Malaysian Journal of Civil Engineering 28(2):218-236 (2016)

ANALYTICAL STUDY OF NATURAL DRAUGHT COOLING TOWER ON VERTICAL PILES USING FINITE ELEMENT METHOD

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Abstract: The study aimed to analyse the behavior of natural draught cooling tower (NDCT) resting on a vertical pile foundation specifically focusing on prevailing soil conditions in the coastal areas. 27 different cases of shell thickness variation models are studied. The study adopted FEM analysis of NDCT and its foundation as a composite model which also facilitate to study the impact of providing a vertical pile foundation on the behavior of NDCT super structure. Results demonstrated that the reactions on all the piles are within the allowable pile capacities in all cases 1 to 27. In addition, our arc over which lift occurs in the foundation was 0º.The pile support reactions indicate that the horizontal loads on all the piles are varying based on the loads from the superstructure and when the NDCT super structure and its foundation were analysed with composite model.Maximum displacement of the shell and pile forces are reducing by increasing the top level of bottom ring beam.Further, our paper did show the deflection profile and pile reaction variation profile closer to realistic/actual behavior of NDCT than a conventional model.Therefore, the methodology adopted in this paper to study the behavior of 3D modeling of NDCT and its foundation could able to predict the dynamic responses of wind structure. From the results of the study it was established that in coastal areas NDCT can be supported on simple vertical piles instead of conventional raker piles. Further the study also identified optimum shell thickness profiles to be adopted to obtain the optimum foundation and the super-stable structure for NDCT resting on vertical pile foundation.

Keywords: *Cooling towers, shell thickness, thermal power, vertical pile foundation, wind load*

1.0 Introduction

The natural draught cooling tower is very important and an essential component in the thermal, nuclear power plants. Due to their complexities in geometry, the analysis of such type of structures has attracted many types of research throughout the world. It is proposed to set up two numbers of NDCT for each 700 MWe capacity NPP project, where the sill diameter of NDCT is expected to be as large as 120 m and the height is expected to the order of 165m (Patil *et al.*, 2007). In this, just a linear extrapolation from normal sizes of 120m to a height 165m is not possible, because the overall dimension like height and diameter are increased non-proportionally in comparison with shell thickness and reinforcement. Thus the dynamic behavior changes in an unfavorable way, leading to more bending action in the shell. The cooling tower is largest thin shell structures of NPP which are highly sensitive to dynamic wind actions, and their response varies randomly in time and space. At such large dimension, rational assessment of wind loading condition and structural response along with shape of tower is of much importance for the state of stress (structural safety), for the elastic stability (overall stiffness) and for the vibration properties (dynamic load amplification) of the structural response, for the initiation of concrete cracking (durability) compared to smaller towers (Busch *et al.*, 2002). The optimization procedure including the derived most optimum shape for the tall NDCT, which is being proposed to be constructed at Kakrapara is discussed in detail by Patil *et al.* (2007).

Cooling towers are the main part of the various industrial process as well as thermal power plants. They are often used in power generation plants to cool the condenser feed-water (Singh and Rajput, 2012). Here, the cooling tower uses ambient air to cool warm water coming from the condenser in a secondary cycle. There are many cooling tower designs or configurations. In dry cooling tower water is passed through finned tubes forming a heat exchanger, so only sensible heat is transferred to the air. In the wet cooling tower, the water is sprayed directly into the air, so evaporation occurs, and both latent heat and sensible heat are exchanged. In the hybrid tower, a combination of both a roaches is used. Cooling towers can further be categorised into forced or natural draft towers. Forced units tend to be relatively small structures where fans drive the air flow. In a natural draft cooling tower, the air flow is generated by natural convection only. The draft is established by the density difference between the warm air inside the tower and the cold dense ambient air outside the tower. In a wet cooling tower, the water vapor inside the tower contributes to the buoyancy and tower draft. A further classification is between counter-flow and cross-flow cooling towers. In the cross-flow configuration, the air flows at some angle to water flow, whereas in counter-flow the air flows in the onsite direction to water flow (Singh and Rajput, 2012). Now a day’s most of the thermal power plants are setting up near the coastal areas due to availability of sea water and imported coal. In India most of the coastal areas contains prevailing soil conditions i.e. these soils are mostly layered soils with top layers of sandy soils followed by clay layers and further down we will get hard strata soil layer for resting the piles at depths in the order of 25 m to 50 m below natural ground level.As NDCT is a heavy structure and requires pile foundation in this type of soils.With this background the present paper aimed to analyses the behavior of NDCT resting on vertical pile foundation specifically focusing on prevailing soil conditions in the coastal areas. The study considered 3-D modelling of NDCT super structure and its foundation as a composite model. Finally, the study concluded with the findings and further recommendations.

2.0 Literature Review

Several studies have been conducted previously. The majority of the studies have conducted behavior of NDCTs where raker piles foundation and to our knowledge, not many studies have studied the structural quality using vertical pile foundation especially using Finite element analysis. Ramanjaneyulu *et al.* (2003) explored a study on seismic response analysis of column supported natural draught cooling tower shells. Natural draught cooling towers (NDCTs) belong to the category of large civil engineering structures and are commonly used in nuclear or thermal power plants. Detailed dynamic analysis has to be carried out for the design of cooling towers subjected to seismic excitation, considering the flexibility of the columns. Finite ring element formulations for dynamic analysis of cooling tower shell subjected to seismic excitation are presented in this paper. The geometry of a typical tall natural draught cooling tower is considered in this study for carrying out investigations. Transient response of the hyperbolic cooling tower shell subjected to earthquake loading has been analyzed by direct time integration using acceleration-time history of North-South component of El-Centro earthquake. Parametric studies have also been carried out to study the influence of flexibility of column supports and damping on the seismic response of cooling tower shell, and the results are discussed in the paper.

Abedi-Nik *et al.* (2008) explored a study on the damaging effects of earthquake excitation on concrete cooling towers. This study presents the results of a finite element investigation of a representative 'dry' cooling tower, using realistic horizontal and vertical acceleration data obtained from the recent and widely reported Tabas, Naghan and Bam earthquakes in Iran. The results of both linear and nonlinear analyses reveal about the locations of plastic hinges within the supporting columns and the ramifications of the plastic hinges on the stability of the cooling tower. It is concluded that for the (typical) cooling tower configuration analyzed, the columns that are instrumental in providing a load path are influenced greatly by earthquake loading.

