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Numerical Modelling of Shallow Foundation on Multi-Layer Soil with varying Stiffness

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ABSTRACT

The load-deformation observation under the footing is essential for foundation design. Either experimental methods or numerical modelling generally determines this phenomenon in engineering practices. This study determined the settlement of shallow foundations on Multi-layer soil profile numerically. The settlement behavior was investigated through numerical modelling with Plaxis 2D. This study site was Jamshoro region, located in province Sindh, Pakistan. From the geotechnical investigation, the soil of Jamshoro region consists of a combination of different soils, mainly shale and limestone. This type of soil shows common challenges for the serviceable and sustainable design and construction of structural foundations. The standard penetration test conducted accompanied by other geotechnical tests on shale and limestone to determine the input parameters for the model and observe the soil profile. The Mohr-Coloumb model used for shale and linear elastic for limestone. The settlement of the foundation is attended by varying the limestone layer's depth. In this research, the settlement reduced under the footing by increasing the thickness of the limestone layer. The study observed that stiffness of lower layer significantly reduces the settlement of shallow foundation. Therefore, the effect of lower layer should be considered for the designing of foundation on multi-layered soil.

Keywords: Plaxis; shale; settlement; layered soil; numerical modelling

INTRODUCTION

Soil is seldom homogeneous in real life. Non-homogeneity can be both natural and man-made. Natural soil is nonhomogeneous due to various processes, including erosional removal of overburden, chemical bonding, and changes in static ground water levels. Changes in sea level in the past can result in layered soil. Many earthworks, such as fills and pavements, are made up of various soil types horizontal strata. Foundations are typically built to achieve standards of strength and serviceability to support structure and equipment. Serviceability requirements dictate that the foundation should operate to fulfil its design requirement under normal operating loads. The strength criteria of the foundation aim to ensure adequate reserve strength to withstand the heavy loads encountered due to severe environmental factors. In most instances, the settlement and strength requirements may be viewed as unrelated design tasks (Chen & McCarron 1991). The settlement is one of the main parameters considered in designing the shallow foundations (Johnson, Christensen, Sivakugan, & Karunasena 2015; Kim, Park, & Jeong 2017). According to the (B. Das & Sivakugan 2007), the settlement criterion is more important than the bearing capacity in shallow foundation design. Particularly, for the foundation widths greater than 1.5 m which is the more common case in construction projects.

In shallow foundations, the settlement such as immediate and secondary settlement of compression. Due to load application after the structure is constructed, immediate settlement is encountered (B. M. Das 2015). The clay deposits are less heterogenous than sand deposits; therefore, sand deposits are more prone to higher differential settlements than clay deposits (Mohammed, Sharafati, Al-Ansari, & Yaseen 2020). Besides the settlement of footings depends on many variables, including the shape and size of the footing, embedding depth, layering and soil mass non-homogeneity, etc (Dodagoudar & Shyamala, 2015).

At present, it is possible to analyze the foundations by Finite-element methods (F.E.M.), and limit equilibrium approach. Numerical methods are the third pillar after implementing the finite element (F.E.) processes. This approach helps understand engineering structures' issues through validation of theory and experimentation (Schneider-Muntau & Bathaeian 2018). The established non-linear methods for computing settlements cannot be used in the cases of large footings, therefore numerical modelling is a viable alternative (Kristić, Prskalo, & Szavits-Nossan 2019; Schmertmann 1970).

The famous methods for settlement projections are widely discussed in (Burland, Burbidge, Wilson, & TERZAGHI 1985; Frydman & Burd 1997; Meyerhof 1956; Schmertmann 1970; Schmertmann, Hartman, & Brown 1978). The first coherent approach for assessing a square footing settlement on granular soils was proposed by (Terzaghi, Peck, & Mesri 1996) carried out the plate load studies to calculate the risk associated with settlement prediction methods. (Sivakugan & Johnson 2004) developed a probabilistic system based on the settlement records in the literature. They suggested four different settlement probabilistic prediction approaches that allow the designer to measure the likelihood of exceeding a specific limiting value for the actual settlement.

