Use of Compressible Layer for Raft Footing Design with Winkler Method

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ABSTRACT

Raft footing is a commonly used shallow foundation system, which is largely contingent upon the founding condition. The primary challenges encountered in footing design often revolve around managing maximum settlement and differential settlement. The Winkler method is commonly employed to analyze a raft footing by modelling the founding soil as discrete elements characterized with soil subgrade modulus (k_s). The stiffness of the subgrade modulus is largely influenced by the Young's modulus of founding material (E_s), the Poisson's ratio of soil (υ), and the width of the footing (B). An innovative approach of employing compressible layers beneath a raft footing to reduce its effective footing width for design. These compressible layers, strategically positioned under low-loaded concentrated areas or the middle portion of the raft, enable control over the effective width of the footing, leading to an increased soil subgrade modulus (k_s). The outcomes include significant improvement on calculated values for maximum settlement and differential settlement.

1 INTRODUCTION

Structures supported by raft footings are commonly employed to address bearing capacity and settlement challenges. The pivotal aspect of raft footing analysis lies in determining the distribution of contact pressure and associated settlement beneath the structure. The analysis of raft footings involves the Winkler method, implemented through computer-software (SAFE), in terms of the effect of soil subgrade modulus (k_s), i.e. the interaction between founding soil and foundation represented by a series of linear elastic springs for discrete founding soil elements. This parameter, crucial in raft footing design, is intricately linked to the Young's modulus of founding material (E_s), the Poisson's ratio of soil (υ), and the width of the footing (B).

In the design of raft footings, the bearing capacity is typically high due to the substantial width of the raft footing. This is particularly evident when raft footings are adopted for deep basements, as the overburden pressure at the base of the raft footing and in the surrounding ground can significantly enhance the bearing capacity. As a result, the bearing capacity check is generally less crucial than the settlement assessment in raft footing design.

Settlement assessment in raft footing design is conducted through deformation analysis using SAFE modeling under Serviceability Limit State (SLS) loading combinations. The deformation results are influenced by the soil subgrade modulus (k_s) and the stiffness of the footing. The soil subgrade modulus (k_s) is inversely proportional to the width of the footing, resulting in lower k_s values for wider a raft footing. Consequently, geotechnical design to achieve settlement and differential settlement criteria can be challenging in raft footing design.

The above design findings also mentioned in GEO Publication No. 1/2006 that raft foundation are relatively large in size. Hence, the bearing capacity is generally not the controlling factor in design. Differential and total settlements usually govern the design. A common approach for the raft foundation design is to model the ground support as spring using the subgrade reaction (i.e. Winkler) method.

The function of compressible layer beneath a raft footing is similar to the sleeving for pile foundation or basement wall isolation layer, as they both serve to mitigate load transfer. By installing compressible layers beneath a raft footing, the width of the effective bearing area of the footing can be reduced. Therefore, the soil subgrade modulus (k_s) can be significantly increased, and this results in a reduction of the settlement and differential settlement under the footing. The following sections will discuss on theory behind and recommend the practices of application of a compressible layer beneath a raft footing.

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2 DETERMINATION OF SOIL SUBGRADE MODULUS

The soil subgrade modulus (k_s) represents the relationship between soil pressure and displacement, commonly employed in structural analysis of footing foundations. It is important to note that the value of the soil subgrade modulus is not a fixed constant for a given soil; rather, it varies based on factors including the properties of the founding material, the dimensions of the footing (length and width), and the depth of embedment.

A comprehensive study by Terzaghi (1955) of the parameters affecting the soil subgrade modulus indicated that the value decreases with the width of the footing. To illustrate the influence of the width of the footing on k_s, the concept of the bulb of pressure can be used. While the footing widths increase from *B* to *n x B*, the depths of the stress bulb would increase from *D* to *n x D*, respectively. The influence of the depth of the pressure bulb on the settlement of the loaded area depends on the soil deformation characteristics of the subgrade. If the soil deformation characteristics remain relatively consistent across the depths, it can be assumed that settlement increases in direct proportion to the depth of the stress bulb. As the settlement of a footing increases, resulting in a larger width, the subgrade modulus would consequently decrease.

Terzaghi proposed that k_s for full-sized footings could be obtained from a plate-load test using the following equations:

For footings on sand,

$$k_s = k_1 \left(\frac{B+B_1}{2B}\right)^2 \tag{1}$$

For footings on clay,

$$k_s = k_1 \left(\frac{B_1}{B}\right) \tag{2}$$

where B_1 = side dimension of the square base used in the plate-load tests to produce k_1 and B = width of footing. However, the above equations deteriorate when B/B_1 is greater than 3.

