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Engineering Performance of the Foundation of Thanjavur Brihadeeswarar Temple

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Abstract. Ancient and historical structures have always impressed the current generations. Especially, a few of these structures are not only visually attractive but are extremely stable owing to the kind of architecture and materials used in building them. The objective of the present study is to understand the engineering performance of Thanjavur Brihadeeswarar temple Garphagriha tower foundation for Static load condition. This temple was constructed by the great Raja Raja Cholan who ruled Tamil Nadu in the period 1010 CE with help of Architect Kunjalamallan. The entire structure is made of the granites by using buzzle technology which means force applied at the top to prevent the movement of rock without any binder. Based on the discussion with an archaeologist who worked in Thanjavur Brihadeeswarar temple, it is understood that the Thanjavur temple Garbhagriha tower foundation is resting on sandbox (cushion type). Sandbox is a technique of filling of sand mixture in relatively dense condition within a rigid boundary. Generally, the temple foundation designed for zero settlement. The study deals with numerical analysis for static load condition of temple tower foundation in sandbox. To determine the size of the foundation for zero settlement criteria, the thickness and depth of boundary are varied. Through static load analysis, engineering performance (settlement and vertical stress distribution variations) of the temple is evaluated.

Keywords: Thanjavur Brihadeeswarar temple foundation, sandbox, static load, settlement, vertical stress distribution.

1 Introduction

The Indian heritage is respected and held in high esteem throughout the world. One of the major features of this rich heritage includes the ancient religious monuments. Ancient era was the witness when religious practices flourished the most and temples became the world's storehouse of knowledge and culture. Ancient temple is representing the history of culture, religion, science and technology. India has many splendid temples that have found a place in the World Heritage list. These include Sun temple at Konark, Khajuraho temple, Ajanta Caves, Brihadeeswarar Temple and Sanchi Stupas. These temples are resistant to most natural calamities due to their geometry, material and construction technique. The foundation is considered to be the major contributing factor for their structural stability. Their work could be carried out in many different aspects, taking into account in particular: the kind of foundation and the object placed upon it, the material, the shape and dimensions of the foundation, bearing capacity and settlement of foundation and geological substructure conditions. Stone foundations were mostly used for ancient structures and public utility structures. Various types of stones were used, depending on the function of specific elements of a building. Granite, limestone, sandstone, sandstone volcanic tuff, and marble was used for this type of foundation. Research on ancient foundation techniques can bring about a huge impact on today’s foundation technologies. Most of the studies carried out so far concentrate more on superstructures like architecture, material, arrangement, order, pattern, science behind the distribution of spaces. But there has been noticeably less study on the foundations of the historical structures, especially Indian temples, since most of these temples are still living and it is very difficult to access or get permission to excavate to understand the nature of the foundations. There is no study about Thanjavur Brihadeeswarar temple foundation. Since the present study is about static load behaviour of foundation of Thanjavur Brihadeeswarar temple Garphagriha tower.

The Thanjavur temple was constructed by the great Raja Raja Cholan who ruled Tamil Nadu in the period 1010 CE with help of architect Kunjalamallan. It took nearly 7 years to construct the above temple. The Brihadeeswarar temple plan and development, utilizes the axial and symmetrical geometry rules. The temple complex is a rectangle that is almost two stacked squares, covering 240.79 meters east to west, and 121.92 meters north to south. The height of the temple is about 59.75m to 65.85m (As per IGNCA =59.82 m). The entire structure is made of the granites by using buzzle technology which means force applied at the top to prevent the movement of rock without any binder. The main Vimana (Shikhara) is a massive 16 stories tower of which 13 are tapering squares. It dominates the main quadrangle. It sits above a 30.18 meters (99.0 ft.) sided square [2]. During Thousand-year celebration function in 2010 Archaeology Department have drilled a borehole for up to 100 feet distance in which they have got sand only. This sand obtained was different from soil nearby area. The location coordinates of this temple is $10^0$46’58” N 79^0 7’ 54” E [11]. The aerial photographic view of the Thanjavur Brihadeeswarar temple is shown in figure 1. The inner and outer view of the grabhagriha tower is shown in figure 2.