Settlement and bearing capacity of foundation models with various vertical cross-sectional shapes under the applied load action is presented on non-cohesive subsoil bases. Many studies on different foundation sections, such as rectangular, wedge, and T shape were experimentally tested. The study generally showed higher bearing capacity and lower settlement with rectangular vertical cross-sectional shapes than wedge and T shapes (Enkhtur, Nguyen, Kim, & Kim 2013). An experimental study was performed by (Gupta & Trivedi 2009) on the effect of cell confinement on bearing capacity and settlement of circular footing on silty sand. Laboratory tests conducted on clean sand and sand containing up to 25% silt. The reaction of a footing without confinement was initially determined and then contrasted to that of confining footing. They observed that soil confinement plays a vital role in increasing the bearing capacity and reduction of settlement. The ultimate bearing capacity of footings on a sand layer that overlays a clay layer was investigated by (Oda & Win 1990). They concluded that the plastic flow in the clay layer takes place in the lateral direction. An exerting drag force on the upper sand layer results in the loss of bearing capacity of the soil. The bearing ability of the weak clay layer overlaid by a dense sand layer was measured based on the assumption that the failure surface pattern is a punching shear failure in the weak clay layer through the sand layer. And the failure mode is a function of soil properties (Al-Shenawy & Al-Karni 2005).

This research (Sawicki, Świdziński, & Zadroga 1998) aimed to critically analyze in situ testing methods to predict the settlement of shallow foundations. Accordingly, a 1.8m (6ft) diameter concrete footing was tested under a static loading. The foundation settlement predictions were made using both conventional and finite element approaches. The Mohr-Coulomb (elastic perfectly-plastic) model provided better estimates than the hardening soil model for all in situ test-derived parameters.

Researchers have provided an overview of settlements on an air-dry, non-cohesive compacting subsoil of cyclically loaded shallow foundations (Sawicki et al. 1998).

(Ouabel, Zadjaoui, & Bendiouis-Benchouk, 2020) studied the theoretical and numerical estimation of the settlement under the shallow base with the contribution of the characteristics of the results of the pressurometric tests. The first is the classical method, and the second is the empirical method based on the direct analysis of the in situ test.

A new genetic programming (G.P.) strategy for forecasting settlement of shallow foundations is discussed in this paper. Using a broad database of standard penetration test (S.P.T.) the G.P. model was created and checked. The outcomes of the built G.P. model is contrasted with those of a variety of conventional methods widely used and models based on the artificial neural network (ANN) (Mohammed et al. 2020).

The mechanical behavior of unsaturated soils, depending on the form of the soil and various pore-water and pore-air conditions, can be interpreted using either a modified total stress or a modified efficient stress system. The technique proposed is tested in unsaturated cohesive soils with model base test results (Oh & Vanapalli 2018).

In order to estimate the ultimate unit bearing pressure of strip footing under three different conditions, 2D finite element analysis was used. Laboratory model test under 1-g, centrifuge test under n-g, and large-scale test under 1-g. The hardening soil model was used for cohesionless soil to account for the rise in shear strength and stiffness with depth. The axial unit bearing pressure-settlement curves were collected on the basis of the numerical results (Lee, Bae, Kim, Baek, & Youn 2016).

Nowadays, more ring foundations are used exclusively for axi-symmetric structures. A numerical analysis was performed in study conducted by (Choobbasti et al. 2010) using PLAXIS software. This study assessed bearing capacity and settlement of ring footing.

The material parameters of the soil medium are naturally variable. Aside from the non-homogeneity that causes layered soil, soil characteristics can vary within each layer due to its inherent variability. Even when extensive in situ tests are carried out at the construction site, analytical methods and physical modelling of actual spatial soil heterogeneity remains challenging. When there is the bedrock beneath the soil, obtaining an analytical solution for stress and displacement is extremely difficult due to the bedrock's constraint on the soil. This study deals with the determination of settlement of shallow foundation numerically with consideration of vertical homogeneity of soil in form of modulus of elasticity and shear strength parameters of multi-layer soil profile in Plaxis 2D. This research consists of four phases: compilation of all the in-situ and laboratory data available and soil profiles extracted for each plot in the area; the use of well-known correlation to predict engineering parameters; the final soil structure modeling interaction. A database of soil engineering parameters for the study area is compiled based on six boreholes and experimental data in situ and the laboratory. In this study, the numerical modeling with Plaxis 2D is to be performed to evaluate the settlement on the multi-layer soil profile of Jamshoro area.

RESEARCH METHODOLOGY

Finite Element Analysis performed with the Plaxis 2D program. The Plain-strain model was selected to describe the problem. The elasto-plastic Mohr-Coloumb model selected to simulate the soil behavior of Jamhsoro Shale. As a first order (linear) simulation of actual soil efficiency, the known Mohr-Coulomb constitutive law was used.

The undrained conditions were chosen for this study, and the foundation is believed to be a rigid elastic. The symmetry axis and the proper vertical boundaries are constrained laterally. In both vertical and horizontal directions, the bottom boundary restrained. On the vertical edges, horizontal fixity was added, while the model's bottom edge is considered to be non-yielding and constrained from both vertical and horizontal movements. The footing modelled with linear elastic model. The Mohr Coulomb model parameters, such as modulus of elasticity of soil, shear strength parameters such as cohesion, and angle of internal friction were inserted as input parameters. The value of the dilatancy angle was zero (φ-30).