2.1 Current Design Practice for Subgrade Modulus

Even though there are many different equations to determine soil subgrade modulus for footing design, the most commonly adopted equation was proposed by Vesic (1961) that the subgrade modulus could be computed using the stress-strain modulus E_s as

$$k_s = \frac{E_s}{B(1-\upsilon^2)} \tag{3}$$

where E_s = Young's modulus of soil, B = width of footing and υ = Poisson's ratio of soil.

The estimated soil subgrade modulus (k_s), calculated by Vesic's equation, serves as input for SAFE modeling in the footing design. The model generates outputs including structural forces such as bending moments and shear forces of footing elements under Ultimate Limit State (ULS) loading combinations, as well as deformation profiles and design bearing pressures under Serviceability Limit State (SLS) loading combinations.

However, there are certain design scenarios where Vesic's equation may be proved too simplistic and insufficient to address, such as footings founding on,

- multi-layer of founding materials;
- soil overlain on shallow bedrock; and
- certain depth below ground with excavated in-situ overburden.

2.2 Suggested Modified Method for Subgrade Modulus

To address the aforementioned complex design scenarios, a modified method is proposed for estimating the subgrade modulus (k_s) from first principles. As previously discussed, the soil subgrade modulus represents the conceptual relationship between soil pressure and deformation. The fundamental equation is defined as follows:

$$k_s = \frac{q}{s} \tag{4}$$

where q = applied pressure and s = induced settlement when q is applied.

For estimation of the soil subgrade modulus, it is suggested to work the other way around to calculate the induced settlement by applying a certain design pressure and considering multi-layer of founding materials with varies depth or with shallow bedrock, i.e. Step 4 to Step 7 below, instead of homogeneous soil stratum by Vesic's equation (Eq 3). The excavated in-situ overburden effect can also be considered under Step 2 and Step 3 to work out the net pressure of the footing. Then, the basic equation (Eq. 4) can be applied to obtain the soil subgrade modulus. The procedures are presented in Figure 1 and listed as follows:

Step 1: Assume a design pressure that can be derived with (Dead Load + Live Load) / Footing Area multiplied by 1.25.
Step 2: Calculate the effective overburden pressure of the excavated soil if the footing is underneath a deep basement. For the calculation of effective overburden pressure, the groundwater level can be taken at the lowest measured groundwater table which the founding materials have experienced such loading.
Step 3: Work out the net pressure for the estimation of settlement, which is equal to the design pressure subtracting the effective overburden pressure.
Step 4: Classify the founding materials underneath the footing into different strata based on the soil types and their deformation properties, i.e. Young's modulus of the soil.
Step 5: Determine the load spread influence factors, based on stress bulb graph (refer to Figure 2 and description below), load spread influence factors (i.e., q/q_o = ratio of applied pressure to induced stress at the certain depth below the footing) at the mid-depth for each soil strata.
Step 6: Estimate the individual settlement for each soil strata by the product of the thickness of each layer, stress at mid-depth and coefficient of volume compressibility (m_v).
Step 7: Calculate the total settlement by summing up the individual settlement for each soil strata.
Step 8: Apply the basic equation (Eq. 4) to obtain the soil subgrade modulus in the 1st iteration.
Step 9: Run the SAFE model with the estimated soil subgrade modulus (Step 8) and find the bearing pressure from the SAFE output under the Dead + Live loading combination.
Step 10: Compare the calculated bearing pressure outputs (Step 9) with the assumed design pressure (Step 1). If the difference between the two values is greater than 10%, adopt the calculated design pressure output (Step 9) to repeat the Step (1) to Step (8).
Step 11: Carry out the iteration until the difference to be within 10%.

