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Research Paper

Vertical Stress Distribution at Soil Layers with Various Consistencies under the Footing Contact Area

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ABSTRACT

According to the Elastic Theory by Boussinesq, vertical stress distribution under the footing contact area will diminish with distance from the contact area and it is irrespective of the soil consistency. This study aimed at investigating the effect of the soil stratigraphy and consistency on vertical stress distribution at soil layers under the footing contact area. Soil investigation with CPT tests and relevant laboratory tests were carried out to obtain a reference of compressible soil layer thickness and relevant soil characteristics. The soil stratigraphy and parameters in conjunction with the vertical stress distribution were varied for two different types of soil, a typical granular soil e.g. sand and cohesive soil e.g. clay. Numerical analysis was performed to investigate the effect of the soil parameters on the vertical stress distribution. The results revealed a similarity between those obtained from the Elastic Theory (manual analysis) and numerical study using the PLAXIS software. However, the results of the numerical study showed a significant influence of the soil consistency on the vertical stress distribution at soil layers under the footing contact area.

1. Introduction

The stress distribution underground surfaces due to upper structure loads affects the safety factor of bearing capacity and settlement for the foundation structure. The Elastic theory regarding the stress distribution has been used to determine the stress and depth of stress influence beneath the footing contact area (Craig, 1997; Das, 1995). This theory does not take account of the type and consistency of soil as a medium of the stress distribution. Therefore, the stress distributions through soil layers under the upper structure loads using the Elastic theory are equal for all types and consistency of soil. Furthermore, the misconception in specifying type and dimension of foundation may result in the structural failure. A shallow foundation with large contact area such as a raft foundation may have a critical safety factor against bearing capacity and settlement when resting on layered soils with soft soil layers closed to its contact area.

The amount of software including PLAXIS has been developed to determine the stress distribution at soil layers beneath the footing contact area and consequently its settlement by considering parameters of soil as a medium of the stress propagation. The use of this software enables to perform numerical analysis modeling for a footing resting on various types and consistencies of soil. Numerical analysis modeling with PLAXIS has been performed by Darjanto *et al*. (2015) to investigate the effect of the upper structure loads on settlement of the cobweb foundation. Another numerical analysis modeling with PLAXIS also has been carried out by Widodo (2015) to examine the effect of embankment loads on the excess porewater pressure distribution mobilised under

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the embankment in Tanjung Emas Harbour, Semarang. The numerical modeling also has been performed by Shashkin (2007 a and b) using Finite Element Method (FEM) to specify the mechanism of stress distribution under footing of the 16-stories apartment building and its settlement. The results of the analysis modeling showed logical and similar trend: smaller stress with the increase distance from the footing contact area. Nevertheless, those results cannot be directly compared each other due to different input parameters regarding loads and soil properties used in the numerical modeling.

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2. Research methodology

Research site was chosen at Makassar Industrial Area (KIMA), Indonesia where bedrock layer existed at relatively shallow depth in order to easily identify the stress distribution under the footing contact area and its settlement consequence. Soil investigation with Cone Penetrometer Test (CPT) and soil sampling method for laboratory testing in Soil Testing Laboratory, Civil Engineering Department, Ujung Pandang State Polytechnic, Indonesia were carried out to provide soil parameters.

Parametric study was performed to determine the effect of soil stratigraphy and consistency on the distribution of stress and settlement under the footing contact area. The soil stratigraphy and parameters regarding its stress and compressibility were varied. In this study, two different types of soil were applied i.e.: granular (sand) and cohesive (clay) soils, and each of these soil types were assumed to be homogeneous and heterogeneous layers with two extreme soil consistencies respectively, loose and dense for sand and soft and stiff for clay as illustrated later. Typical values of the soil parameter for each soil consistency were used in this study.

Numerical analysis was performed using PLAXIS, currently popular and reliable software with Finite Element Method. Various soil parameters and related field conditions could be applied using this analysis to provide more accurate results.