The uniformly distributed load was applied on footing as line load in Plaxis with staged construction technique. The footing was initially activated and after that line load. The laboratory tests such as sieve analysis, liquid limit, plastic limit, shear strength and unconfined compression strength were conducted on the obtained soil samples. The results of laboratory tests were kept as the input parameters in Plaxis program. After the model's geometry was established and assigning the material properties to all clusters, the next step was to divide the geometry into element in mesh generation. The medium size of mesh was set in account for more accuracy and reduced program processing time. The Plaxis 2D software allows the "robust triangulation scheme" to generate finite element meshes automatically. Five simple meshing styles are available in Plaxis 2D, namely very coarse',' coarse',' medium',' fine', and very fine', each with a gradually refined mesh coarseness factor. The mesh should be adequately and optimally perfect for obtaining accurate numerical results. A rather coarse mesh may fail to capture the domain's important responses, whereas probability accumulates numerical errors beyond the optimally fine mesh. Also, very fine meshing should be avoided because calculations would take excessive time. With further provisions of local refinements, as required by the merit of the problem and the position of the answer points in the numerical simulation, any simple meshing scheme can be adopted. The plane strain model and 15 nodes were selected to simulate the soil medium. Compared to the 6-noded triangular components, it offers more nodes and Gauss points to assist in the comparatively precise determination of displacements and stresses. The model dimensions have been so selected that the deformation in the soil does not intersect the model's boundaries. There is a need to determine initial stresses in Plaxis simulations. For the specification of these stresses, two possibilities are in software: 'K_0-procedure' and 'Gravity loading'. As a guideline, in the case of a horizontal surface, the K_0 procedure should be used. The "standard fixity" condition has been employed in the numerical model.

RESULTS

Extensive soil investigation and laboratory work have been conducted in the Jamshoro vicinity (Figure 1a). The standard penetration test was conducted at each 5 ft depth. A typical subsurface profile of this area contains a stiff shale consolidated layer underlain by an extended layer of fractured limestone rock in Figure (1b). The specific gravity of shale was 2.60, and soil was classified as A-7-5 according to AASHTO soil classification system. The maximum dry density was identified through proctor test and calculated as1.9 gm/cm^3. The field density test was performed, and the value was obtained as 1.2 gm/cm^3. The sieve analysis performed, and the particle size distribution (PSD) curve is shown in Figure 2. The consolidation test was carried out in odometer and co-efficient of consolidation (Cc) and co-efficent of swelling as (Cs) found as 0.228 and 0.068 respectively. The undrained shear test performed in shear box apparatus and the shear strength parameters of soils calculated as c = 150 kN/m^2, and angle of internal friction = 0. (Where, c represents the cohesion).

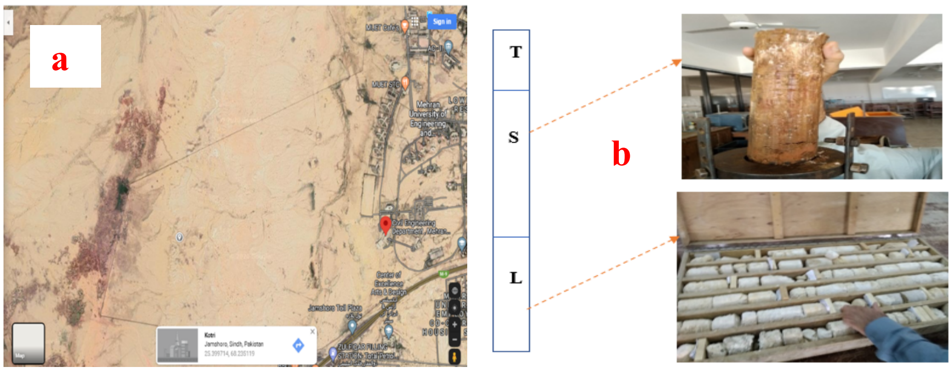

FIGURE. 1 (a) Study area, Figure 1 (b) Typical Soil profile of study area (T = Top soil, S = Shale & L = Limestone)

