

APPLICATION OF COMPOUND DEEP CEMENT MIXED WALLS FOR RETAINING STRUCTURES IN EXCAVATIONS

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ABSTRACT

Deep cement mixed (DCM) columns are widely used as retaining structures to support deep excavations due to low cost and their ability in reducing seepage. However, the tensile strength of DCM walls is very low. Hence, large wall sections are necessary to avoid development of high tensile stresses when DCM walls are used to support deep excavations. In this paper application of compound DCM walls, which integrate DCM walls and bored piles, to support deep excavations are investigated aiming to develop resilient design methods for compound DCM walls. Three-dimensional finite element modelling is used in simulating the wall behaviour during deep excavations, considering the full geometry of the compound DCM wall. Numerical model is validated using a case study of a compound DCM wall constructed in Shanghai, China. Finally the use of arched DCM walls with different curvatures in between bored piles is investigated. Results of this study clearly demonstrates the advantages and limitations of increased curvature of compound DCM walls with respect to both ground deformations surrounding the excavation and tensile stresses developed in the compound DCM wall.

1 INTRODUCTION

Deep Cement Mixed (DCM) walls are useful as retaining structures because they can retain earth and act as seepage barriers in the case of deep excavations. Retaining walls made out of DCM columns can be self-supported gravity structures or they can be supported by external elements such as anchors or bracings. However, due to very low tensile strength of cement stabilised soils, DCM walls do not have enough lateral load carrying capacity, which limits the maximum support depth of excavations. Hence different configurations of walls have been used in practice to make use of compressive strength of DCM walls while reducing the tensile stresses developed towards the DCM wall surface facing the excavation. If tensile stresses are developed, there is a tendency to develop cracks in the DCM wall increasing the permeability and deformation of the wall substantially. Normally steel reinforcements are used to increase the capacity of DCM walls to withstand tensile stresses, but the inclusion of reinforcements will increase the cost of retaining structure.

Shao et al. (1998) reported a case study, which used three rows of continuous parallel DCM columns with a discontinuous web structure as a self-supporting gravity wall without any reinforcement or external supports such as anchors or struts. Nicholson et al. (1998) introduced Vertical Earth Reinforced Technology known as VERT walls as a composite gravity wall. In a composite VERT wall system, a row of secant DCM columns are formed at the face of the excavation. Then rows of DCM columns are formed within the gravity retaining wall to provide additional strength. Number of rows and the clear spacing between DCM columns in the VERT wall system depends on the size of the excavation and the ground conditions. Finally DCM columns are capped together using soil slurry spoil from DCM column construction or in situ shallow cement mixing to provide a relieving platform for surcharge loads.

If planar DCM walls are used without steel inclusions, width of the wall needs to be about 50-60% of the excavation depth to minimise the tensile stresses developed over the wall section. In situations where availability of land for retaining wall construction is limited, design of planar walls without reinforcements is a challenge. Therefore DCM walls with steel inclusions are gaining widespread popularity as an excavation support and a seepage barrier in many projects (e.g., Yang 2003, Rutherford et al. 2007 and Gerressen and Vohs 2012). Briaud et al. (2000) reported the behaviour of a full scale VERT wall constructed in a sandy soil at National Geotechnical Experimentation site at Texas A&M University. They proposed to reinforce the front columns and to measure the tensile stresses developed in DCM columns routinely to ensure the factor of safety against cracking. Five modes of deformation; pure shear deformation, rigid body rotation, rigid body translation, rigid body settlement and bending were explained using the deflection values obtained.

In the conventional method of DCM wall construction, overlapping columns are formed by augers rotating about the vertical axis. In 2003, Bauer Maschinen developed Cutter Soil Mixing (CSM) method where rectangular overlapping DCM panels are formed by counter rotating wheels about the horizontal axis (Gerressen and Vohs, 2012). In both

methods, wide flange beams are inserted before the hardening of the cemented soil to increase the lateral load carrying capacity of the retaining structure.

Circular shaped retaining walls were constructed successfully without any reinforcement. This is possible due to the geometry of the wall as it has the capacity to develop compressive stresses while reducing the tensile stresses developed over the wall section. Blackwell (1992) discussed a circular DCM column structure consisting of three concentric unreinforced overlapping rings of 750 mm diameter columns constructed to support manholes. Application of semicircular DCM walls for excavation support were discussed by Stoetzer et al. (2005) and Capelo et al. (2012) using the CSM technology where the circular shape is approximated by a series straight wall panels.