Angalekar and Kulkarni (2013) explored a study to analyze natural draught hyperbolic cooling towers through the application of finite element method using the concept of the equivalent plate. This study explains the application of software package for practical application while taking into account of natural draught hyperbolic cooling towers. The significant aspect is to reflect column providing supports to the tower might be replaced by equivalent shell elements so as to implement the developed software. To demonstrate this, a single case of the tower having alternative ‘I’ and ‘V’ supports is considered. It is reflected that the behaviour with regards to equivalent plates are similar to the behavior, in which column support inappropriate is counted. To have this, the need is to apply the wind load over the structure.

Radwańska and Waszczyszyn (1995) conducted a numerical analysis of three models: (P) perfect shell of revolution, (M) shell with measured imperfections, (T) shell with a theoretical imperfection corresponding to the primary buckling mode under dead load. The buckling analysis was related to the linearized eigenvalue problem of elastic shells. The shell mid-surface was approximated by eight-node quadrilateral isoparametric finite elements. Computations were carried out using the ANKA computer code. Critical values of the load parameter enable confirmation of partial correlation between existing imperfections and buckling modes under dead load. The most disadvantageous direction of the wind load application on the real shell was found, in order to evaluate the decrease in the load-carrying capacity of the cooling tower shell against buckling. Theoretically modelled imperfections give rather unrealistic values of buckling loads of the real shell.

Ke *et al.* (2015) explored a study to analyze stability and reinforcement of super large exhaust cooling towers on the basis of wind tunnel test. This study was in context to the largest exhaust cooling tower in Asia. Through analyses, the surface wind pressure distribution, multi-tower proportional coefficient, and wind-induced vibration coefficient of the exhaust cooling towers from the most unfavorable wind direction were obtained. On this basis, finite-element software and self-made preprocessing and post processing programs were employed to analyze the ultimate load-carrying capacity and overall and local stabilities of exhaust cooling tower in three conditions, which include (1) no opening, (2) opening without strengthening, and (3) opening with different strengthening schemes, then the ultimate load-carrying capacity of exhaust cooling tower during construction under different load combinations was also analyzed. For a cooling tower with an opening, obvious stress aggregation was found near the opening, and the minimum safety factor for the local stability of the tower throat area was 4.27.

Gabrielaitis and Papinigis (2010) conducted a study to evaluate the design of pile foundation on the site of the Elektrenai power plant, Lithuania. The foundation is aimed to support equipment of the power plant consisting of the gas turbine, the steam turbine and the generator. Besides high loads, the equipment had a strong dynamic impact on the foundation due to its working conditions and vibration. The pilling solution was adopted due to different reasons: i) the capacity of the soil to support great stresses over it; ii) the special requirements for the main equipment about settlements, movements and stresses. Pilling foundation was evaluated through immediate settlement analysis, which was carried out employing four most widely used methods. It included analysis of the soil data from the cone and dynamic penetration tests, boreholes and laboratory tests. Soil properties were estimated from site investigation and soil exploration program according to Lithuanian standards. Pile settlement analysis showed that settlement value was 14 mm (pile toe settlement), and settlement value of elastic deformation of the pile from vertical compressive loads was 3 mm. For such structure, foundation settlement should not be more than 16 mm (i.e., no more than 2 % of pile diameter). It was estimated that for a pile of diameter 800 mm, pile length of 24 m was sufficient to endure overall loads.

Zhang *et al.* (2015) analyzed a new spiral source heat transfer model for simulating the heat transfer performance of pile foundation Ground Heat Exchangers (GHEs) with the existence of groundwater transfusion. The model adopted for the study is heat conduction and convection of groundwater into account and is more accurate. The analytical solutions of the model are obtained to exhibit the temperature response at any point in the underground medium around the pile foundation GHEs. The pure conduction case and combined heat transfer case are compared, and the heat exchange efficiency between the pile foundation GHEs and surrounding medium can be improved as a result of the influence of groundwater transfusion. The research contributes to more understanding of the potential for pile foundation GHEs and the degrees which the heat transfer efficiency affected by groundwater flow. However, there are some shortages and deficiencies are improved and overcome, specifically in terms of the configuration of spiral heat transfer tubes.

The study would shed light on the two aspects in terms of practical point of view and from academic perspective. First one is from the academic point of view, where the research would contribute on the change or replacement of pile foundation in terms of from raker to vertical pile for Natural draught cooling towers. The findings of the study would thereby contribute theoretically in terms of enhancement of rivet theory. Earlier studies have analyzed the behavioral of tower foundation considering the foundation is rested on soil or on raker piles. Further, in general, this study would also enhance our understanding of structures of pile foundation. Secondly, in terms of practical implications, the findings would enable the structural engineers involved in the NDCT supported on pile foundation to replace raker piles with vertical piles especially in the coastal areas.

3.0 Methodology

3.1 Geometry, Soil Profile and STVM

Many large capacity, thermal power plants are being set up in coastal areas because of the imported coal and sea water availability; this large capacity, thermal power plant normally requires the natural draught cooling towers of height 150 m and above. NDCT consist of the shell structure, internal structure, water distribution system, miscellaneous structures. Figure 1 shows the general arrangement of the NDCT considered.

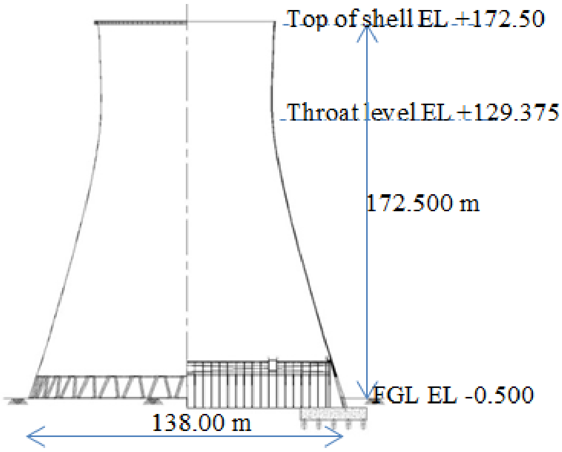
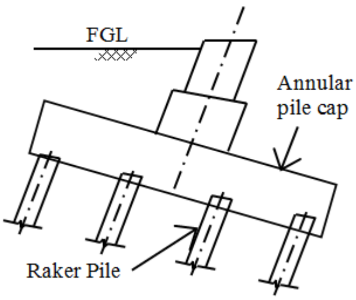


Figure 1: General Arrangement of NDCT

Continuous foundations shall be provided for cooling towers more than 75 m in height. The two important criteria's to be satisfied in the design of foundation for NDCT are safe transfer of horizontal loads & uplift of the foundation. Most of the natural draught cooling towers in the world are supported by either inclined annular open foundation or racker pile foundation with annular pile cap as shown in figures 2 and 3 depending on the soil profile. For NDCT supported by annular open foundation, rock anchors will be provided only if there is any uplift pressure on the foundation supported on hard rock.