The Elastic Theory provided in many literatures, the Influence Factor Curve and Newmark Diagram have been worldwide used to specify the stress distribution through soil layers beneath contact area of footings with various shapes. This method does not take account of type and consistency of soils in specifying stress distribution and its settlement impact. Therefore, this study considered the various scenario of soil layer in specifying the distribution of stress and settlement using the PLAXIS software as the fishbone diagram shown in **Figure 1.**

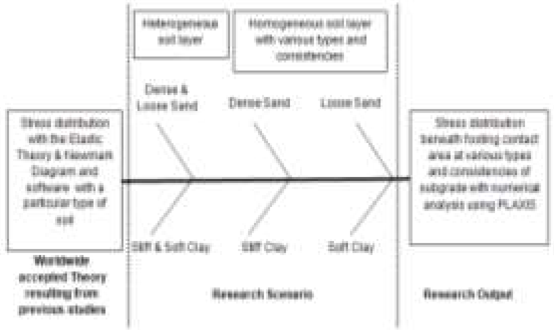

Fig. 1. Fishbone diagram of research design

The research procedure was carried out as follows:

1) Field investigation with Cone Penetrometer Test (CPT)
   This investigation was carried out to determine the thickness of compressible soil layer or the depth of bedrock level and soil parameters required in the analysis. The laboratory tests covered Unconfined Compressive Strength, Direct Shear, Permeability and Consolidation tests.
2) Design of Parametric Study Scenario
   Scenario of loading and soil stratification was presented in **Figure 2** and **Table 1.**

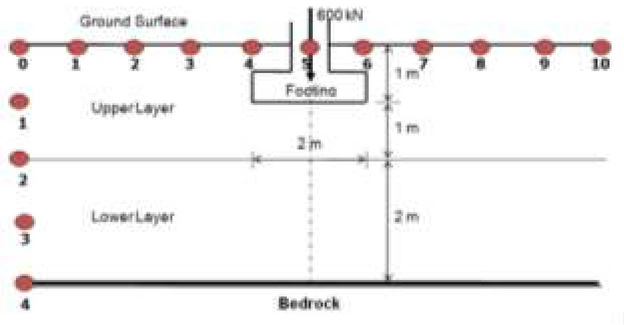

Fig. 2. Scenario of footing loading, soil stratigraphy and investigated points of stress distribution

Table 1. Description of soil stratification

No.	Scenario of Soil Stratification	Upper Layer	Lower Layer
1	Homogeneous/Single Dense Sand Layer	Dense Sand	Dense Sand
2	Homogeneous/Single Loose Sand Layer	Loose Sand	Loose Sand
3	Heterogeneous/Double Sand Layer	Dense Sand	Loose Sand
4	Homogeneous/Single Stiff Clay Layer	Stiff Clay	Stiff Clay
5	Homogeneous/Single Soft Clay Layer	Soft Clay	Soft Clay
6	Heterogeneous/Double Clay Layer	Stiff Clay	Soft Clay

3) Stress Distribution and Settlement Analyses
These analyses were manually performed using Influence Factor Curve. Results obtained from the manual analysis were compared with those resulting from the numerical analysis using PLAXIS software. Typical values of soil parameters regarding its type and consistency obtained from relevant references (Das, 1994; Craig, 1997) were used in this analysis as presented in **Table 2.**

Table 2. Soil parameters used in this analysis

Parameter	Unit	Sand		Clay	
		Loose	Dense	Soft	Stiff
Elastic Modulus (E_s)	kPa	12000	35000	10000	45000
Cohesion (c)	kPa			15	150
Internal Friction Angle (ϕ)	°	30	40		
Permeability Coefficient (k)	m/s	5×10^{-3}	5×10^{-5}	10^{-9}	10^{-11}
Saturated Unit Weight (γ_s)	kN/m^3	19	21	15	20
Dry Unit Weight (γ_d)	kN/m^3	15	18	13	17
Poisson Ratio (μ)		0,20	0,35	0,40	0,45
Dilation Angle (ψ)	°	0	10	0	0

3. Results and discussion

The distribution of vertical stress beneath 2 m x 2 m footing imposed by building (assumption of 3 stories) load of 600 kN resulting from manual calculation using the Elastic Theory by J.V. Boussinesq (Das, 1994; Craig, 1997) was presented in **Figure 3.** The maximum stress occurs at the centre of footing contact area and significantly decreases with the increase of soil layer depth until 2 m deep under the contact area, and this stress reduction becomes smaller with further depth. The magnitude of this stress proportionally decreases into horizontal distance from the contact centre with the increase of soil layer depth from the contact area. The stress reduction into horizontal distance is larger at soil layer closer to the contact area. This stress reduction converges at the horizontal distance of 2 m and even its configuration exchanges with further horizontal distance, larger stress with deeper layer from the contact area. Only very small stress of the footing contact area propagates into horizontal distance larger than 2 m from the centre of footing. The stress diminishes with the increase of horizontal distance and depth from the footing contact centre at the soil layer below the footing contact area. Almost no stress change with the increase of soil layer depth beneath the footing contact area outside the edge of footing, while the stress significantly decreases at the soil layer under the footing contact area. This phenomenon shows the stress dissipation into deeper soil layer from the footing contact area and larger horizontal distance until 2 m from the footing contact centre.