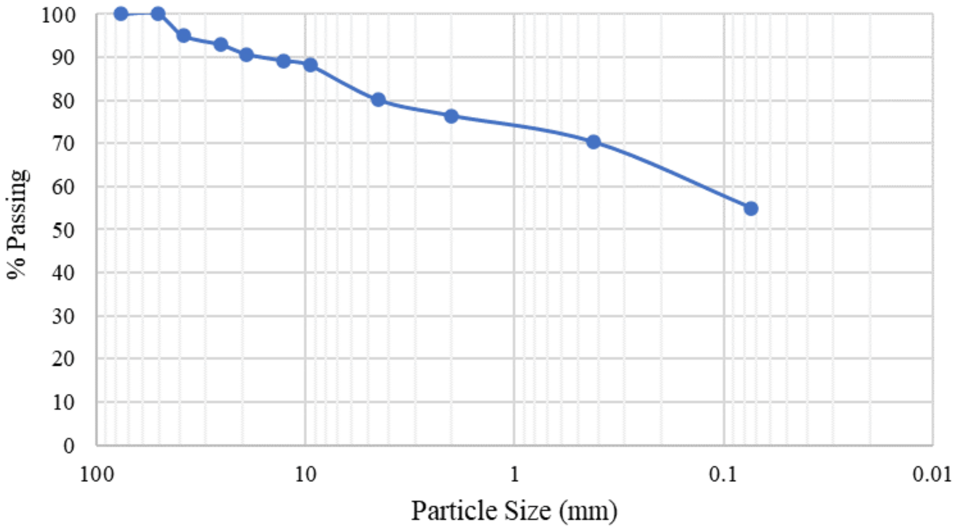

FIGURE 2. Particle Sieve Analysis

Computing the foundation settlement under the load model conditions was simulated similar to field conditions in Plaxis. The model conditions shown in Figure 4.

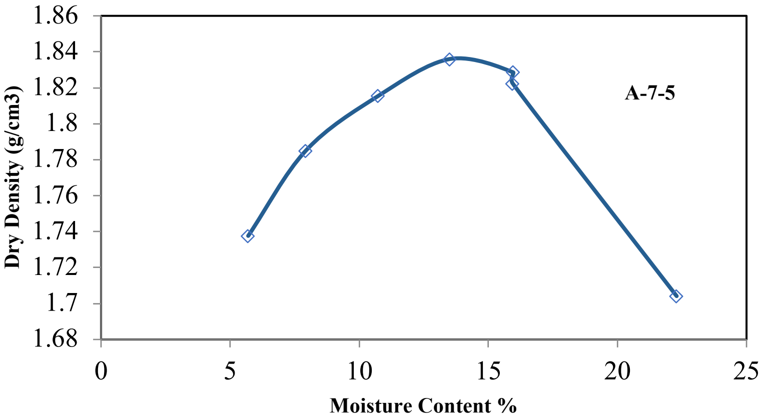

FIGURE 3. Modified Proctor Results

TABLE 1. Soil properties

Unit weight, γ (kN/m^3)	19	
Modulus of Elasticity E	Shale (E_1)	37000 kN/m^2
	Limestone (E_2)	9 x 10^6 kN/m^2
Undrained Cohesion, C (kN/m^2)	150	
Friction angle, ϕ (degrees)	0	
Poisson's ratio,	0.3	
Dilatancy angle, Ψ (degrees)	0	
Liquid Limit	70 %	
Plastic limit	30 %	
Plasticity Index	40 %	
Shrinkage limit	15%	
Permeability	0.027 m/day	
Cc and Cs	0.228 and 0.068	