Fig. 1. Aerial view of the Thanjavur Big temple

Fig. 2. Outer and Inner view of Thanjavur temple Garbhagriha Tower

2 Literature Review

Tan et al (2015) studied about visual modelling of Chinese temple construction for student education. This study concludes that, temple construction site present with incompetent soil, to increase the strength without excavating deeper depth. To excavate the soil at shallow depth, fill with dense sand. To install the stones around the perimeter and insides also. This method of installation gives higher strength without excavating deeper depth. Daka et al (2018) studied about the sandbox technique which was used to build the foundation for two major temples in Telangana viz. Ramappa temple and Thousand pillar temple. As part of this study, experiments were carried out on sand (dry and wet) and wet red soil materials by building a model which mimics the sandbox technique. In this context, piezoelectric knock sensors are used to capture the vibrations. This study determined the dampening of vibrations for sand (dry & wet) and wet Red soil for various types of loads. Wethyavivorn et al (2016) studied about the model verification of Thai historic masonry monuments. Two dominant styles of Thai historic masonry monuments, bell-shaped and corn shaped, were investigated. Both styles of monuments were analyzed under their self-weight using homogenized material properties. Based on the results it was concluded that the mass of underlying subsoil foundation which must be included in the model is at least 99.8% of the mass of the monument. Iwasaki et al (2019) studied about the authenticity of the soils and foundation of heritage structure of Bayon temple, Angkor, Cambodia. The heritage structure of Bayon in Angkor stands upon shallow direct foundation. Based on this study it was concluded that the original ground was excavated 2-3 meters from the surface and filled back with compacted sandy soil and the manmade fill shows very high bearing strength due to special characteristics of the grain size distribution of sandy soil. Sargunan (2009) studied the "THE BIG TEMPLE, THANJAVUR"[2]. The architects conducted load tests on small sections of the rock (at foundation level). The test plot was around 1.2 m x 1.2 m and four stone blocks are stacked up layer by layer at 0.6 m x 0.6 m x 0.6 m. Based on this study it was concluded that the tower was designed for zero settlement.

3 Methodology

The present study is focused on the behaviour of Thanjavur temple garbhagriha tower foundation for static load condition. The various factors influencing the performance of ancient monuments are identified based on the detailed review of literatures. The influence of these parameters on the behaviour of the foundation is to be investigated by numerical analysis. The numerical analysis is performed by using PLAXIS 3D software. Subsoil profile details of this place collected from the State Ground and Surface water Resources Data centre, Tharamani, Chennai. The soil interface material is modelled as a 10 noded tetrahedral element. Soil is modelled by using the Mohr-Coulomb model. The various parameters are to be considered for the numerical study and they are a) Without the boundary b) Thickness of the boundary c) Height of the boundary. The cross-section view of the foundation model [2]shown in figure 3.

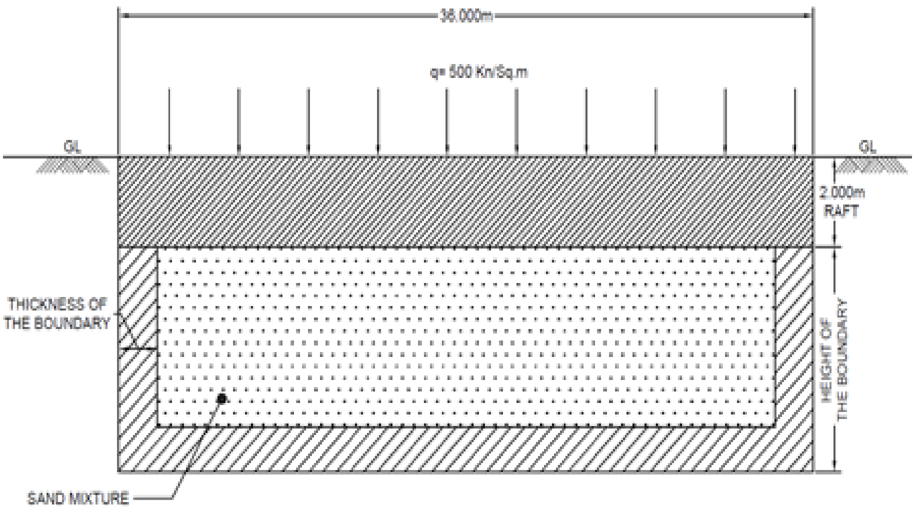

Fig. 3. Cross section view of foundation model

4 Validation of The Software

To verify the FEM model, the data reported by Mutalik Desai and Akshay V. Mutalik Desai (2017) is selected. The soil and foundation details as reported by the author are given in Table 1. The author modelled the foundation in PLAXIS 2D modelling software. For the validation, the soil layer and the foundation model are simulated using PLAXIS 3D.