Another construction technology used to minimize tensile stresses developed in DCM walls is the compound DCM walls with a series of arches made of DCM columns. These arches are supported by concrete bored piles at the end of the arches. The lateral load transfer mechanism is totally different to that of a traditional planar retaining wall. Here the arch shape is used to keep the DCM wall predominantly under compression. Hence the geometry of DCM walls with arches makes it possible to use them to support deep excavations without steel inclusions. Shao et al. (2005) reported a case history involving an arch shaped earth retaining structure to support a 9 m deep excavation.

This paper presents the finite element simulation of the above mentioned case study reported by Shao et al. (2005). In this case, the wall is made of a series of arches constructed using secant DCM columns. ABAQUS/Standard finite element program was used for the three-dimensional finite element modelling presented in the paper. Finally a parametric study is carried out to investigate the influence of curvature of the arch section constructed using a series of secant DCM columns on the deformation of the wall and stress distribution within the wall, especially the extent of tensile stresses developed within the arch section.

2 DESCRIPTION OF THE CASE HISTORY

The case study used in this section is an excavation carried out for the construction of an underground sewer line located on Jiangsu Road in Shanghai, China (Shao et al., 2005). The pipe used for the sewer line has an inner diameter of 2.46 m and a thickness of 0.2 m. The excavation is 9 m deep, 160 m long and needs to be at least 4.6 m wide to facilitate the installation of the pipe. A five storey manufacturing building supported by pile foundations is located 2 m away from the excavation. Another five storey building supported by a shallow spread footing is 2.5 away from the excavation. Along the entire length of the excavation, there is a single storey factory building with a basement. The shortest distance between the excavation and the factory building is about 3 m. Hence the ground deformations due to excavation need to be minimized to avoid damages to the existing foundations and buildings supported by them. A compound DCM wall with DCM column arches and bored piles at the toe of the arches was selected to support the 9 m deep excavation. The DCM wall is internally braced by two levels of struts as shown in Figure 1. The base of the excavation was stabilized by chemical grouting to avoid the requirement for higher embedment depth of the wall and to minimise the seepage through the bottom of the wall.

The DCM columns used for the construction of arch wall are 700 mm in diameter. The twin columns were constructed using a double auger mixing machine and they have an effective width of 1 m due to overlap between columns. The circular arch has a span, L , of 4.5 m and a radius, R , of 3.2 m. The effective wall thickness is doubled to 2 m from 5 to 10 m depth to increase the wall stiffness. This increased wall thickness is achieved by using two sets of twin columns. Reinforced concrete bored piles with 600 mm diameter are installed at the toe of the arches. The first level of struts was a reinforced concrete slab with dimensions 400 x 500 mm and it was placed 0.7 m below the surface level. The second level of struts was a set of wide flange beams and they were installed at a level of 5.5 m below the first level of struts, as shown in Figure 1.

The subsurface consists of very soft silty clay and clayey silt deposits from 2 to 15 m below the ground surface. The uppermost 2.0 m thick layer is a fill, which is underlain by a 4.4 m of dark gray soft clay. An 8 m thick soft silty clayey deposit is found at the depth of 6.4 m. The water table is at a depth of 1 m below the ground surface. Soil parameters are summarized in Table 1 (Shao et al., 2005) and discussed in Section 3.1.

The construction was started with the installation of twin DCM columns in arch shape. Then the installation of reinforced concrete bored piles was carried out. Bottom of the excavation was improved by injecting the cement based slurry before the excavation. After that the slab was casted and the excavation was carried out up to 5.5 m. Next, wide flange steel struts were installed and the rest of the excavation was carried out.