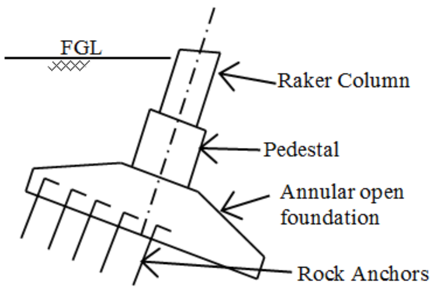


Figure 2: Annular open foundation or NDCT Figure 3: Racker pile foundation for NDCT

In coastal areas due to prevailing soil condition’s pile foundation are required for this type of heavy structures. The soil profile considered, is the most relevant strata available in the coastal areas of south India. Variation of SPT ‘N’ values along the depth is shown in figure 4. For this type of prevailing soil conditions shown in figure 4, pile foundation is required for the heavy NDCT structure. NDCT transfers large lateral loads to the foundation. When large lateral loads are to be resisted by a pile group, it has been a common practice to use piles driven at a slope with the vertical, i.e., raker (batter) piles, which facilitate the axial transfer of forces. Construction of racker piles is questionablein this soil profile beacause it is very difficult to provide inclined boreholes, and there is always the possibility of the collapse of bore holes. Alternatively, racker piles with steel liner can be provided which is uneconomical. If raker piles are not possible, then NDCT should support on vertical piles. For NDCT supported on vertical piles, pile cap will be perpendicular to piles whilst pedestals will not be perpendicular to pile cap, this will create a development of additional forces which need to be handled carefully for the integrity and safe design of the structure.

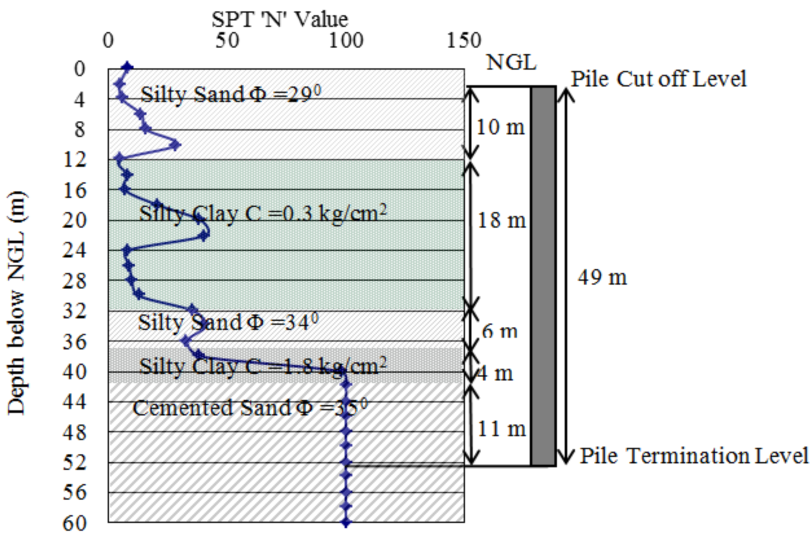


Figure 4: Variation of SPT ‘N’ Value the Soil Profile considered

Shell thickness is varied along the tower height in 27 different shell thickness variation models (STVM) as shown in figures 5 to 11. Each model identified with the separate case number from case 1 to case 27.