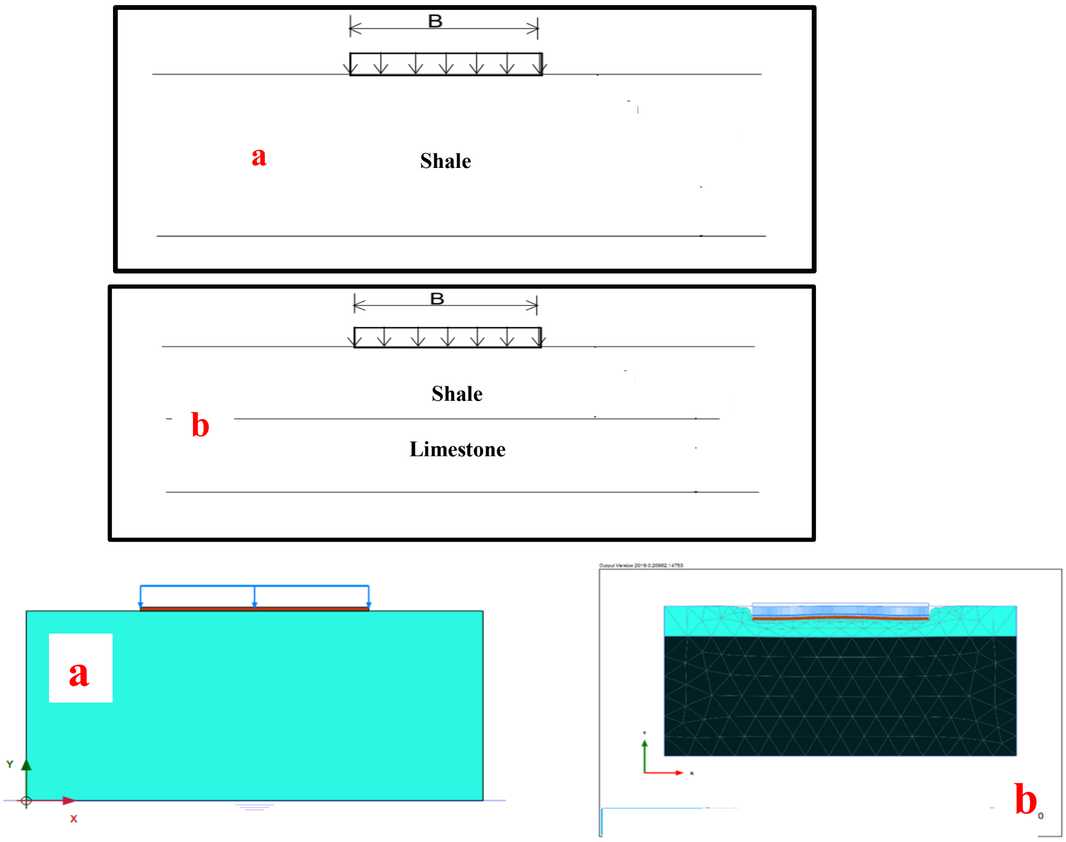

FIGURE 4. a) Model conditions for Shale b) Model Conditions for Layard Soil

In the Plaxis, Initial stage – during modeling in Palxis software, at the initial stage the initial stress state of soil is generated before construction. The initial stage is also called the K_0 procedure. The displacements after K_0 procedure are set to be zero. The second stage of modeling is known as loading stage. In this stage, data are obtained from the loading branch of the load settlement curve. The default values of K_0 and R_{inter} were used in modelling.

The raft width was taken as 50 m, and uniformly distributed load (U.D.L.) load was applied on the top of the raft as a building load. The load varied from 200 kN/m^2 to 600 kN/m^2. The load of 1 kg/cm^2 (100 kPa) on the soil, resembles a one- or two-stories house. In this present study, the higher load characterize the multi-story building. Moreover, the higher load is to significantly observe the effect of varying multi-layer soil profiles on settlement. The settlement of 0.289 m was recorded under the load of 200 kN/m^2, while 0.94 m on 600 kN/m^2. The simulation results are shown in Figure 5 - 8. The simulation results show the higher settlement below the footing and decreased with depth. Moreover, when the hard layer was at 10 m, the settlement reduced to 0.238 m from 0.94 m.

The effect of modulus of elasticity of multi-layer soil profile on settlement of foundation presented in Figure 10. The lower settlement Figure 10 depicts the load in layered soil and higher settlement due to limestone layer. The stress variation in y-direction in the soil is due to applied load on one and two layers shown in Figure 13. The settlement in shale under the load of 200 kN/m^2, 400 kN/m^2 and 600 kN/m^2 were calculated as 0.289, 0.565 and 0.940 m individually. However, simulating the same conditions by considering the hard layer (limestone) closer at 10, 20 and 30 meters, the settlements under the load of 600 kN/m^2 were observed as 0.238, 0.458, and 0.684 m, respectively. In Figure 11, vertical stress with depth decreased considerably with the limestone layer below the shale layer compared to only shale layer. The parametric research conducted by (Mandeel, Mekkiyah, & Al-Ameri, 2020) is carried out using the finite element technique (FEM) to elaborate the behavior of a full-scale foundation resting on layered soil under vertical concentric loading, which more effectively represents field circumstances. The thickness of the soil layers, the friction angle, cohesiveness, and the width of the foundation were all adjusted to see how they affected the bearing capacity of layered soil.