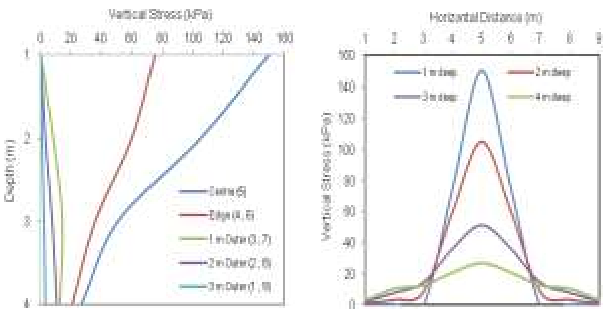

Fig. 3. The stress distribution of footing contact area

The parametric study was carried out with the numerical analysis using PLAXIS software. The soil parameters were varied including type, stratification and parameters in conjunction with the stress distribution such as shear stress and coefficient of permeability as previously described. The results of this analysis were presented based on type and stratification of soils as follows:

1) Sand Layer

The numerical analysis for the sand layer beneath the footing contact area was devided into 3 types of soil layer i.e.: (i) homogeneous dense sand layer 3 m thick, (ii) heterogeneous sand layer with dense sand at upper layer 1 m thick and loose sand at lower layer 2 m thick and (iii) homogeneous loose sand layer 3 m thick. The results of this analysis was presented in 3 versions: (a) vertical stress contours, (b) depth vs vertical stress curves and (c) horizontal distance vs vertical stress curves for each type of soil layer. The stress distribution imposed by building load of 600 kN at the homogeneous dense sand layer beneath the footing contact area of 2 m x 2 m was illustrated in **Figure 4.**

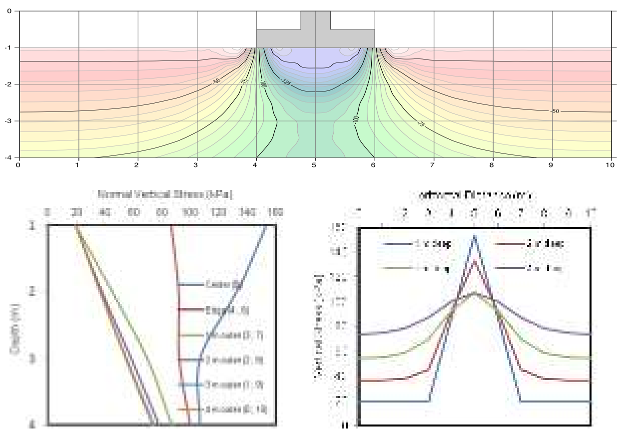

Fig. 4. The stress distribution at the homogeneous dense sand layer

The stress distribution obtained from analysis using the PLAXIS software generally shows a similar trend with that resulting from the manual analysis i.e.: the stress dissipation with the increase of distance from the the footing contact area. However, the stress reduction at a homogeneous dense sand layer with the increase of soil layer depth beneath the footing contact centre is much smaller than that resulting from manual calculation and no further stress reduction at depth ≥ 2 m. This stress reduction converges at the edge of footing (1 m horizontal distance from the footing contact centre), then the stress distribution exchanges with further horizontal distance, even relatively constant stress at horizontal distance ≥ 3 m. Almost no stress change with depth at soil layer beneath the edge of footing, while the stress reduction occurs at the soil layer under the footing contact centre until 2 m in depth, in contrast the stress increases with deeper soil layer outside the footing contact area.

On the other hand, the stress distribution imposed by building load of 600 kN at the homogeneous loose sand layer beneath the footing contact area of 2 m x 2 m was illustrated in **Figure 5**.