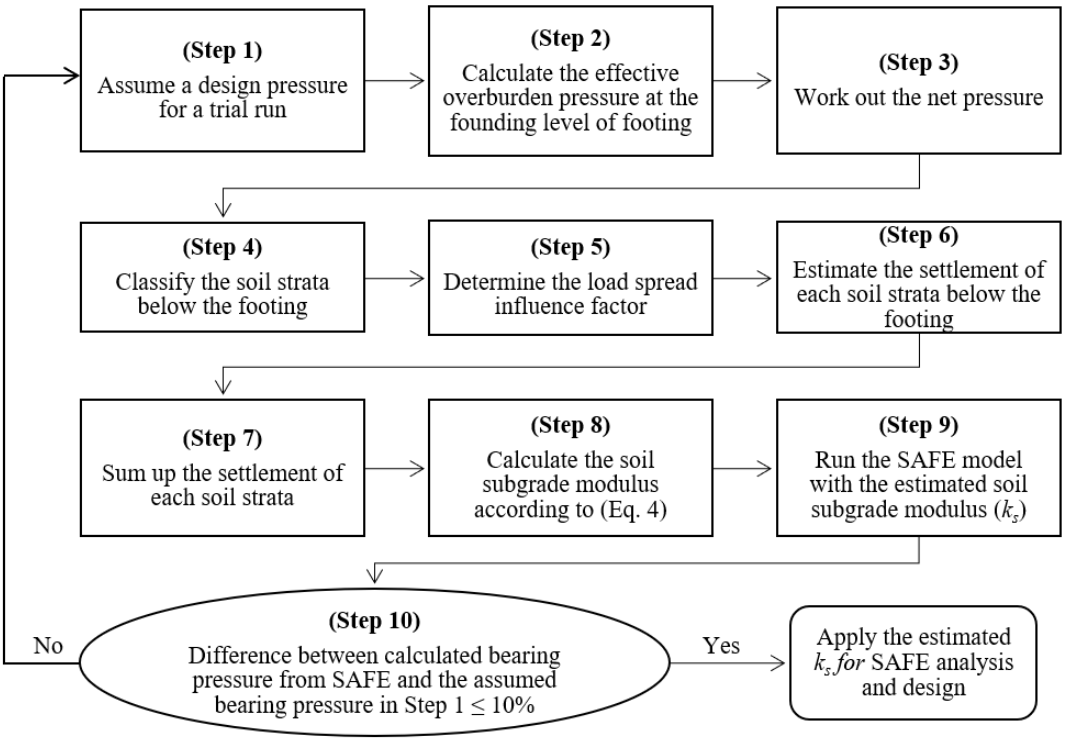

Figure 1: Flow Chart for Modified Method for Subgrade Modulus

A vertical pressure profile, also known as pressure bulb was proposed by Bowles (1974) based on Boussinesq equation. The pressure bulb (Figure 2) shows the relationship between the pressure bulbs and depth below the footing.

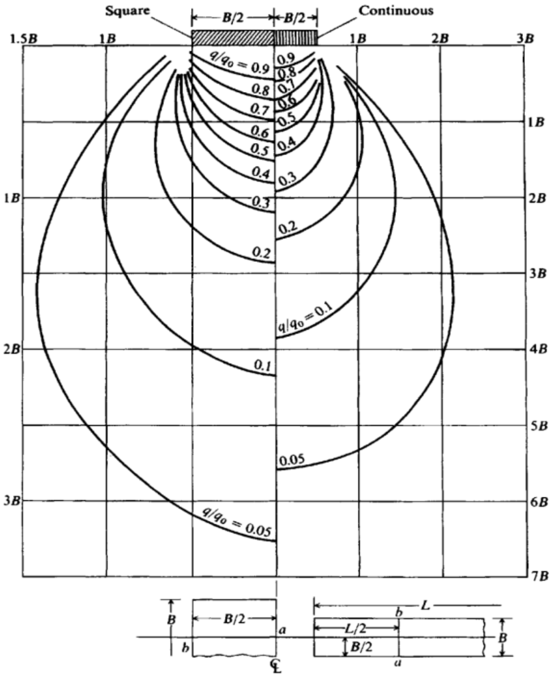

Figure 2: Pressure Bulbs based on the Boussinesq Equation for Square and Strip Footing

In consideration of the uncertainties in subgrade modulus estimation, it is advisable to conduct sensitivity analyses for Ultimate Limit State (ULS) structural and bearing design to enhance the robustness of the design. In certain scenarios, a higher subgrade modulus stiffness may result in significant bending moments and shear forces in a raft footing. This phenomenon can be explained by the relative stiffness factor proposed by Meyerhof (1953), which categorizes footings as either flexible or rigid bodies based on the ratio of footing structural stiffness to founding material stiffness. A smaller relative stiffness factor, indicative of a larger subgrade modulus of the founding material, may render the footing more 'flexible', increase of the design forces. It is recommended that sensitivity analyses cover a range of 50% to 150% of the estimated subgrade modulus for bearing capacity and structural checking.

2.3 Plate Load Test to Verify the Subgrade Modulus of Founding Material

The Plate load test is introduced in the Code of Practice for Foundations 2017 which specified the procedure and acceptance criteria for the test. The main purpose of plate load test is to verify the bearing capacity of the founding soil, as well as the Young's Modulus (E_s) of the founding materials. The two acceptance criteria are listed below:

- To verify the bearing capacity of the founding soil, the maximum settlement of the test plate shall not exceed 0.15B, where B is the width or diameter of the test plate; and
- To verify the Young's modulus of founding soil, the settlement of the plate after the completion of the first cycle of the load test shall not exceed the settlement calculated from Eq. (4) or Eq. (5) below.

$$S = \frac{W_t(1-\upsilon^2)}{1.13\,E_s\,B} \quad \text{for square test plate} \tag{4}$$

$$S = \frac{W_t(1-\upsilon^2)}{E_s\,B} \quad \text{for circular test plate} \tag{5}$$

where S = the settlement of the test plate measured at test load, W_t = test load of, E_s = Young's modulus of soil, B = width or diameter of test plate and υ = Poisson's ratio of soil.