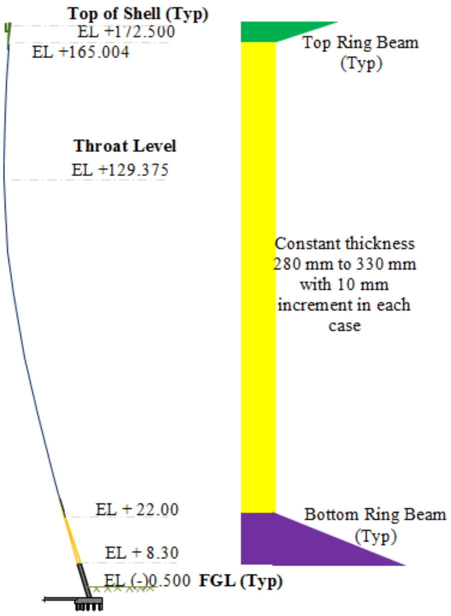


Figure. 5 Shell thickness variation model for Case 1 to 6

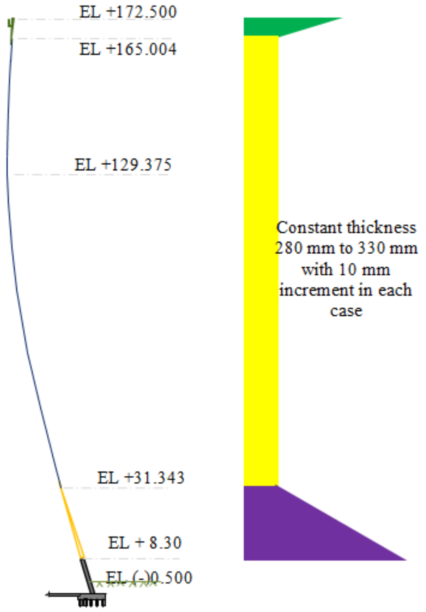


Figure. 6 Shell thickness variation model for Case 7 to 12

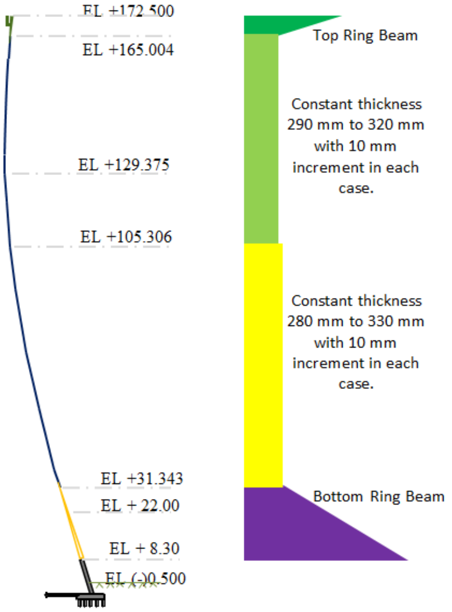


Figure. 7 Shell thickness variation model for Case 13 to 17

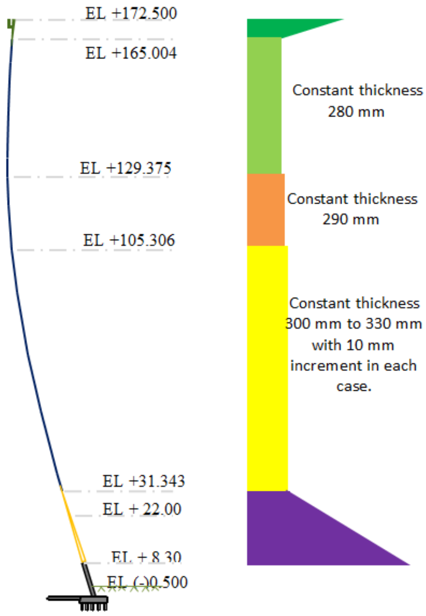


Figure.8 Shell thickness variation model for Case 18 to 21

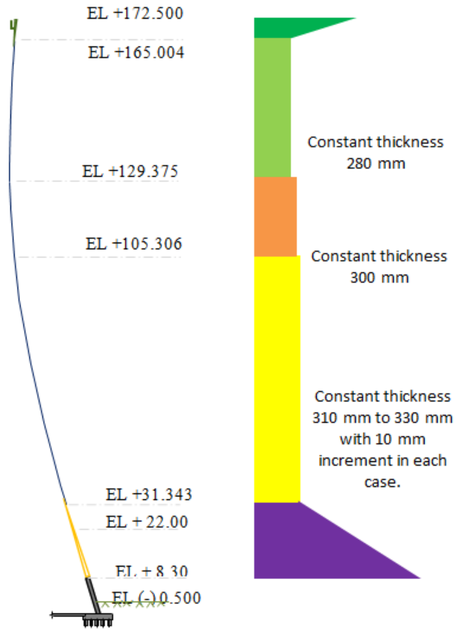


Figure. 9 Shell thickness variation model for Case 22 to 24

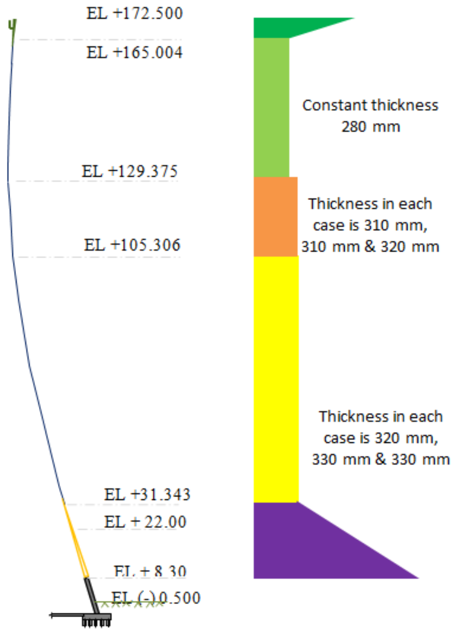


Figure. 10 Shell thickness variation model for Case 25 to 27

Although minimum shell thickness satisfying buckling check was 250 mm but in this study, minimum shell thickness was considered as 280 mm to have sufficient factor of safety againest buckling and maximum shell thickness was not exceeded 330mm in all cases 1 to 27.

3.2. Piling Layout

In this instance, not just the vertical load transfer, but also the horizontal load distribution shall be guaranteed. From the preliminary calculations, it found that this tower requires 900 mm diameter pile. Based on the engineering properties of the soil, safe working pile capacities in compression, tension & lateral are calculated. Pile capacity and spring stiffness values in horizontal & vertical direction are mentioned in table 1.

Table 1: Pile Capacity and Stiffness

Pile Diameter	Pile Capacity			Stiffness	
	Compression	Tensio	Lateral	Vertical (Ky)	Horizontal (Kx & Kz)
mm	kN	kN	kN	kN/m	kN/m
900	4800	800	280	600000	56000

NDCT is supported on annular pile cap of 12.1 m width, 2.3 m thickness is provided with 840 numbers of piles which are arranged in 5 rows with 168 no's in each row. Figure 5 shows the part plan and sectional view of piling layout adopted. The pedestal of size 1.5 m wide, and 2.6 m length supports two raker columns, and these pedestals connect with the pond wall as shown in figure 11.