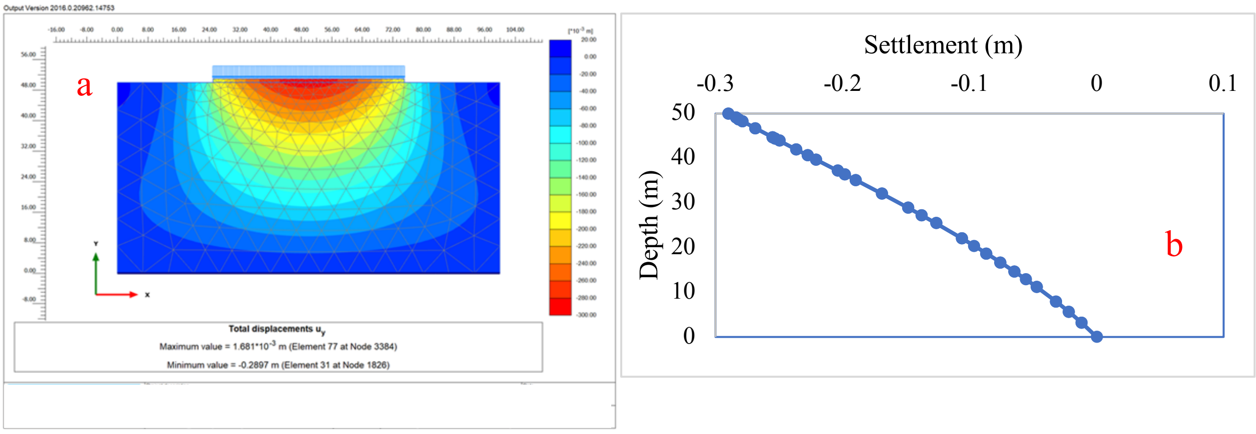

FIGURE 5. a) Contours of Settlement of Footing b) Variation of settlement with Depth (@200 kPa)

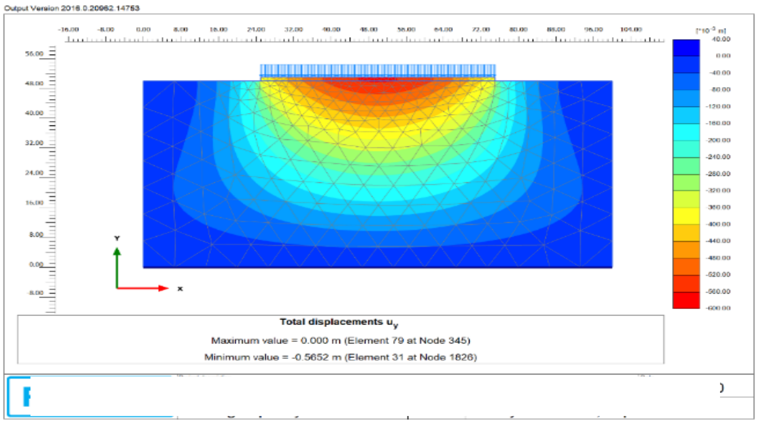

FIGURE 6. Settlement of Footing under the load of 400 kN/m^2

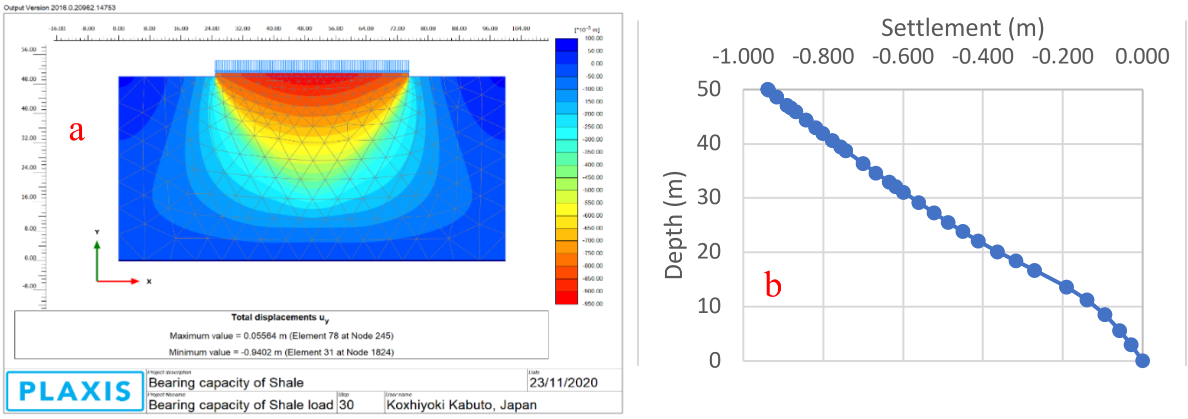

FIGURE 7: a) Contours of Settlement of Footing b) Variation of settlement with Depth (@600 kPa)