The settlement from the plate load test will be adopted to back-calculate the Young's modulus (E_s) using Eq. (4) or Eq. (5). If the back-calculated E_s value is smaller than the design value of E_s, a design review shall be carried out based on the back-calculated E_s values. Subsequently, the soil subgrade modulus shall be updated to reflect the actual Es from the plate load test, and the SAFE design models shall undergo re-analysis to verify both the Ultimate Limit State (ULS) structural and bearing design, as well as the Serviceability Limit State (SLS) deformation assessment to be satisfied.

3 DESIGN CONCEPT OF COMPRESSIBLE LAYER APPLICATION

In light of the preceding discussion, it is evident that the width of the footing (B) plays a crucial role in determining the soil subgrade modulus (k_s). A reduction in the effective footing width results in an increment of the soil subgrade modulus (k_s). To reduce the effective footing width, compressible layers by means of non-bearing zone are employed to be placed beneath the footing at areas of low-load concentration. By implementing the compressible layers, the effective width of the footing can be efficiently limited and managed, thereby enhance the soil subgrade modulus beneath the footing.

On the other hand, placement of compressible layers underneath a portion of the footing would reduce the bearing area and so may cause higher bearing pressure. It is suggested that the proposed compressible layers should be placed in low-loaded areas which can minimize the adverse effect on increment of the design bearing pressure. As mentioned above, the pressure capacity check is normally less critical for the design of raft footing with certain depth of soil embedment.

Conversely, improving the soil subgrade modulus can greatly enhance the settlement and differential settlement outcomes of the raft footing, which are particularly important in raft footing design.

There would be some concessions between the bearing capacity checking and the settlement assessment for the application of compressible layers underneath portions of the raft footing. This typically involves several rounds of trial iteration to determine the optimal location / portion as well as the size of the compressible layers to be required.

4 PARAMETRIC STUDY FOR THE IMPLEMENTATION OF COMPRESSIBLE LAYER

A simple parametric study was carried out to test the effect on a footing design with or without compressible layer (i.e. non-bearing zone) by using the computer software (SAFE). The results of maximum bearing pressure and maximum settlement as well as differential settlement of the footings were compared. A typical raft footing of 10m(width) x 10m(length) x 0.5m(thick) was modeled with and without the implementation of compressible layer beneath the footing. To emphasize the differential settlement effect, a line load of 175 kN/m was applied with a 0.5 m offset from each of the four edges of the footing.

- For Case 1, no compressible layer was applied. The whole footing was fully founded on the bearing material.
- For Case 2, a 4m(width) x 4m(length) compressible layer was positioned at the center of the footing, creating a non-bearing zone beneath the footing.

The SAFE model settings for the two cases are shown in Figure 3 and the results are presented in Figure 4 and summarized in Table 1 below.