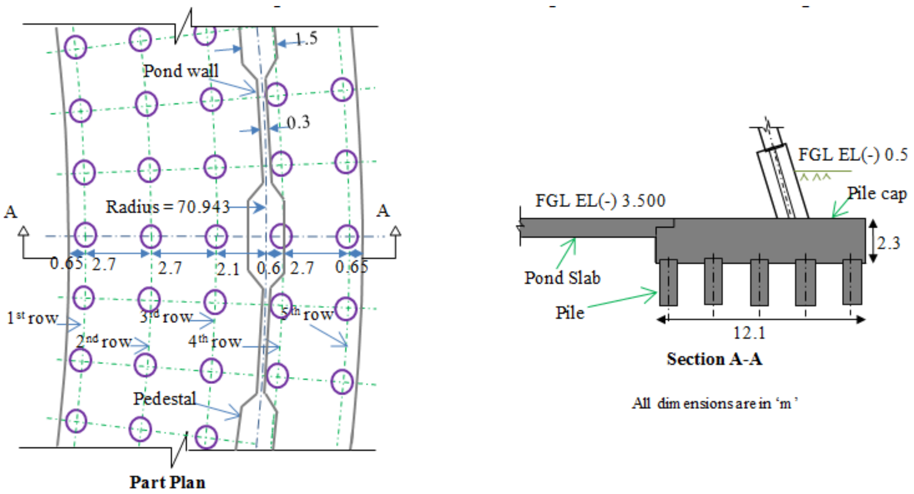


Figure 11 : Part plan & section showing piling layout

3.3 Formulation of Composite Model of NDCT Rests on the Vertical Pile Foundation

Staad.pro software is used for 3-d finite element modelling of the natural draught cooling tower supporting on vertical pile foundation. As shown in figure 12, composite model of NDCT rests on the vertical pile foundation is modelled using two nodded beam elements for raker columns, three and four nodded shell elements for tower shell, pond wall, pedestals, pile cap and piles are represented as elastic springs with stiffness in vertical, horizontal directions. An optimum mesh size has been adopted after a convergence study. The top edge of the shell structure was free to translate and rotate in all directions while the base was supported on elastic springs. In dead load (D.L.) case Self-weight of all NDCT structural components such as shell, raker columns, pedestals, pile cap is assigned using self-weight command of the software. Lateral pressure due to soil and surcharge was applied on the wall and pedestals as shown in figure 13 and Vertical pressure due to soil and surcharge load was applied to pile cap as shown in figure 14 are also considered in dead load (D.L.) case. Dynamic wind analysis was carried out as per the relevant provisions of IS 875 part 3. Wind pressure calculated as per gust factor method was employed along the height of NDCT using circumferential wind pressure coefficients shown in appendix-A of IS 11504 after magnifying an

Interference factor (IF) of 1.573. Figures 15 & 16 shows the wind pressure applied on NDCT in load case Wind load (W.L.). The finite element model has been analysed for all load cases and load combinations with the aim of calibrating.

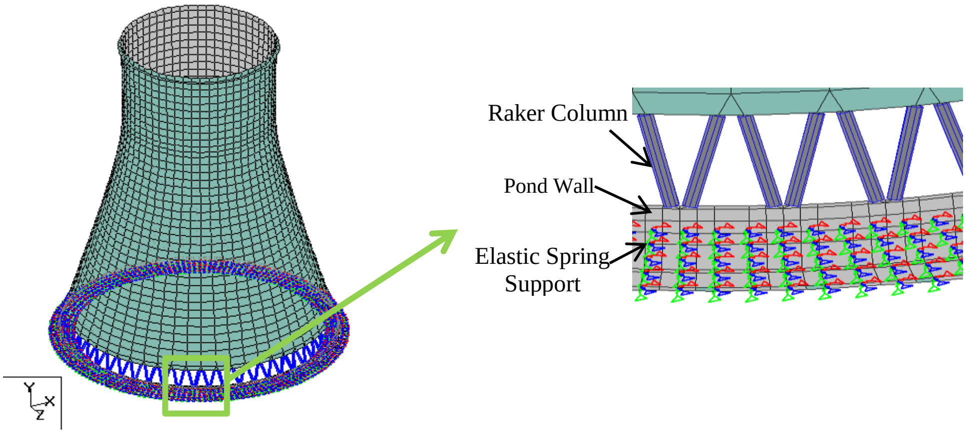


Figure 12: FEM model of NDCT Composite model

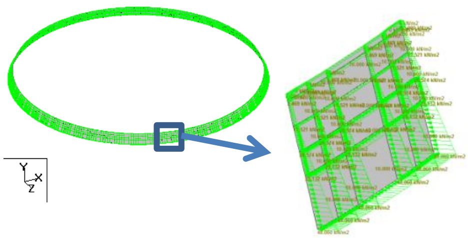


Figure 13: Lateral pressures due to soil and surcharge on the wall and pedestals

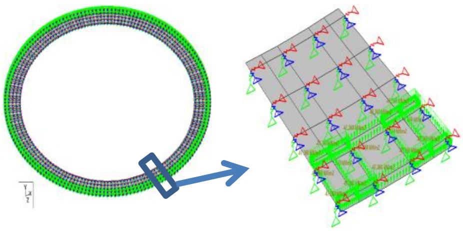


Figure 14: Vertical pressures due to soil and surcharge on the pile cap

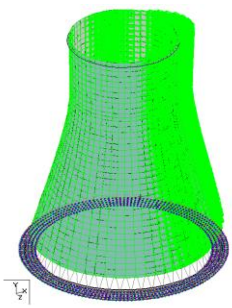


Figure 15: Wind pressure on the NDCT shell -3D view

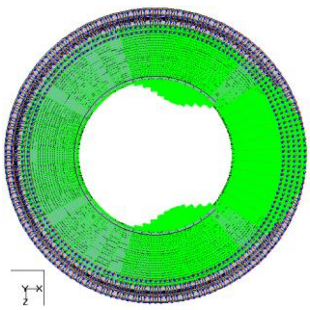


Figure 16: Wind pressure on the NDCT shell -top view

4.0 Results and Discussions

4.1 Variations of Pile Forces

Support reactions on each spring i.e. pile forces in longitudinal, lateral and vertical directions are captured from the FEM analysis results for cases 1 to 27 in L/C 1.0 DL +1.0 WL. The resultant pile forces in the horizontal direction are computed and maximum horizontal force(MHF) in each case on all piles are plotted as shown in image 17. From the FEM analysis results, Maximum compressive forces (MCF) in each row of piles are identified for cases 1 to 27 in L/C 1.0 DL +1.0 WL and the variation of MCF are plotted as shown in figures 18. From the FEM analysis results, Maximum tensile forces (MTF) in each row of piles are identified for cases 1 to 27 in L/C 1.0 DL +1.0 WL and the variation of MTF are plotted as shown in figures 19.

4.1.1 Variation of Horizontal Forces on Piles

The following are the findings obtained due to the variation of MHF forces on piles. MHF profiles are varying from 1st row of piles to 5th row of piles in all cases 1 to 27. MHF on piles occurs in the 2nd row of piles in case 1 to 27. The findings observed that case 6 (271.3 kN), 7 (274.4 kN), 13 (275.7 kN), 18 (275.7 kN) 22 (276.4 kN), and 25 (277 kN) are transferring less horizontal or lateral force to the foundation. The findings overall, showed that the maximum horizontal pile force is 277 kN.