Table 1. Soil and Footing parameters (Mutalik Desai and Akshay V. Mutalik Desai (2017))

Parameter	Value
Material model	Mohr-coulomb
Material type	Drained
Unsaturated Unit Weight (kN/m^3)	16
Saturated Unit Weight (kN/m^3)	17.12
Young's Modulus (E) (kN/m^2)	40000
Poisson's ratio (μ)	0.3
Cohesion (c) (kN/m^2)	0
Angle of internal friction (Φ) (degree)	30
Width of the footing (B) (mm)	2000
Thickness (d) (m)	0.353

In 3D modelling, boundary dimension of 50 m x 50 m x 20 m is used. The output details obtained from the PLAXIS 3D modelling are given in the form of settlement contour in figure 5. The settlement contour is given by Mutalik Desai and Akshay V. Mutalik Desai (2017)) is presented in figure 4. From the results, the settlement of the foundation is found to be 73 mm, which is almost comparable with the settlement data reported by Mutalik Desai and Akshay V. Mutalik Desai (2017)). The settlement results are comparable and hence the modelling and analysis are valid.

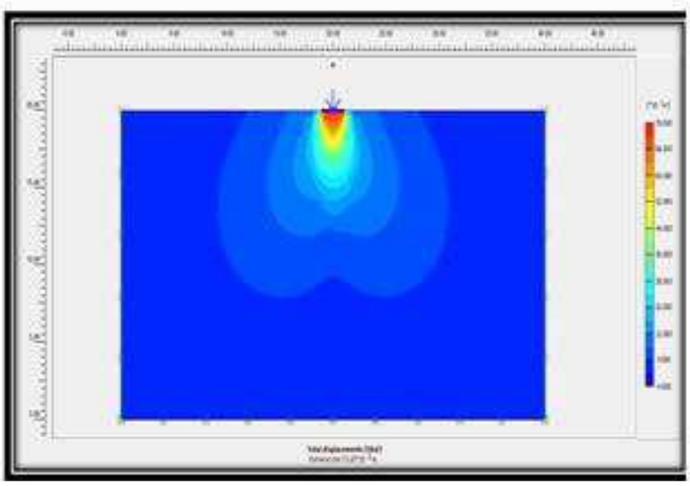

Fig. 4. Output from PLAXIS 2D -Settlement Contour
(Mutalik Desai and Akshay V. Mutalik Desai (2017))

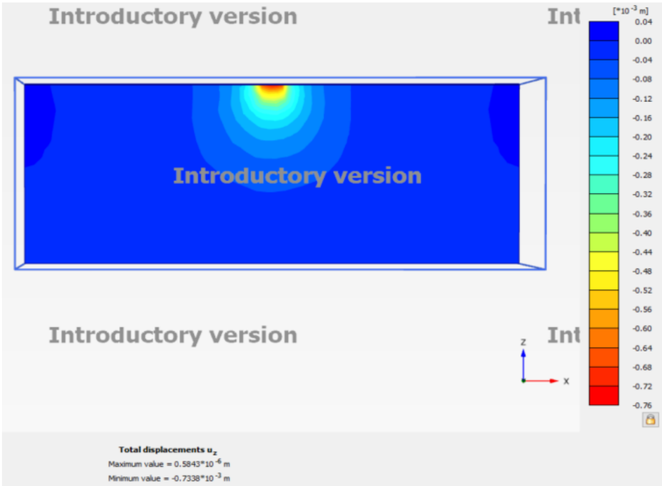

Fig. 5. Output from PLAXIS 3D -Settlement Contour

Table 2. Comparison of settlement results

Methods	Vertical Settlement (mm)
PLAXIS 2D (Mutalik Desai and Akshay V. Mutalik Desai (2017))	80 mm
PLAXIS 3D (validation analysis)	74 mm