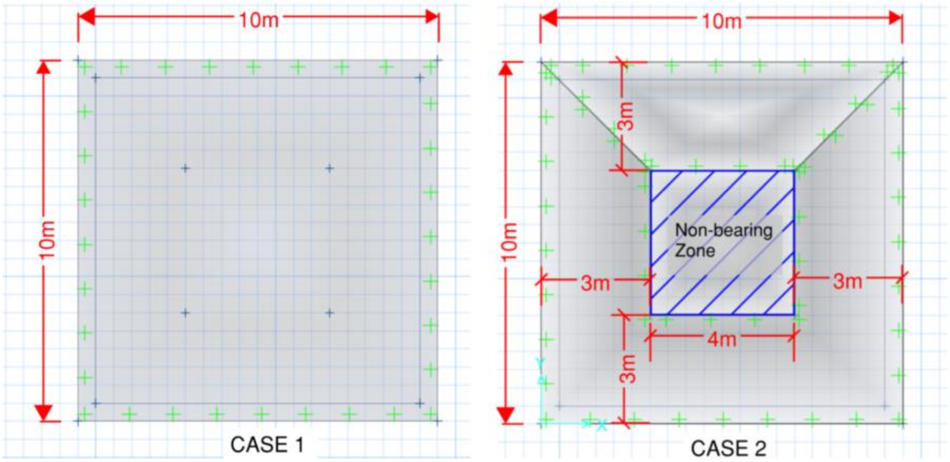

Figure 3: SAFE Models Settings for the Parametric Study

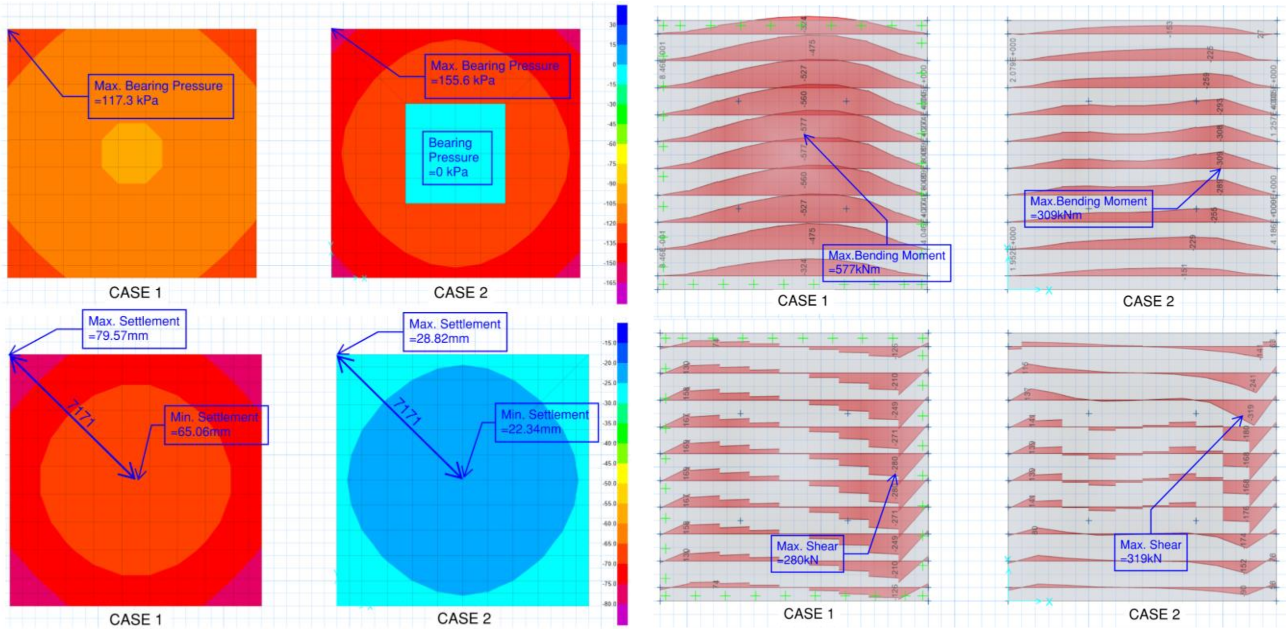

Figure 4: SAFE Analysis Results for the Parametric Study

Table 1: Summary of Inputs and Outputs of Parametric Study

Case	Inputs			Outputs				
	Width of Compressible Layer (m)	**Effective Width of Footing, B (m)**	**Subgrade reaction modulus, k_s* (kN/m^3)**	**Max. bearing pressure (kPa)**	**Max. Bending Moment (kNm)**	**Max. Shear Force (kN)**	**Max. Settlement (mm)**	**Max. Angular Rotation**
1	0	10	1600	127	577	280	80	1:487
2	4	3	5400	156	309	319	29	1:1091

*Remark: * Subgrade reaction modulus were calculated according to Eq. (3), where Es = 15MPa and ν = 0.3 were assumed.*

Based on the results of the parametric study, it is noticed that the maximum settlement and angular rotation of footing (also reflecting on the differential settlement) of Case 2 is much smaller than those of Case 1, whereas the maximum bearing pressure of Case 1 is slightly larger than that of Case 2. According to the above parametric study, the benefits resulting from the application of compressible layer is remarkable for the settlement and differential settlement assessment, which is normally critical for raft footing design.

A sensitivity analysis was also carried out for Case 2, which reviewed the analysis results from 50% and 150% of the subgrade modulus. The results of these two sensitivity analyses, namely Case 2A with 50% subgrade modulus and Case 2B with 150% subgrade modulus, are presented in Figure 5 and Table 2.