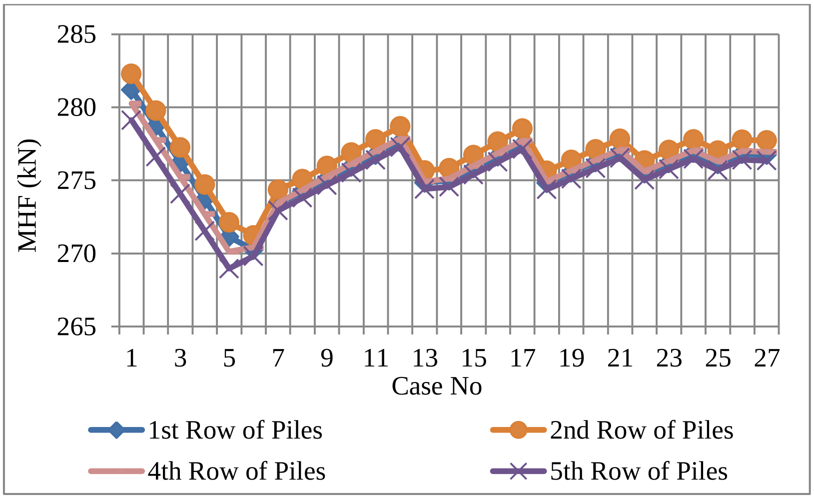


Figure 17: Variation of MHF on piles

4.1.2 Variation of Vertical Forces on Piles

From Figure 18, the findings revealed that MCF values are increasing from 5th row of piles to 1st row of piles for all cases 1 to 27 i.e. outer rows of piles is experiencing more compressive force compared to the inner row of piles. In specific, Case 1 (2845 kN), 7(2937 kN), 13(2955 kN), 18(2957 kN), 22(2967 kN) and 25(2978 kN) are transferring the minimum compressive force to the foundation than the targeted value <4800 kN. The maximum vertical force (compression) on the pile is 2967.38 kN which occurs in 1st row of piles.

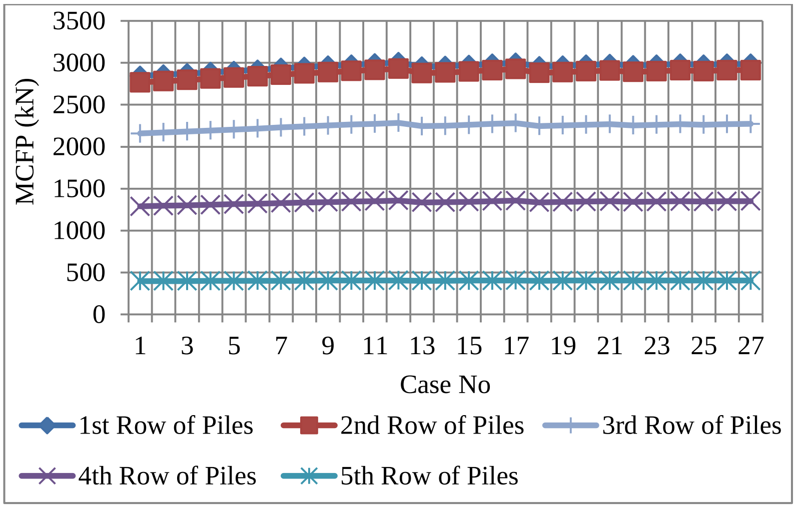


Figure 18: Variation of MCF on piles

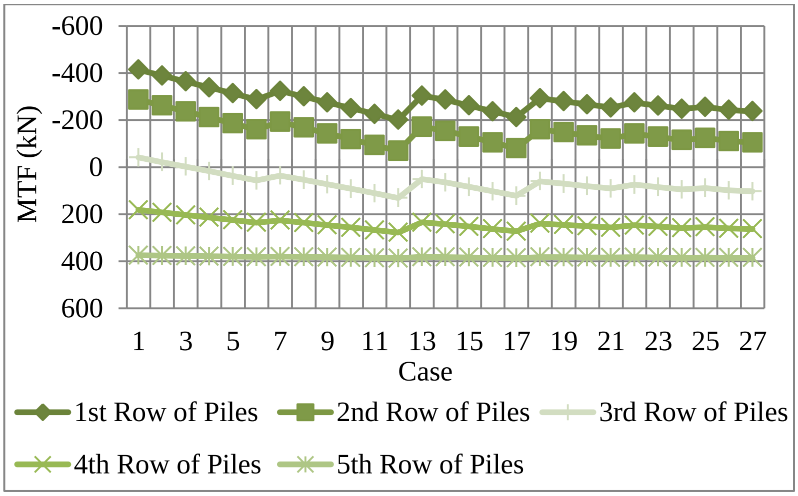


Figure 19: Variation of MTF on piles

Figure 19 showed that the maximum tensile force (MTF) values are occurring in the 1st row of piles and reducing towards a 5th row of piles for all cases 1 to 27 i.e. outer rows of piles is experiencing more tensile force compared to the inner row of piles. The findings showed that Case 6 (-287 kN), 12 (-201 kN), 17 (-212), 21(-253), 24 (-248) and 27 (-237.5 kN) are transferring the minimum tensile force to the foundation in comparison to tensile capacity of pile i.e. -800kN.

4.2 *Lift Off Check*

In the composite model for L/C 1.0 DL +1.5 WL, the reactions on each spring i.e. Pile forces in the vertical direction are captured from the FEM analysis results and the variety of vertical forces on piles (VFP) for L/C 1.0 DL + 1.5 WL are shown in Figures 20 and 24. The findings showed that the minimum vertical force (tension) on the pile is -274.527 kN < Tensile capacity of the pile (-800 kN) Hence no uplift.

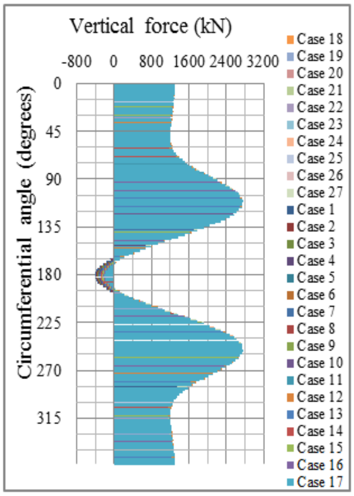


Figure 20: Variation of VFP on 1st row of piles

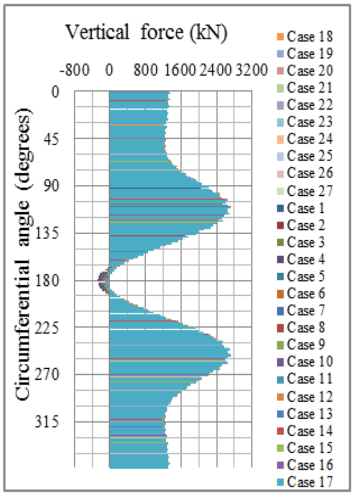


Figure 21: Variation of VFP on 2nd row of piles.