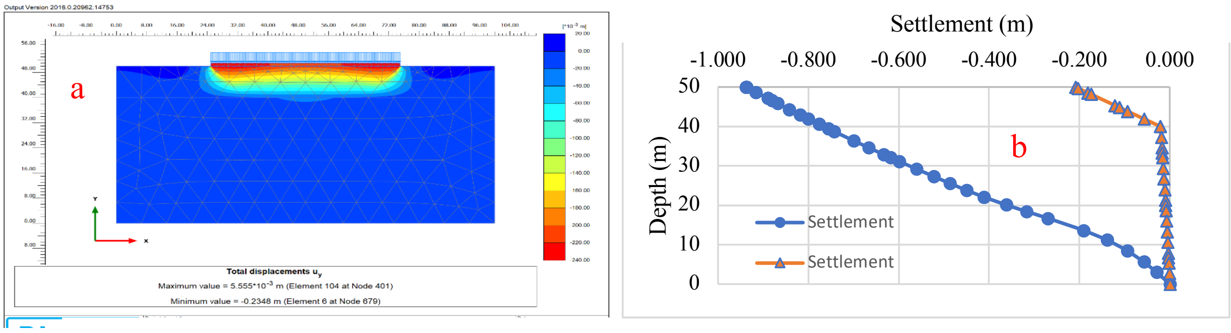

FIGURE 8. a) Contours of settlement of Footing with limestone Layer at 10 meters @ Load 600 kN/m^2 b) Variation of settlement with Depth

Chow and Small (2005) presented a numerical method for analysing the vertical deformation of smooth, rigid foundations of any shape in homogenous and stratified soil media. The flexibility coefficients for a layered soil medium were calculated using an axisymmetric finite element analysis, which is effectively two-dimensional (2D). For the response of rectangular foundations on several common soil profiles, parametric solutions were offered. The use of a simplified method of superposing solutions for homogenous, elastic strata to predict the settlement of rectangular foundations on a layered soil medium was also studied.

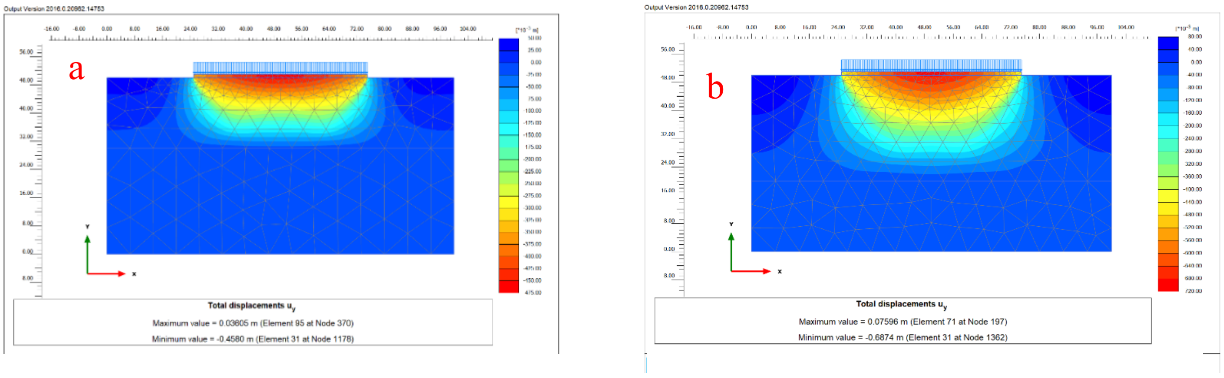

FIGURE 9: Contours of settlement and limestone Layer at 20 meters b) Contours of settlement and limestone Layer at 30 meters

Azam, Hsieh, and Wang (1991) investigated the behaviour of strip footings on a homogeneous and two-layered soil using plane strain 2D finite element analysis. Both soil domains, with and without void, were used to investigate the effect of continuous void. When the depth of bedrock was equal to or greater than six times the breadth of the footing, the influence of bedrock on footing response was found to be minimal. The thickness of the top layer and the strength ratio of the two layers were discovered to be critical criteria determining the footing's response in a two-layered soil. The position of the void, depth to bedrock, layer thickness ratio, and layer strength ratio all influenced the degree of void influence on footing response.