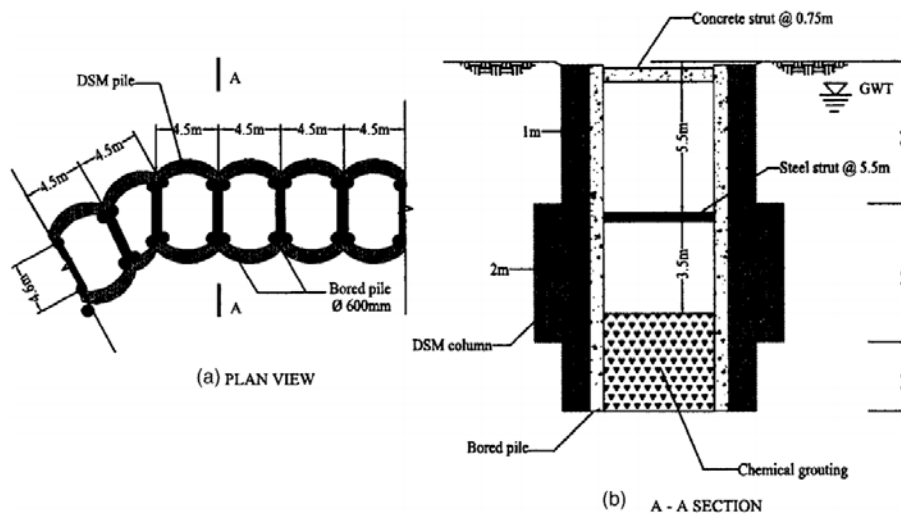


Figure 1: Plan view and cross section of the excavation (after Shao et al., 2005).

Table 1: Material properties used in the finite element model.

Material	Young's modulus of elasticity, E (MPa)	Poisson's ratio, ν	Cohesion c , (kPa)	Friction angle, ϕ ($^{\circ}$)	Unit weight, γ (kN/m 3)
Fill	40*	0.33*	5*	38*	18.5
Soft clay	4.2	0.4*	14	20	19.2
Soft silty clay	15*	0.4*	10	10	18.8
Grouting	420	0.3	20	20	20.0
DCM columns	72.5	0.3	210	25	20.0

Note: * denotes properties assumed based on published data for similar soil types.

3 NUMERICAL MODEL

The case study was modelled considering the three-dimensional geometry using the ABAQUS/Standard finite element program and the results were compared with the measured field data. Due to repetition of arches along the excavation, only one arch section between bored piles was considered in the finite element analysis as shown in Figure 2. Due to the limitation of data availability for the case study, a drained total stress analysis was carried out. Finite element mesh is developed using twenty-node solid continuum elements with reduced integration. The bottom boundary of the finite element mesh is restrained in x , y and z directions. The two vertical boundaries in the y - z plane are restrained in the x direction and the other two boundaries in the x - z plane are restrained in the y direction. The stress-strain behaviour of soil layers and DCM columns were simulated using the Mohr-Coulomb criteria with non-associated flow rule. In ABAQUS/Standard, when the friction and dilation angles are not the same, a non-associated flow rule is used. Although

strain softening behaviour is significant for cement stabilised soils, softening behaviour is not included in the analysis due to unavailability of material properties to simulate the strain softening behaviour. The concrete bored piles and the arch are connected and no relative movement is allowed between bored piles and the toe of the arch. This is a reasonable assumption because the wall and piles are constructed in-situ.

During the finite element analysis, excavation is simulated by removing elements. Due to unavailability of stiffness of struts, it is assumed that once a strut is installed at a particular level, bored piles will not displace laterally in the x direction. In the first step of the analysis first two rows of elements are removed simulating a 1 m deep excavation. Then in the second step, the first set of struts is installed. During analysis steps three to six, 4 m of soil was removed and then the second set of struts is installed. During the last three steps of the analysis another 4 m of soil is excavated, making the total excavated depth to 9 m.