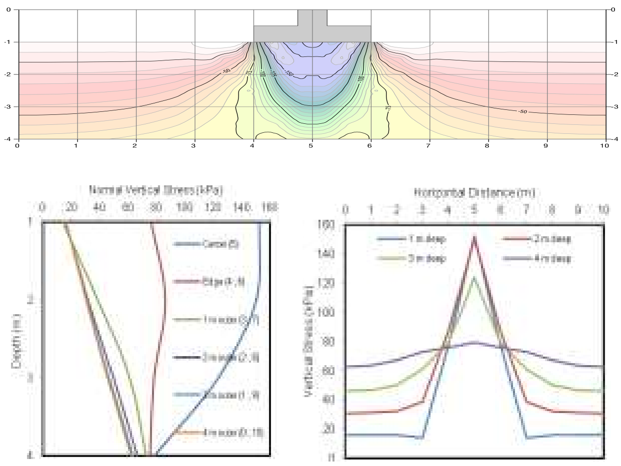

Fig. 5. The stress distribution at the homogeneous loose sand layer

No stress reduction in 1 m soil layer thick below the footing contact centre and this stress reduction becomes larger with further soil layer depth at a homogeneous loose sand layer beneath the footing. Similarly, this stress reduction also converges at the edge of footing (1 m horizontal distance from the footing contact centre), then the stress distribution exchanges with further horizontal distance, even relatively constant stress at horizontal distance ≥ 3 m. Only small change of the stress with depth at soil layer beneath the edge of footing while the stress reduction occurs at the soil layer under the footing contact centre in soil layer depth ≥ 1 m, in contrast the stress increases with deeper soil layer outside the footing contact area. This phenomenon shows that no stress absorbtion at 1 m layer tickness below the footing contact area due to loose arrangement of soil particles. Therefore, soil layer under the footing contact becomes compacted with punch shear failure mechanism imposed by the contact stress.

Furthermore the stress distribution imposed by building load of 600 kN at the heterogeneous sand layer beneath the footing contact area of 2 m x 2 m was illustrated in **Figure 6**.

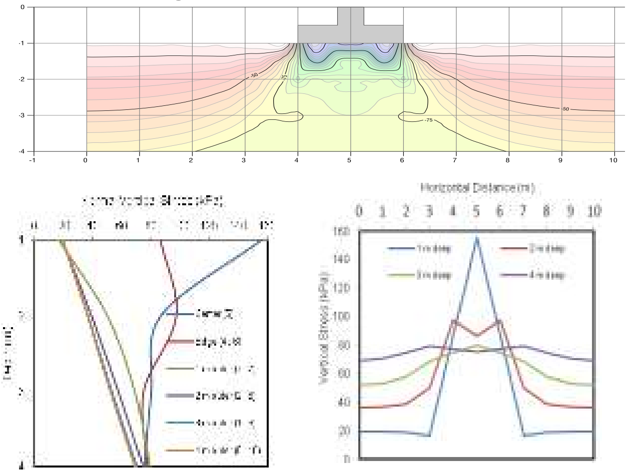

Fig. 6. The stress distribution at the heterogeneous sand layer

Similarly the stress drastically decreases with the increase of depth at the upper layer, 1 m thick dense sand for the heterogeneous sand layer beneath the centre of footing contact area, then it does not decrease further down at the loose sand layer. The stress distribution beneath the edge and outside of the footing contact area is similar to those at the previous soil stratification. Generally the largest stress reduction occurs at the dense sand layer (upper layer) beneath the footing contact centre because the dense sand layer with the highest relative density contributes to reduce significantly the stress propagation.

The results of the numerical analysis generally show that the maximum stress occurs at the centre of the footing contact area, then diminishes into further distances (horizontal distance and depth) at sand layer below the footing contact area which is in line with the study by Yamin et al. (2017). The stress decreases more significantly at a dense sand layer, because a larger amount of the contact stress is absorbed by a dense than a loose sand layer. Nevertheless, a loose sand layer closer to the footing contact area is compacted immediately since the contact stress is applied, thus the maximum stress beneath the centre of footing contact area is approximately the same as that at the dense sand layer.