The properties of materials used in the numerical analysis are tabulated below (Table 3). The properties of the materials are taken from the corresponding IS codes. [7] [8] [9] [10]

Table 3. Properties of materials

Properties	Laterites	Sandstone	Granite	Sand mixture
Density (γ) (kN/m^3)	20	21	27	20
Young's Modulus (E) (kPa)	1 x 10^6	30 x 10^6	(40-70)x 10^6	100 x 10^3
Poisson's Ratio (μ)	0.3	0.2	0.2	0.3
Angle of internal friction (Φ) (degree)	30	30	51	40
Cohesion (C) (kPa)	5000	30 x 10^6	55000	-

5 Results and Discussion

Displacement and Vertical stress values for the different boundary conditions are determined by considering the Mohr-Coulomb model by using PLAXIS 3D finite element software. A model of 200 m x 200 m x 80 m is created in the PLAXIS in which the foundation is formed to get the displacement and vertical stress values. The results obtained are plotted in the form of graph to show the displacement and vertical stress variations based on boundary conditions. Height of the boundary Vs Displacement for various boundary condition is shown in figure 6.

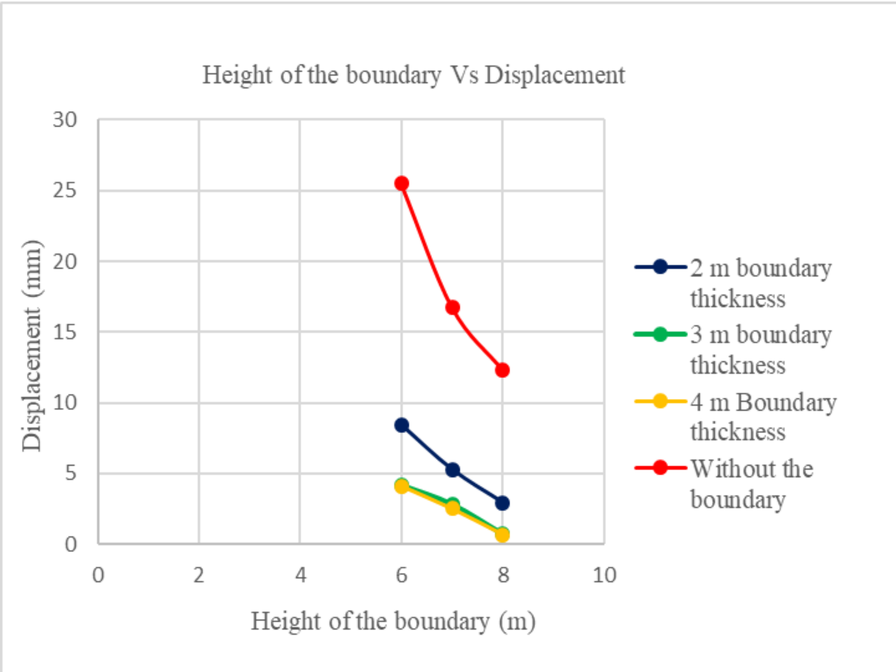

Fig. 6. Height of the boundary Vs Displacement for various boundary conditions

The displacement value of 2 m raft is more than 3 m thickness of the boundary. Because of the boundary thickness increases, displacement distributed along the sides of confinement. Displacement profile for 3 m boundary thickness and 6 m height of the boundary are shown in figure 7.