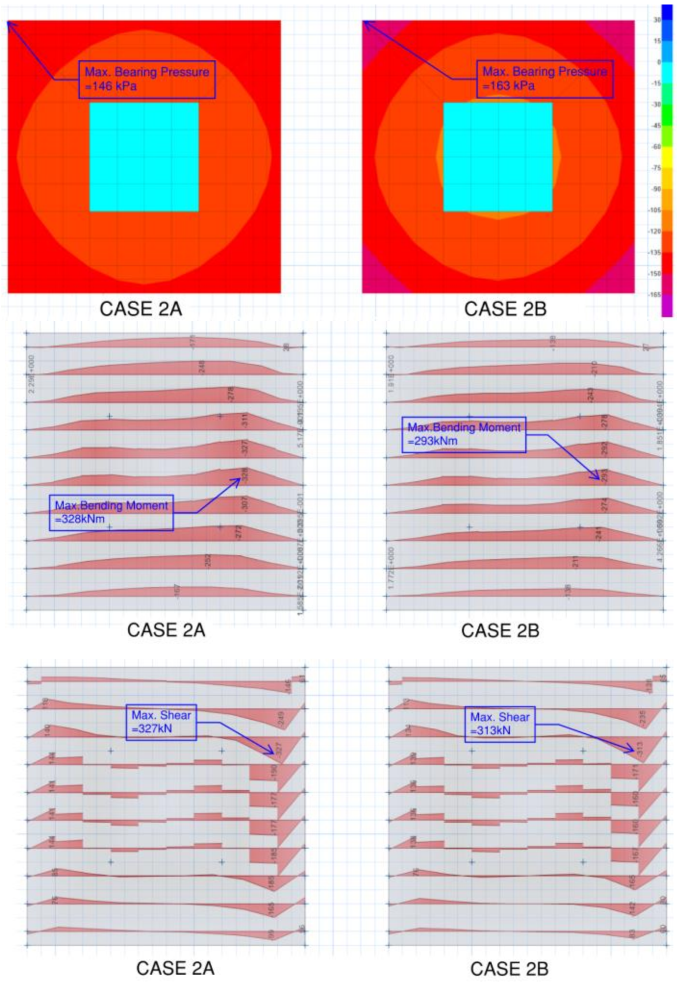

Figure 5: SAFE Analysis Results for Sensitivity Analysis

Table 2: Summary of Input and Output of Sensitivity Analysis

Case	Subgrade Modulus, k_s (kN/m^3)	Max. Bearing Pressure (kPa)	Max. Bending Moment (kNm)	Max. Shear Force (kN)
Case 2A	2700 (50%)	146	328	327
Case 2	5400 (100%)	156	309	319
Case 2B	8100 (150%)	163	293	313

From the sensitivity analysis, it can be noticed that the maximum bearing pressure under the footing is larger when adopting a larger soil subgrade modulus, while the settlement is much smaller in Case 2B (i.e. 150% of the estimated soil subgrade modulus). On the other hand, the bending moment and shear force in the footing are smaller in Case 2B since the deformation of footing is smaller. For this parametric study conditions, the results from the upper bound of the sensitivity analysis (Case 2B) shall be used for the ULS bearing design and the results from the lower bound of the sensitivity analysis (Case 2A) shall be used for the ULS structural design.

5 CASE STUDIES FOR APPLICATION OF COMPRESSIBLE LAYER

The applications of compressible layer have been proposed to a few local projects in Hong Kong. The main purpose was to increase the soil subgrade modulus beneath footing and therefore to reduce the total settlement and differential settlement of the footing. In Case Study 1, the wide footprint of the raft footing led to a reduced value of the soil subgrade modulus for SAFE analysis. As a consequence, this exacerbated challenge associated with settlement in the footing design, posing significant issues that need to be addressed.

On the other hand, when there are some sensitive structures or geological features underneath the footing, the design of the footing shall minimize the induced stresses to those structures / geological features. By limiting the design (contactable) width of a footing, the depth of the stress bulbs can be managed and so to reduce the impact on those structures / geological features. The footing of Case Study 2 was located at the marble areas where cavities were found in depth. The implementation of compressible material could limit the load spreading on the marble surface within acceptable limit.

5.1 Case Study 1- Large Raft Footing for Deep Basement

Case Study 1 was a large raft footing for a deep basement founding on Completely Decomposed Tuff (CDT). In the initial design, Vesic's equation (Eq. 3) was applied to estimate the subgrade modulus for SAFE analysis. Even though the Young's modulus of the founding CDT material was not low which the SPT'N values were around 40 blows, the estimated subgrade modulus was small due to the large footing width (B). After applying the small subgrade modulus in the SAFE analysis, it was revealed that both the maximum settlement and differential settlement were significantly over the design limits, which inevitably became a major challenge to for the raft footing design.

Table 3: Summary of Inputs and Outputs of Initial Design without Compressible Layer

Case	**Effective Width of Footing, *B* (m)**	**Subgrade reaction modulus, k_s (kN/m^3)**	**Max. Bearing Pressure (kPa)**	**Max. Settlement (mm)**	**Max. Angular Rotation**
Initial Design	51	1724	456	264	1:426