2) Clay Layer

The numerical analysis at this clay layer was also devided into 3 types of soil layer i.e.: (i) homogeneous stiff clay layer 3 m thick, (ii) heterogeneous clay layer with stiff clay at upper layer 1 m thick beneath the footing contact area and soft clay at lower layer 2 m thick and (iii) homogeneous soft clay layer 3 m thick. The stress distribution imposed by building load of 600 kN at the homogeneous stiff clay layer beneath the footing contact area of 2 m x 2 m was illustrated in **Figure 7.**

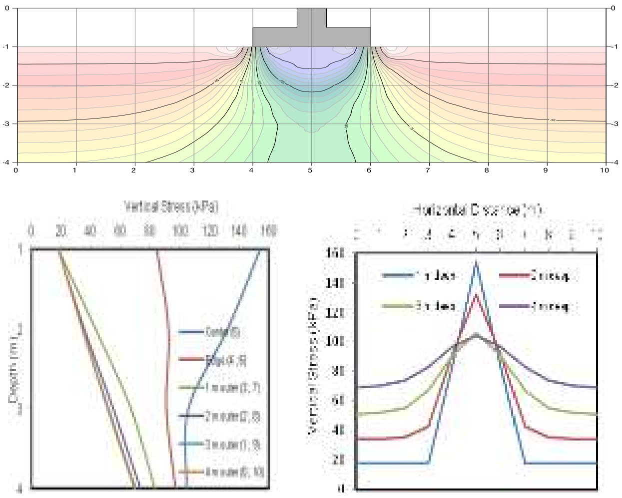

Fig. 7. The stress distribution at the homogeneous stiff clay layer

The stress distribution obtained from analysis using the PLAXIS at the homogeneous stiff clay layer is very similar to that at the homogeneous dense sand layer. The stress decreases at the homogeneous stiff clay layer with the increase of soil layer depth beneath the footing contact centre until 2 m in depth. This stress reduction converges at the edge of footing (1 m horizontal distance from the footing contact centre), then the stress distribution exchanges with further horizontal distance, even relatively constant stress at horizontal distance ≥ 3 m. Almost no stress change with depth at soil layer beneath the edge of footing, while the stress reduction occurs at the soil layer under the footing contact centre until 2 m in depth, in contrast the stress increases with deeper soil layer outside the footing contact area.

On the other hand, the stress distribution imposed by building load of 600 kN at the homogeneous soft clay layer beneath the footing contact area of 2 m x 2 m was illustrated in **Figure 8.**

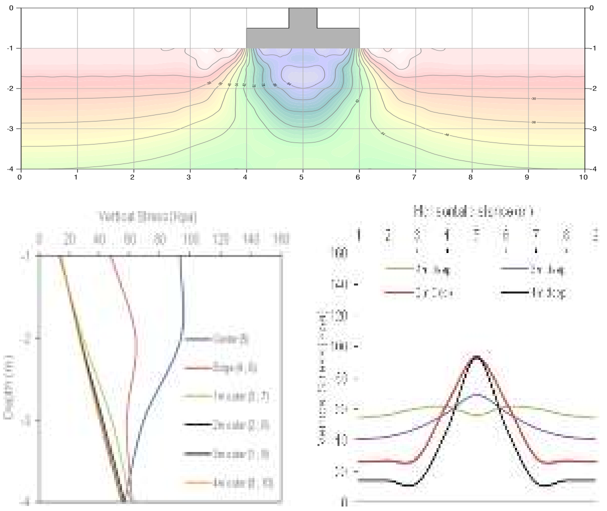

Fig. 8. The stress distribution at the homogeneous soft clay layer

No stress reduction in 1 m soil layer thick below the footing contact centre like at the homogeneous soft clay layer, but this stress reduction decreases with further soil layer depth at the homogeneous soft clay layer beneath the footing. Similarly, this stress reduction also converges at about the edge of footing (1 m horizontal distance from the footing contact centre), then the stress distribution exchanges with further horizontal distance, even relatively constant stress at horizontal distance ≥ 3 m. The stress tends to increase with depth, but this trend changes in soil layer with further depth below the footing contact area, the stress decreases with further depth (≥ 1 m). This phenomenon shows that the stress mobilized at soft clay layer is much smaller than that at stiff clay layer. This indicates that only stress adsorbtion at 1 m layer tickness below the footing contact area due to loose arrangement of soil particles. Therefore, soil layer under the footing contact becomes compacted with punch shear failure mechanism

Furthermore the stress distribution imposed by building load of 600 kN at the heterogeneous clay layer beneath the footing contact area of 2 m x 2 m was illustrated in **Figure 9.**

Similar to the stress distribution at the heterogeneous sand layer under the footing contact area, the stress at the heterogeneous clay layer drastically decreases with the increase of depth at the upper layer, 1 m thick stiff clay layer beneath the centre of footing contact area, then it does not decrease further down at the soft clay layer. The stress distribution beneath the edge and outside of the footing contact area is similar to those at the previous soil stratification. Generally the largest stress reduction occurs at the stiff clay layer (upper layer) beneath the footing contact centre because the stiff clay layer with a highly consolidated layer contributes to reduce significantly the stress propagation.