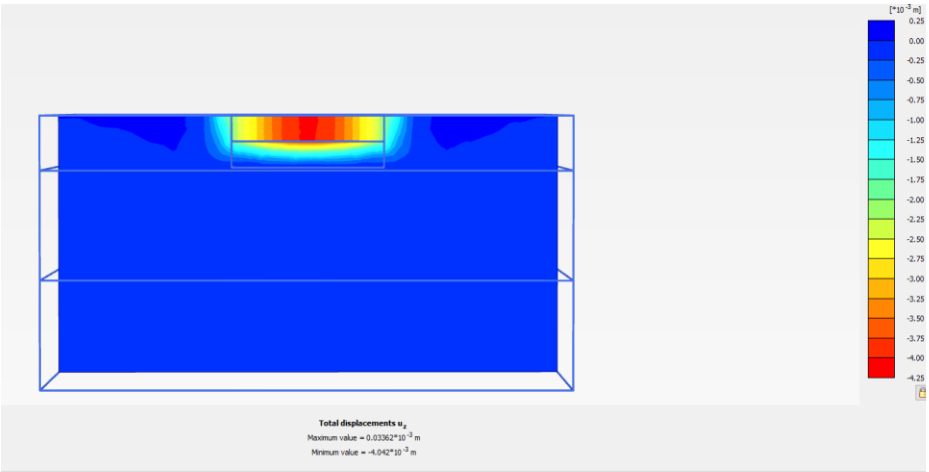

Fig. 7. Displacement profile for 3 m boundary thickness and 6 m height of the boundary

Height of the boundary Vs Vertical stress for various boundary condition are shown in figure 8.

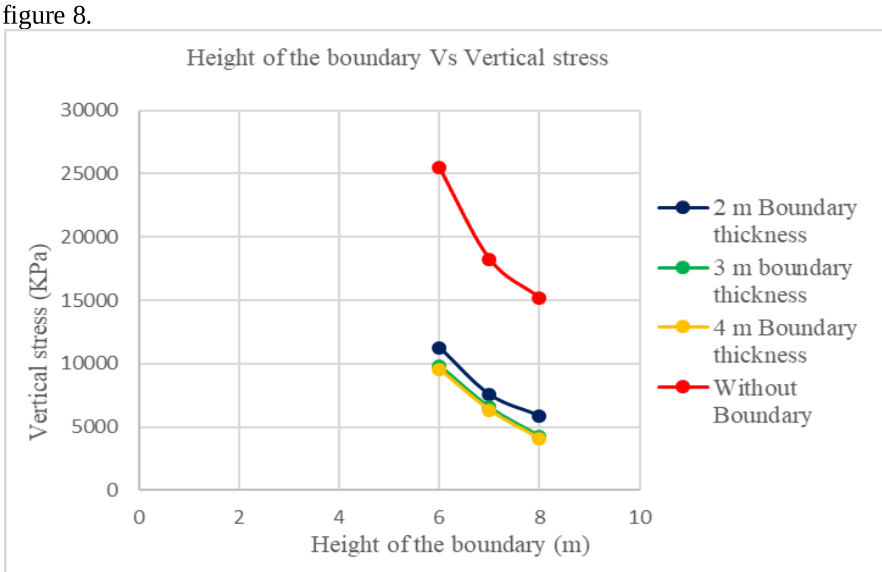

Fig. 8. Height of the boundary Vs Vertical stress for various boundary conditions

The most of the stresses due to applied load are taken by the boundary of the sandbox because of the confinement (see Fig 9). The maximum stress values are obtained at these coordinates of the boundary of the sandbox. Due to the boundary i.e. by providing sandbox, the stresses transferred are less than without boundary. Vertical stress for 3 m boundary thickness and 7 m height of the boundary are shown in figure 9.

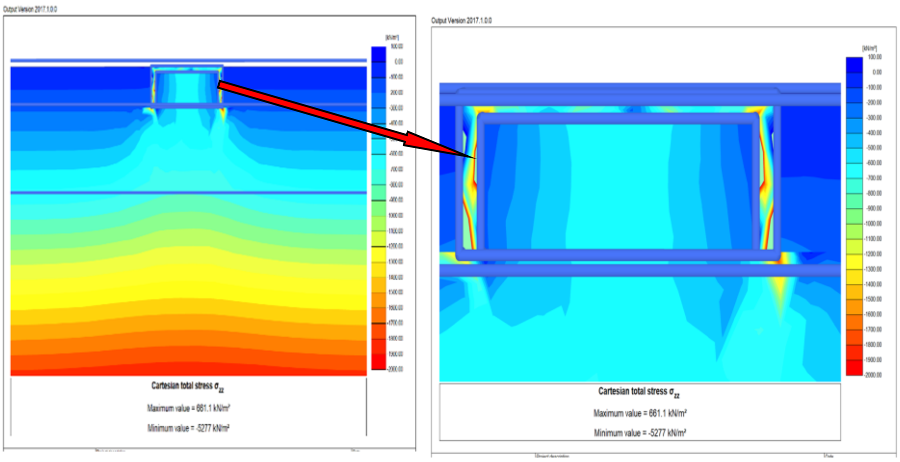

Fig. 9. Vertical stress for 3 m boundary thickness and 7 m height of the boundary