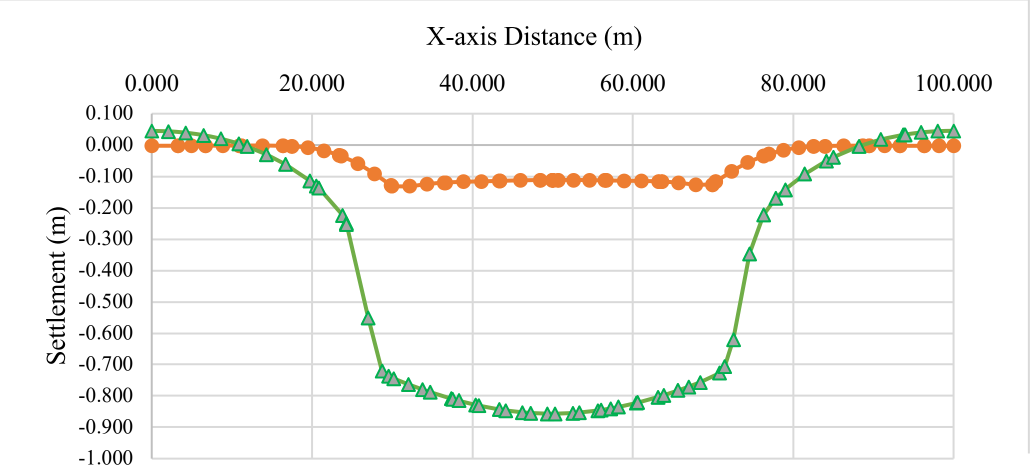

FIGURE 10. Settlement variation along X-direction Load 600 kN/m²

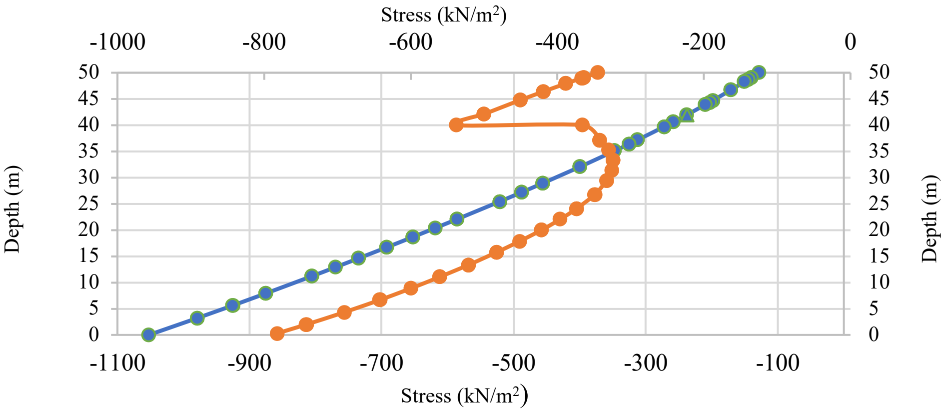

FIGURE 11: Stress Variation with depth @ Load 600 kN/m²

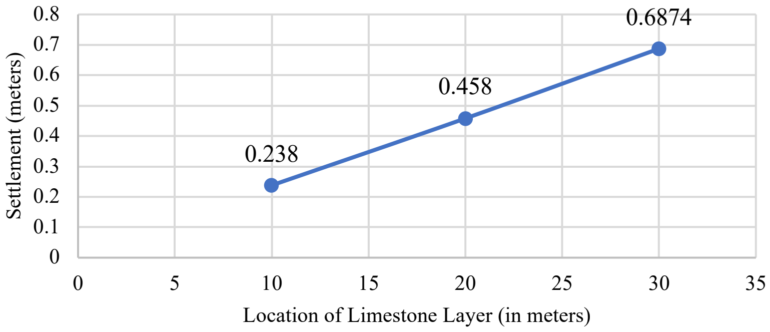

FIGURE 12. Variation of Settlement of footing with depth of limestone layer

The Figure 11 represents the variation of change in vertical stress with depth for homogenous soil and multi-layered soil. There is a higher vertical stress observed in the homogenous soil shale compared to limestone beneath the shale. Figure 12 shows the settlement with limestone layer at a different depth, even though the limestone layer below the shale, the settlement exceeds the serviceability limits for multi-story buildings.

CONCLUSION

This study was designed to investigate the effects of settlement on shale through and propose a solution for the settlement reduction to achieve the standards of strength and serviceability for foundation design and construction. The effect of the settlement was studied through experimental investigation and numerical modeling. This study presents the following conclusion form experimental and numerical analysis:

1. The observed lithology in the study area was shale underlain by limestone with varying thickness. The soil investigation showed the dense to hard shale availability with fractured and weathered limestone.
2. The simulation results showed large deformation in a single shale layer. The deformation decreased due to the limestone layer below the shale layer. Even with the limestone layer at deeper depth affects the shallow foundation behavior. In the analysis of settlement of multi-layer soil, the stiffness of lower layer should be considered for economical design. The settlement of shallow foundation even at 200 kPa, exceeds the allowable settlement criteria in shale.

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DECLARATION OF COMPETING INTEREST

None

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