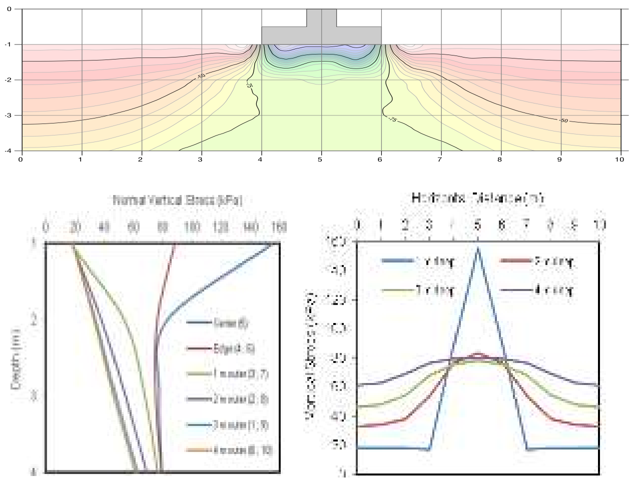

Fig. 9. The stress distribution at the heterogeneous clay layer

The stress distribution at the clay layer is similar to that at the sand layer. The numerical analysis generally shows that the maximum stress occurs at the centre of the footing contact area, then diminishes into further distances (horizontal distance and depth) at clay layer below the footing contact area. The stress decreases more significantly at a stiff clay layer because it can adsorb a larger amount of the contact stress than a soft clay layer. Nevertheless, a soft clay layer closer to the footing contact area could not be consolidated immediately since the contact stress was applied, thus the maximum stress beneath the centre of footing contact area is much lower than that at the stiff clay layer.

In general, the maximum stress occurs at the centre of footing contact area and dissipates into larger distances in horizontal distance and depth. This stress proportionally decreases with depth into horizontal distance, then it exchanges at horizontal distance of 2 m from the contact centre and remains constant with horizontal distance ≥ 3 m. Unlike the stress distribution at sand layer, the maximum stress at the soft clay layer beneath the footing is much smaller than that at the stiff clay layer and sand layer. The different characteristic of both typical types of soil, sand and clay, plays an important role in the stress distribution at the soil layer. The loose sand layer will be immediately compacted since the stress is applied, thus the stress can be generated at the loose sand layer as high as at the dense sand layer. On the other hand, the soft clay layer will be consolidated when the stress is applied, thus the stress generated at the soft clay layer is much lower than that at the stiff clay and sand layers as described previously.

The results show that soil consistency plays an important role in the stress distribution beneath the footing contact area. The stress distribution at granular soils such as sand shows a similar effect at cohesive soils. The dense sand layer shows a similar effect with the stiff clay layer on the distribution of stress which significantly decreases underneath the footing contact centre. In contrast, both the loose sand and soft clay layers cannot significantly absorb the stress propagation, thus almost no reduction of the stress when propagating through these weak soil layer existing below the footing. Constructing footings on such these weak soil layers may not be safe with respect to bearing capacity and settlement. Therefore, the weak soil layer such as loose sand and soft clay layers should be stabilized when the layers used as subgrade or excavated into sufficiently strong soil layer such as dense sand and stiff or hard clay layers.

4. Conclusions

In this work, some points were concluded as follows:

1) The distribution of the footing contact stress decreases as distance from the contact area increases in term of vertical and horizontal distances, and this phenomenon is generally in line between results obtained from manual/classical and numerical analyses.
2) The results of numerical analysis show the effect of soil consistency on the footing contact stress propagation while the soil consistency is not considered in the stress distribution resulting from the manual analysis which is commonly applied so far.
3) The results of numerical analysis using PLAXIS software show significant reduction of the footing contact stress as distance increases at the soil layer with high shear strength such as dense sand and stiff/hard clay, contrarily the stress does not decrease when propagating through the weak soil layer such as loose sand and soft clay layers.
4) Therefore, further study is recomended to investigate the effect of those various stress distribution at different consistencies of soil layer on bearing capacity and settlement.

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Symbols and abbreviations

E_s	Elastic modulus of soil
c	Soil cohesion
ϕ	Internal friction angle
k	Coefficient of permeability
γ_s	Saturated unit weight
γ_d	Dry unit weight
μ	Poisson ratio
ψ	Dilation angle