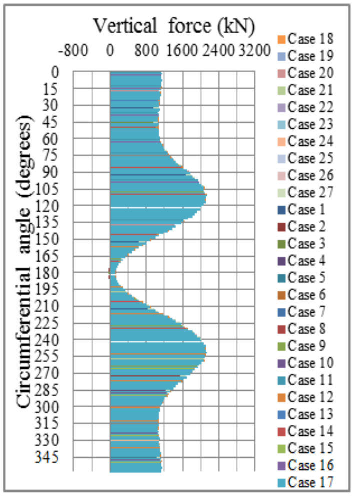


Figure 22: Variation of VFP on 3rd row of piles.

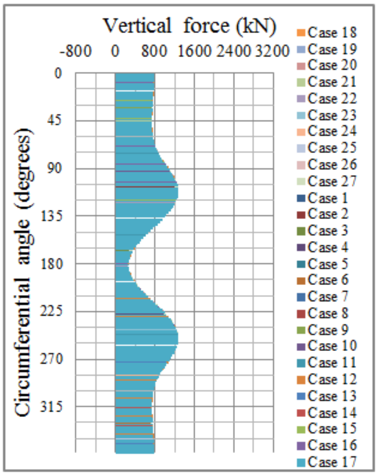


Figure 23: Variation of VFP on 4th row of piles

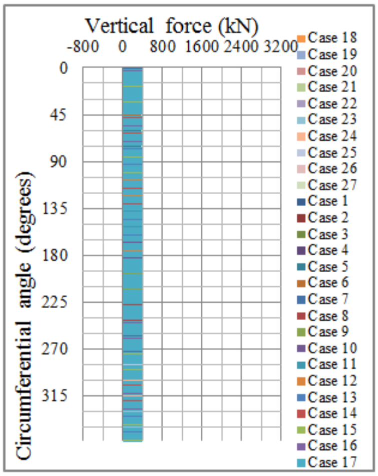


Figure 24: Variation of VFP on 5th row of piles

4.3 *Variations of Displacement*

From STAAD output results displacements at each level along the height of the NDCT in horizontal and vertical directions are captured for cases 1 to 27 in 1.0 DL + 1.0 WL load combination. Maximum Resultant Displacement (MRD) at each level along the height of the NDCT is calculated for case 1 to case 27 and plotted as shown in figures 25 to 29. As the MRD influences the forces in the NDCT, the case which gives lesser values of displacement along the height of the NDCT needs to be identified to get the best thickness profile for NDCT.

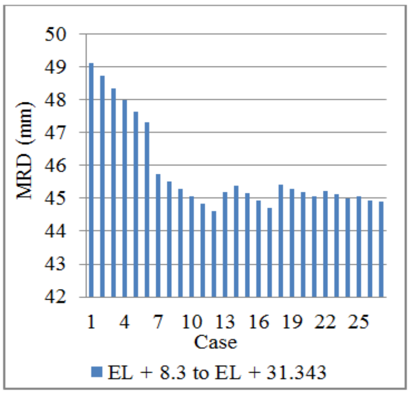


Figure 25: Variation of MRD in shell from EL +8.3 m to EL + 31.343 m

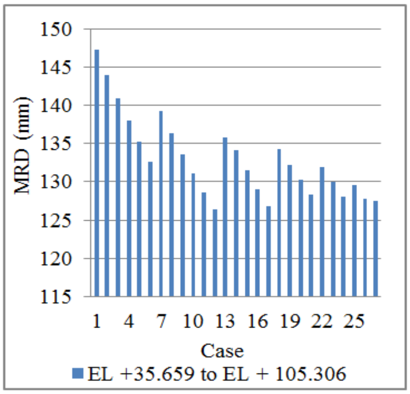


Figure 26: Variation of MRD in shell from EL +35.659 m to EL + 105.306 m

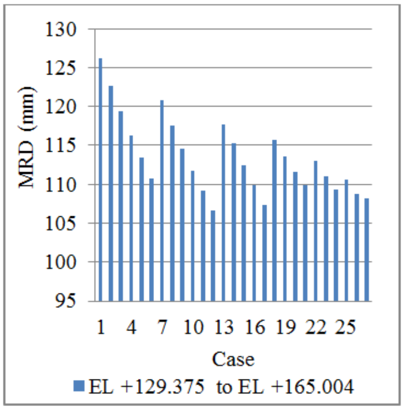


Figure 27: Variation of MRD in shell from EL + 109.741 m to EL + 126.138 m

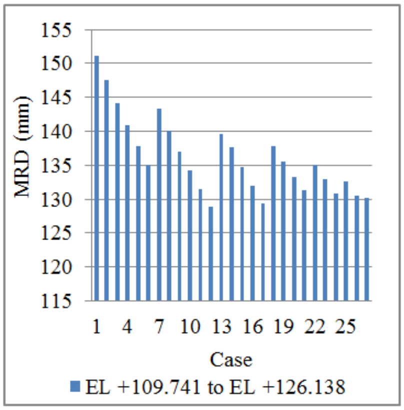


Figure 28: Variation of MRD in shell from EL + 129.375 m to EL + 165.004 m

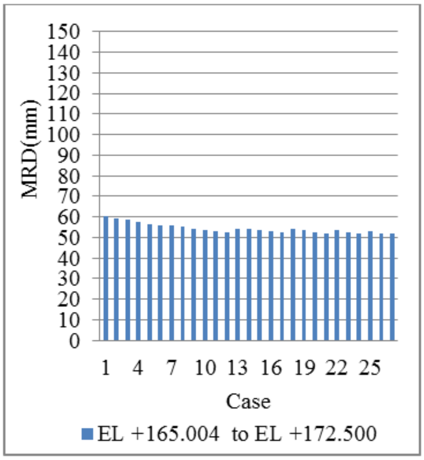


Figure 29: Variation of MRD in shell from EL + 165.004 m to EL + 172.500 m

The above graphs did show that at any height of the NDCT the minimum values of MRD occur in case 6 (for case 1 to 6), 12 (for case 7 to 12), 17 (for case 13 to 17), 21 (for case 18 to 21),24 (for case 22 to 24), and 27 (for case 25 to 27). Therefore, it is concluded that case 6, 12, 17, 21, 24 & 27 are giving the fewer displacement profiles. MRD profiles in case 1,6,12,17,21,24 & 27 are plotted as shown in figure 30 which shows that resultant displacements are high in case 1 & 6 comparing with cases 12, 17, 21, 24 & 27 because of extending the ring beam beyond 22.00 m.