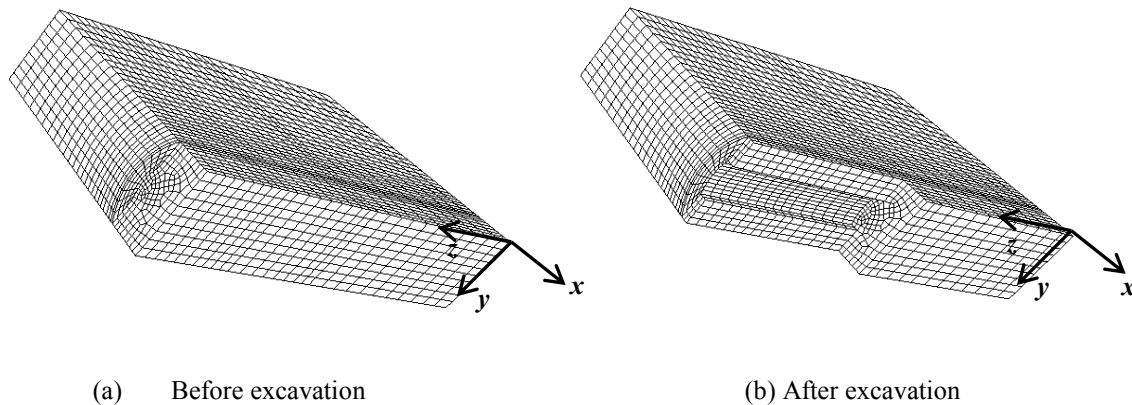


Figure 2: Finite element mesh before and after excavation.

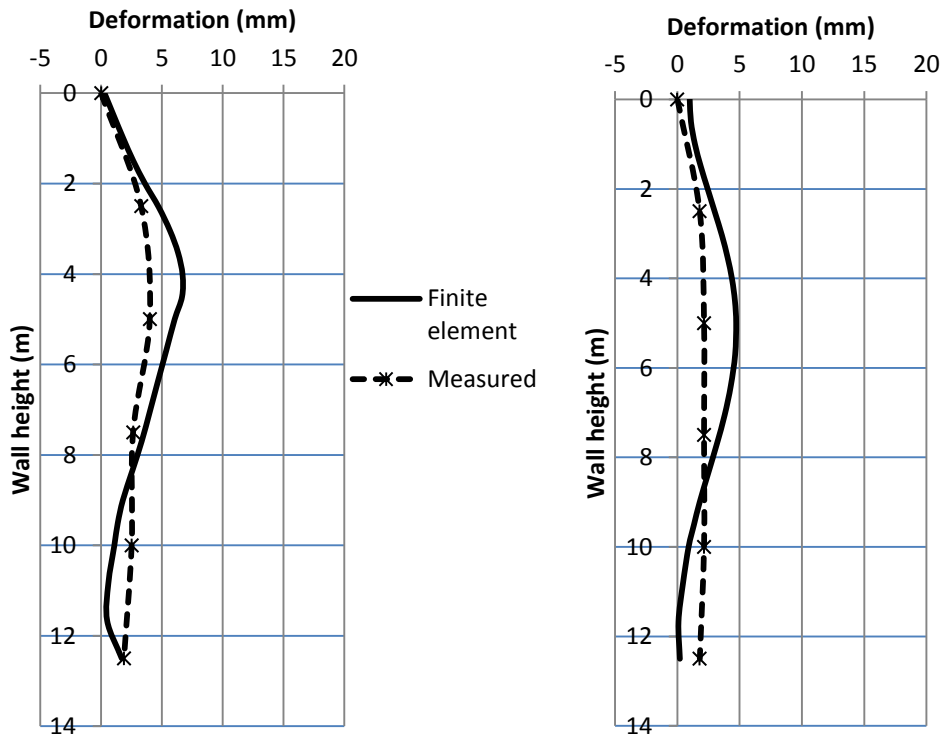
3.1 MATERIAL PROPERTIES

Soil properties used for the finite element analysis are given in Table 1. Properties for all soil layers necessary to carry out the finite element analysis are not given by Shao et al. (2005). Those properties are selected based on published data for similar soil types. Bored piles are modelled assuming elastic behaviour. Bored piles were assigned a Young's modulus of elasticity of 35×10^3 MPa and Poisson's ratio of 0.3.

Samples were collected from test DCM columns constructed before the wall construction to determine the unconfined compressive strength of cement stabilised soil. For the 15 samples tested, average unconfined compressive strength, q_u , was 721 kPa. This value was used to determine the Young's modulus of elasticity and cohesion of DCM columns. For an effective stress analysis, a friction angle of 25° to 33° was proposed by EuroSoilStab (2002). Hence in this study, a friction angle of 25° was used. According to Kivelo (1998) and Broms (1999), the cohesion of artificially cemented soil is about $0.289q_u$, which is about 210 kPa for this case. McGinn and O'Rourke (2003) used a value of $150q_u$ for elastic modulus of cement treated soil by wet mixing method. Probaha et al. (2000) and Ellen et al. (2013) proposed $100q_u$ and $300q_u$ respectively. In this analysis $100q_u$ is used and hence the Young's modulus of elasticity of DCM columns was 72.5 MPa.

