embedment depths between 1H to 2H would be typical for independently developed walls. The increase of the effective retained height from the wall height to the combined height of the tiered walls results in a decrease of the ratio of embedment depth to retained height (from 2H). The corresponding deflection of closely spaced walls is excessive, which was also observed in the sensitivity results of the single wall with embedment depths between 0.5H and 1H.

There were also specific trends identified for the lower and upper retaining walls based on relative heights of each wall, which are discussed below.

5.1.1 Lower Retaining Wall

For a lower wall with a constant height, pile diameter, and embedment depth, the maximum BM (Figure 4a), SF (Figure 5a), and Δ (Figure 6a) of the lower wall tends to increase with an increase of the retained height of the upper wall. This is due to additional pressure from the upper wall which results in increased pole diameter and embedment depth requirements. An example is a comparison of Scenario 1-2 with 4-2, as the walls become more closely spaced, the retained height of the lower wall increases from 2 m to an effective (combined) retained height of 3 m for Scenario 1-2 and 6 m for Scenario 4-2. This leads to additional active pressure on the wall, which is observed by the increase of BM and SF. This also results in a decrease of the embedment ratio from 2H (for remotely spaced walls) to 1.33H (Scenario 1-2) and 0.67H (Scenario 4-2). The associated increase in Δ is related to both an insufficient embedment depth to generate resistance to overturning, and an insufficient pile diameter to limit the mechanical deflection of the wall. The deflections calculated would likely be detrimental to the stability of the walls and use of the land above the walls. Reducing the in-plane spacing between the wall should be compensated by an increase of the pile diameter and embedment depth of the lower wall to resist the increased forces, and the increase is dependent of the proximity of the walls and the combined retained height.

For an upper wall with constant height, the maximum BM (Figure 4b), SF (Figure 5b), and Δ (Figure 6b) for the lower wall tends to decrease with an increase of the retained height of the lower wall. An example is a comparison of Scenario 1-1 with 1-4. As the walls become more closely spaced, the retained height of the lower wall increases for Scenario 1-1 from 1 m to an effective (combined) retained height of 2 m (100% increase of H) and Scenario 4-1 from 4 m to 5 m (25% increase of H). Active pressures are positively related to height, so a smaller increase in H would typically result in a smaller proportional increase in BM and SF, as was observed. The proximity also results in a varied decrease of the embedment ratio from 2H (remotely spaced wall) to 1H (Scenario 1-1) and 1.6H (Scenario 1-4). The diminishing variation in Δ from the baseline with the increase of the lower wall height is suggested to be related to the decrease of the embedment depth ratio coupled with an increase in the pile diameter of the lower wall from 125 mm (Scenario 1-1) to 450 mm (Scenario 1-4).

5.1.2 Upper Retaining Wall

Unlike the lower wall, the trend for BM (Figure 4) and SF (Figure 5) for the upper wall relative to the baseline results is unclear. There is no variation of loading on the upper wall with the proximity of the walls, therefore, BM and SF increases are not expected. The variation observed is likely associated with variations in the deflection of the soil between the walls and associated lateral displacement (shorter upper walls) or bending (longer upper walls).

For a lower wall with a constant height (Figure 6a), the maximum Δ of the upper wall tends to decrease with an increase of the retained height of the upper wall. This is suggested to be due to the increase embedment depth (and pole diameter) of the upper wall which assists in minimising lateral displacement of shorter wall and the increase of bending stiffness as the pole diameter increases. Conversely, given the same height upper wall (Figure 6b), the Δ of the upper wall tends to increase with an increase of the retained height of the lower wall. This is suggested to be related to lateral displacement which is facilitated by increased displacement of the soil block between the walls and the lower wall, discussed above, the soil supporting the upper wall moves as the lower wall deflects and the total deflection of the wall increases with the increase in the combined retained height.

6 CONCLUSION

The baseline single wall models using RS2 and WALLAP identified slight to moderate differences in the calculation of internal forces and deflection of the wall, with RS2 generally calculating additional bending moments, shear forces and deflections than WALLAP. Nevertheless, the variation of the results for the analysis of eight sensitivity parameters relative to the baseline results was similar magnitude for each software, and resulted in variation of internal forces and deflection in agreement with the literature.

The modelling of cantilever pole tiered retaining walls showed that the internal forces (bending moment and shear forces) within the lower wall and associated deflections increased as the walls became more closely spaced, and the effective retained height of the lower wall approaches the combined height of both walls as in-plane spacing between the walls approaches zero. This is due to the transfer of load between the walls, and the variation of the relative depth of embedment and section capacity enabling larger the displacements (overturning and mechanical deflection).

There was no obvious trend with the internal forces for the upper wall, which is expected given there is no additional loading, and variations were dependent of the displacement of the soil between the walls and relative length of the wall, i.e., shorter upper walls were more likely to displace laterally. Deflection of the upper wall was shown to increase as the tiered walls became more closely spaced and as the soil supporting the wall displaced due to the additional loading and associated deflection of the lower wall.

The specific effects on each wall depend on the relative height and wall spacing, and should be assessed specifically when they are close enough for pressure wedges to overlap (i.e., Model 3 or closer). Displacement of the upper wall increasing initially and increases in internal loading increasing sharply with reduced proximity.

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