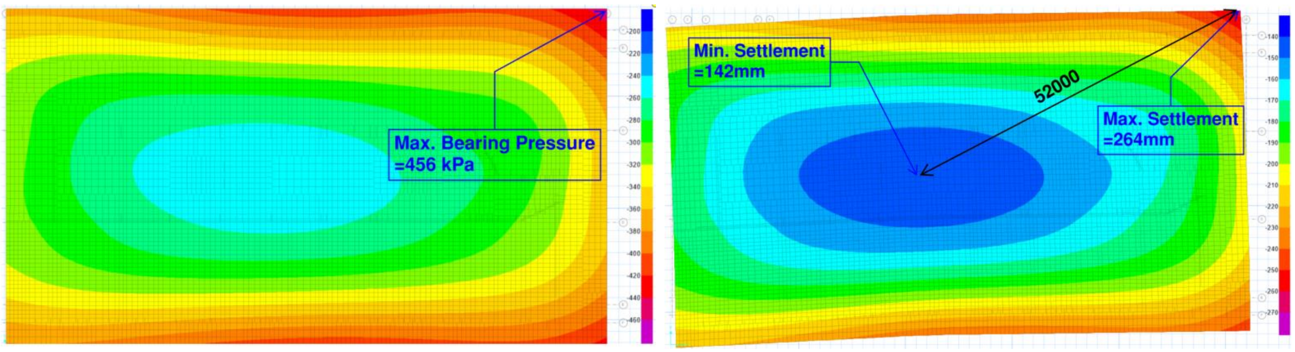

Figure 6: SAFE Analysis Results for Initial Design without Compressible Layer

The initial design showed that both settlement and angular of rotation (i.e., differential settlement) significantly exceeded the recommended acceptance criteria in CoP Foundations 2017 which are 30mm and 1 in 500, respectively. In order to control the design settlement, two measures were considered to improve the subgrade modulus value:

- Apply compressible layer for portions of footing under the low-loaded areas. This would reduce the effective footing width for subgrade modulus calculations.
- Adopt the modified method for estimation of the subgrade modulus as described in Section 2.3. The modified method would take into account for the effect of existing overburden (i.e. depth factor of basement) as well as the increment of soil stiffness with depth.

By applying of the two measures, the subgrade modulus and so the settlement and differential settlement results from SAFE analysis had been significantly improved which were then within the design acceptance limits.

Table 4: Summary of Inputs and Outputs of Improved Design with Compressible Layer

Case	**Effective Width of Footing, *B* (m)**	**Subgrade reaction modulus, k_s* (kN/m^3)**	**Max. Bearing Pressure (kPa)**	**Max. Settlement (mm)**	**Max. Angular Rotation**
Improved Design	8	25,000	614	24.6	1:1203

Remark:

* *Subgrade reaction modulus were calculated based on the reduced footing width as well as the considerations of multi-layer of founding materials and 14m overburden effect as per the modified method mentioned in Section 2.2 of this paper.*

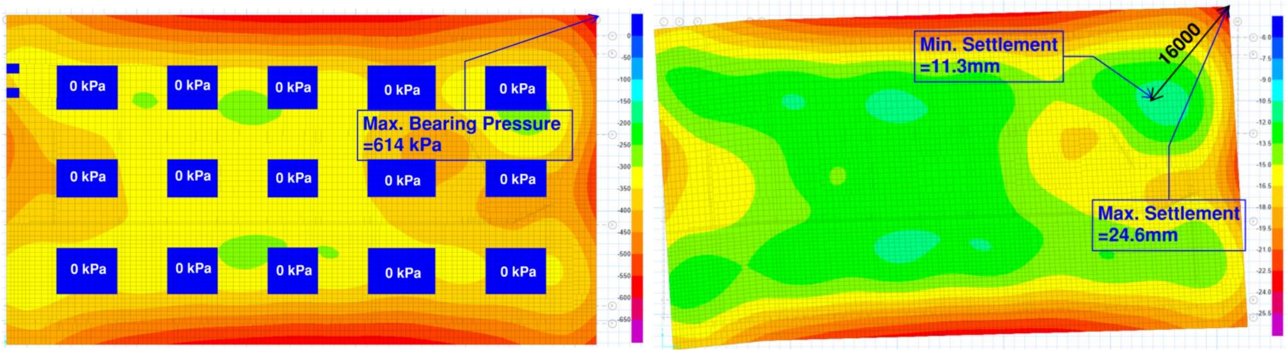

Figure 7: SAFE Models Results for Improved Design with Compressible Layer

As shown in Figure 7 above, the proposed compressible layers were laid beneath the footing to minimize the load transferring from the footing to the founding soil, to create some non-bearing zones and reduce the effective width of the footing thereby increased the soil subgrade modulus. The estimated settlement was effectively reduced without the need of any complicated ground treatment works.

On the other hand, the maximum bearing pressure had increased by 45%. Even though there was quite large percentage increase of the design bearing pressure, it was still well within the design bearing capacity of CDT, i.e. 800kPa for 8m width of footing with overburden.