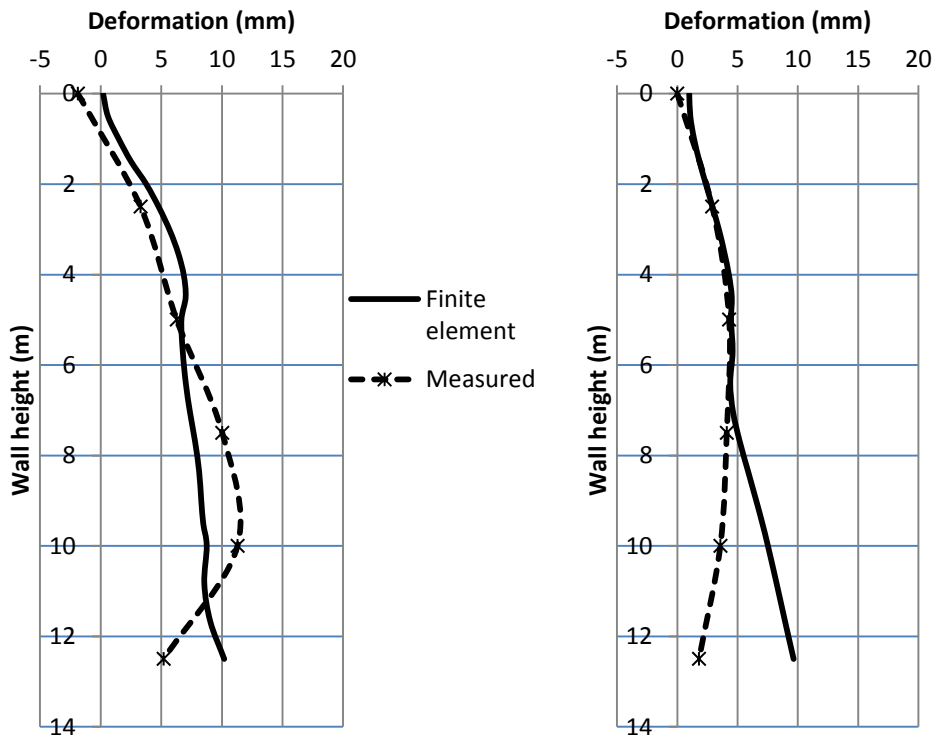
4 COMPARISON OF RESULTS WITH FIELD MEASUREMENTS

In this section, deformation of the arch during excavation obtained from the finite element analysis is compared with field measurements. To obtain wall deformations, inclinometers were installed at several locations of the DCM wall. Figures 3(a) and 3(b) show the wall deformation after 5.5 m of excavation before installation of the second set of struts. Both measured and finite element results show the same trend. The crest of the arch deforms more than the toe. The measured maximum deformations at the toe and the crest are about 2 mm and 4 mm respectively. Finite element results slightly over predicted the measured deformations.



(a) Deformation at the crest of the arch after 5.5 m of excavation.

(b) Deformation at the toe of the arch after 5.5 m of excavation.



(c) Deformation at the crest of the arch after 9 m of excavation.

(d) Deformation at the toe of the arch after 9 m of excavation.

Figure 3: Deformation of the wall at the end of 5.5 m and 9.0 m of excavation.

Figures 3(c) and 3(d) show the wall deformations at the crest and toe of the arch after 9 m of excavation. Over the top 8 m of the wall, finite element results agree well with the measured wall deformations but below 8 m, measured wall deformations show that the wall deformation is decreasing towards the tip. According to the finite element results, wall tip is moving towards the excavation. The difference in measured and computed wall deformations beneath the excavation may be due to the difference between actual and assumed soil properties used for the soft silt clay layer around the excavation. Nevertheless, results obtained from the finite element analysis can be explained using Figures 4 and 5. With increasing excavation depth, soil heave over the base of the excavation increases. As a result, soil starts to flow into the excavation increasing lateral deformation of the wall below the excavation depth. When the excavation depth is 7.7 m, soil flow occurs but it is not very high at the wall base level. With increasing excavation depth, soil deformations increase underneath the grout layer below the excavation. Grout layer will try to reduce the soil heave underneath the excavation due to its high stiffness compared to the surrounding soft silty clay but beneath the grout layer, soil lateral deformations are increasing. As a result, lateral deformation of the wall base increases in the x direction as observed in Figures 3 (c) and (d).