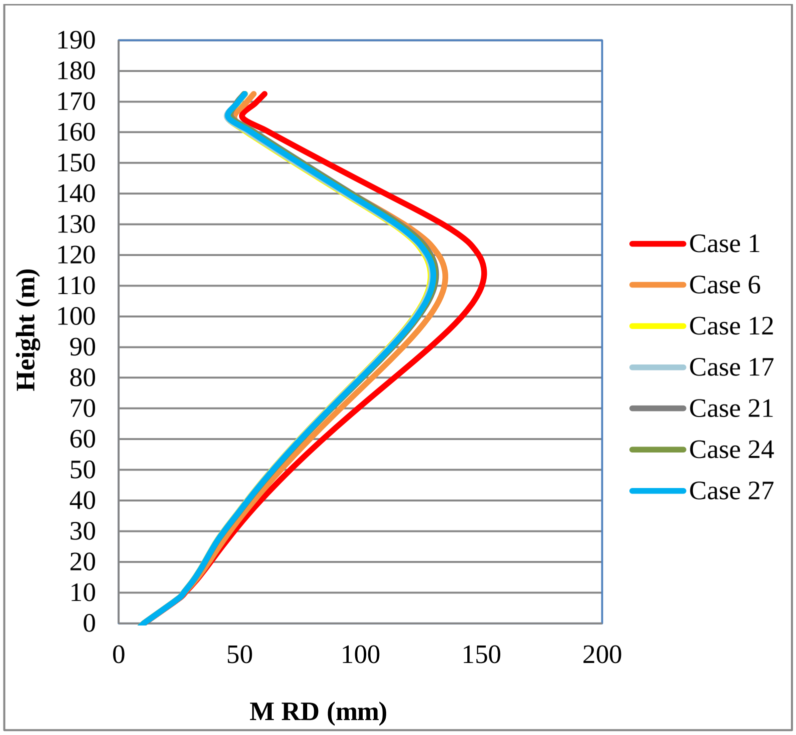


Figure 30: MRD profiles.

5.0 Concluding Remarks

For NDCT resting on a vertical pile foundation in coastal areas, a study has been made to assess the correct behavior of superstructure and foundation adopting a composite model using the Finite element method. Effect of shell thickness variation on the foundation forces has also read. The outcomes of the study showed, maximum pile reactions are well within the pile capacities in all cases of STVM. Cases 6, 7,13,18,22 & 25 are transferring less horizontal/ lateral force to the foundation. Cases 1,7,13,18,22 & 25 are transferring the minimum compressive force to the foundation whilst Cases 6,12,17,21,24 &27 are transferring the minimum tensile force to the foundation. From the distribution of later forces in all cases of STVM, It can be concluded that, formal method of piling analysis using rivet theory would under estimate's the distribution of lateral forces on piles largely (Rivet theory distributes the total horizontal force from each pedestal equally to piles below the corresponding pedestal).

Displacements in the shell are less for cases 6, 12,17,21,24 & 27 compared with other cases. Stiffening of ring beam results in reduction of displacement's along the height of the NDCT in case 7 to case 27.It is suggested that for NDCT of large size resting on vertical piles, composite modeling of NDCT and its foundation is required for better understanding of the behavior of NDCT and its foundation.

Four types of shell thickness varying models of NDCT are identified for optimizing the foundation forces and are shown in figure 31. From the results of the study it was established that in coastal areas NDCT can be supported on simple vertical piles instead of conventional raker piles. The methodology presented here can be extended by studying the behavior NDCT in a wind model by providing different types of stiffening elements like ribs, strakes, rings to the shell, which may reduce wind pressure.

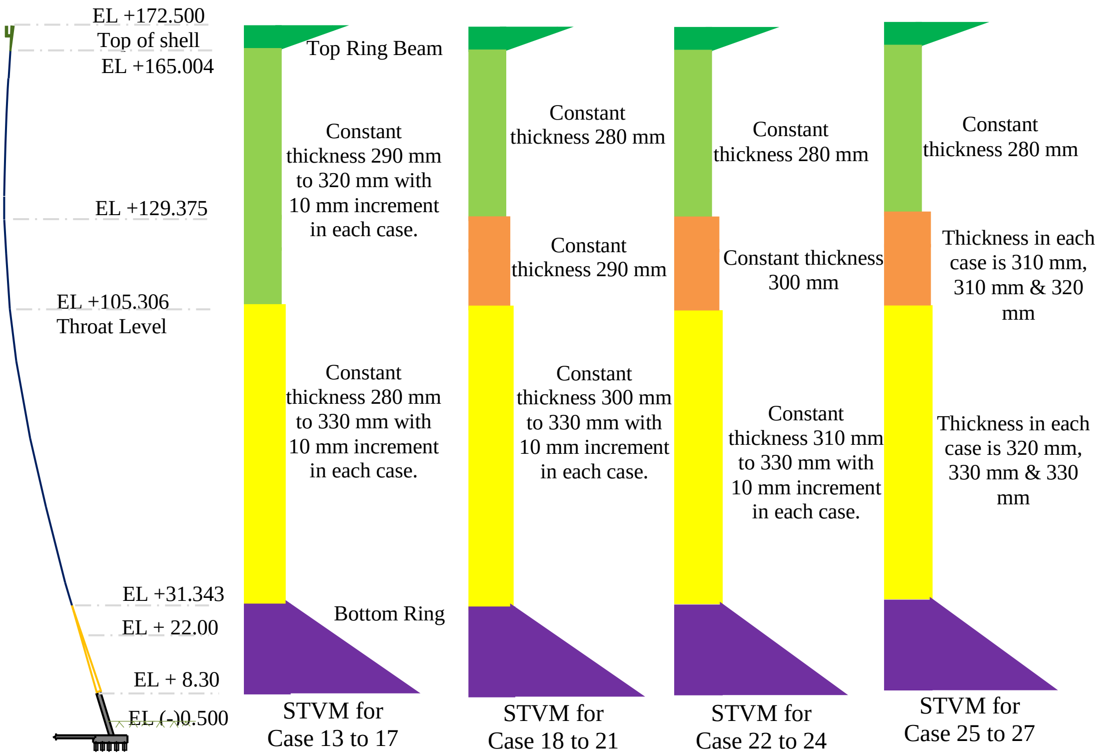


Figure 31: Best STVM's identified for NDCT resting on vertical pile foundation

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