In this temple foundation constructed by granite stone. The young's modulus of granite stone is varying between 40 to 70 kPa. The young's modulus value increases, settlement and stress values decreased. But young's modulus values varying between 60 to 70 kPa, settlement values varying is low. The displacement values for different boundary condition and various young's modulus values are shown in figure 10 and figure 11.

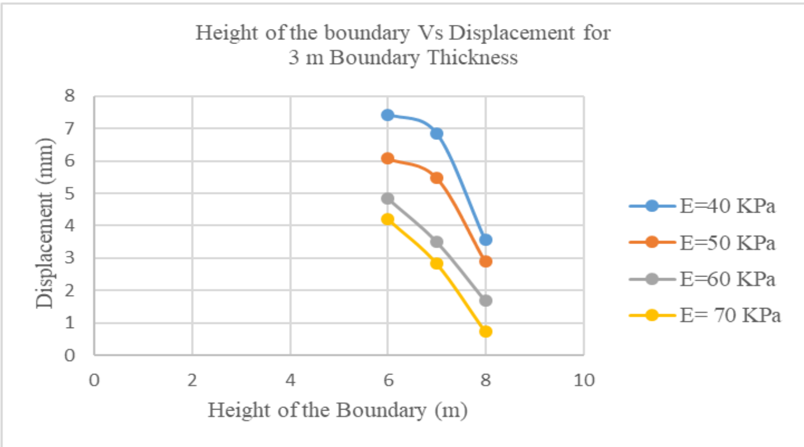

Fig. 10. Height of the boundary Vs Displacement for various young's modulus (E)

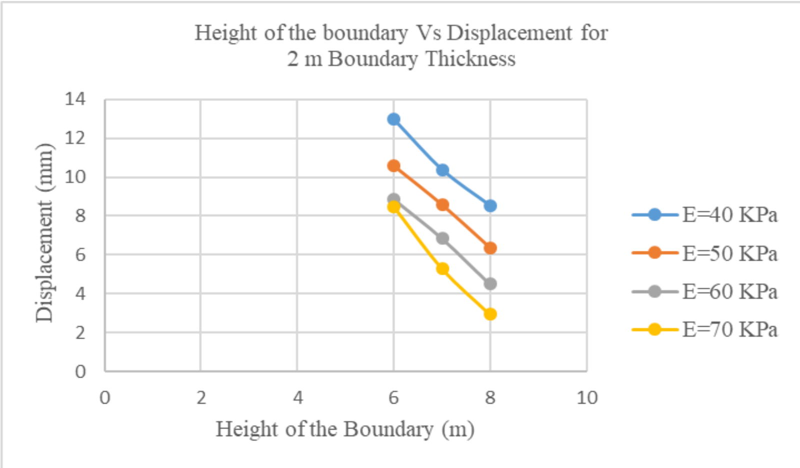

Fig. 11. Height of the boundary Vs Displacement for various young's modulus (E)

6 Conclusions

Based on the results, it was concluded that the Thanjavur Brihadeeswarar temple tower foundation designed for zero settlement. The foundation designed without the boundary, the settlement value was more than the permissible limit. But the foundation designed with boundary, the settlement value was decreased. The shallow foundation 36 m square raft and thickness of the footing is 2 m with 3 m boundary thickness, 8 m Height of the boundary gives the approximately zero settlement and low-stress values compare than the other dimensions. Because of the confinement, the most of the stresses due to self-weight are taken by the boundary of the sandbox.
Among the material properties Elastic modulus of stone (E), Friction angle (ϕ) and compressive strength of stone joints (f_c), the elastic modulus of stone seems to be the governing parameter. This type of foundation resist earthquake loading also. In earthquake loading condition, the energy was observed by sand to transfer the superstructure in low level.

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