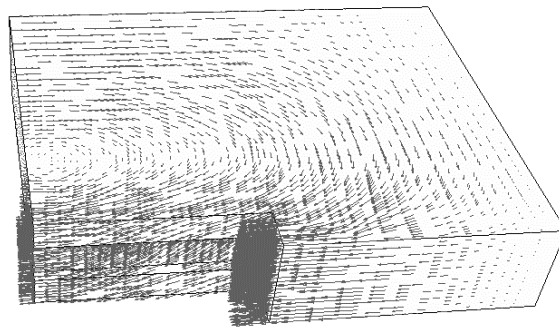


Figure 4: Soil flow around the excavation after 9 m of excavation.

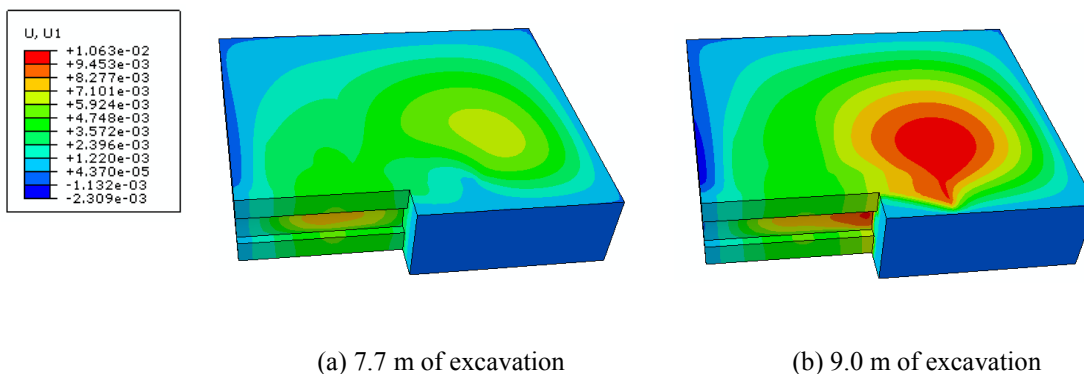


Figure 5: Lateral soil deformation in the x direction.

5. INFLUENCE OF THE CURVATURE OF ARCH ON THE COMPOUND WALL BEHAVIOUR

In this section the effect of curvature of the arch on the compound wall behaviour is investigated. A uniform soft clay deposit is considered for this analysis. The soil and DCM wall behaviour are modelled using the properties given in Table 1. Excavation is simulated as described in the previous section but struts were not used to support the wall. Therefore the depth of excavation is limited to 5 m and the 10 m long DCM wall deformed as a cantilever. Curvature of the arch shaped wall is varied by changing the rise of the arch, h , which is defined as the vertical distance between the toe and the crest of the arch. Figure 6 shows the normal stress distribution in the z direction within the arch wall at the end of 5 m excavation. In this case, due to increased surface area of the arch wall in the yz plane with increasing h , higher lateral earth pressures are applied over the arch with $h = 0.75$ m than those applied over the arch with $h = 0.1$ m. Henceforth both compressive and tensile stresses shown in Figure 6 (b) for the arch with $h = 0.75$ m are higher than those shown in Figure 6 (a) with $h = 0.1$ m. When $h = 0.1$ m, tensile stresses are developed not only over the top of the wall but near the base of the excavation as well. However, the arch with higher curvature does not show any tensile stresses below the top of the wall.

Figure 7 shows the deformation of the wall in the x direction measured at the crest and toe of the arch. Although toe deforms more than the crest in this case, the difference is marginal. Both toe and crest deformations decrease exponentially with increasing curvature of the arch. Therefore it can be concluded that by increasing the curvature of the compound DCM wall, lateral deformation of the wall can be decreased. In addition, any tensile stresses developed below the top of the wall can be mitigated. However, with increasing curvature, loads applied on the wall increases and as a result, both tensile and compressive stresses developed on the wall near the ground surface increases. Hence, curvature of the wall should be increased carefully by taking into account the tensile load carrying capacity of the wall near the top.

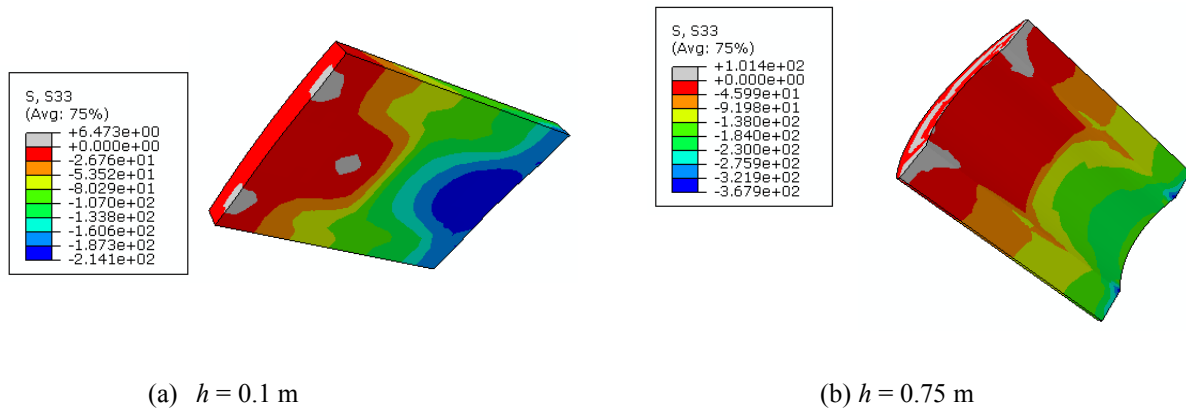


Figure 6. Normal stress distributions in the z direction at the end of 5 m excavation for the 10 m DCM wall.

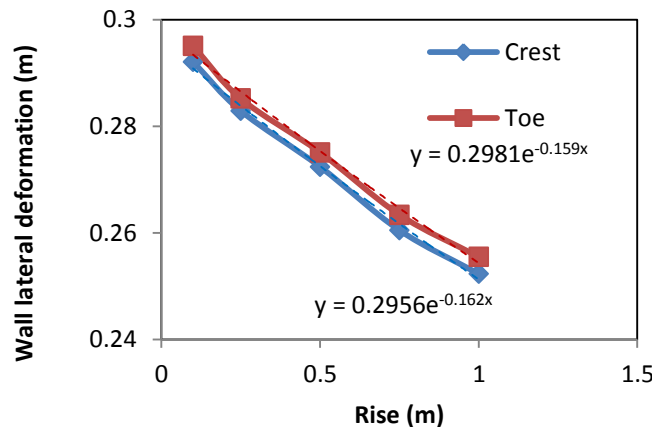


Figure 7: Variation of wall deformation with rise of the arch.

6. CONCLUSIONS

In this paper a case history of a compound DCM wall constructed using DCM columns and bored piles are investigated using a three-dimensional finite element model. The wall section between bored piles is constructed as an arch to reduce the tensile stresses developed in DCM columns. Overall, the measured and computed wall deformations show good agreement. However, when the excavation depth is 9 m, the wall deformation below the excavation computed from the finite element analysis is higher than the measured wall deformation. This may be due to the difference between the assumed soil properties for the soft silty clay layer below the excavation. However, if the soil flow around the excavation base is investigated, it can be justified that the predicted wall movement is acceptable. Using the same numerical model with a uniform soil deposit, a parametric study is carried out varying the curvature of the arch between bored piles. Results from the parametric study show that the increased curvature of the arch has a significant influence on reducing the wall deformation. However, with increasing curvature, surface area of the wall increases and hence the lateral pressures applied over the wall surface increases generating higher compressive and tensile stresses within the wall section. Therefore it can be concluded that wall deformation can be reduced by increasing the curvature of the arch

sections of DCM walls. However, at the same time tensile stresses developed over the arch section may increase developing tensile cracks within the wall, especially closer to the top of the wall.

7. ACKNOWLEDGEMENTS

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