The design approach remained consistence with the current practice, but some trials were carried out to fine-tune the area of non-bearing zone and soil subgrade modulus. No major change to the method of footing construction is envisaged and also similar to the general construction method, just place the compressible material is required to be placed the footing/soil stratum interface strategically prior to the reinforcement fixing.

5.2 Case Study 2 - Footing above the Underground Structure / Adverse Geological Feature

A common challenge in footing design arises when the load spreading from the footing adversely impacting existing structures or sensitive geological features below. The implementation of compressible layer beneath the footing can also help to mitigate this problem by reducing the load spreading influence zone.

Case Study 2 was a footing proposed for areas with presence of marble geology containing cavities. As a result of proposed raft footing, there would be additional pressure exerted on the underlying soil, which would then be spread to the marble rock surface underneath.

In view of the above-mentioned design concern, compressible layers were proposed to be place beneath the footing with the following considerations:

- The proposed compressible layer could significantly limit the influence depth of the additional pressure caused by the proposed structure;
- A certain clearance between the proposed compressible layer shall be kept so as to mitigate the overlapping effect of the pressure bulbs introduced in Section 2.3;
- The design bearing pressure applying to the founding soil would increase due to the reduced bearing area, the bearing capacity of founding soil shall be checked and satisfied.

With these considerations, the optimal locations and widths of the compressible layer may require some iterations to maximize its effectiveness.

Refer to Figure 8, the arrangement of compressible layer was installed below the walls of the proposed structure with designed width and spacing, which intended to minimize the overlapping effect between pressure bulbs. The compressible layers were installed at low-loaded areas so that the bending moment and shear force in footing could be controlled accordingly.

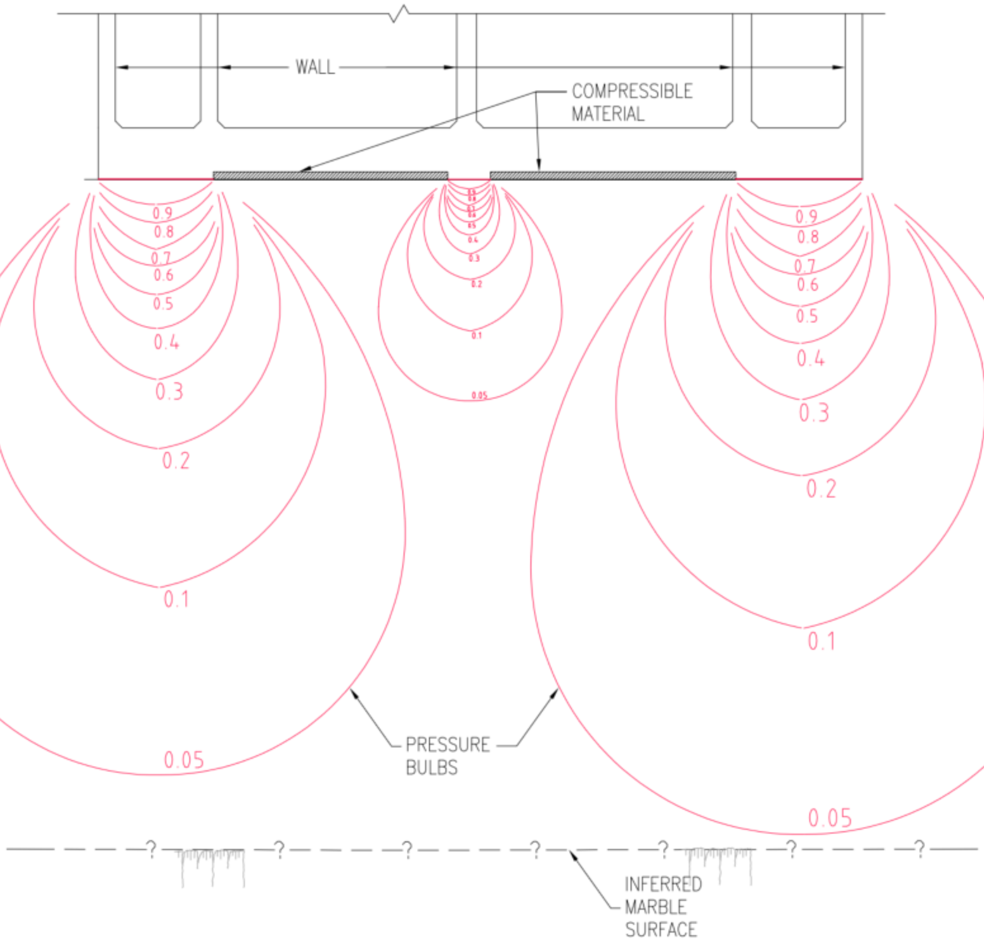

Figure 8: Pressure Bulbs with Application of Compressible Layer

6 SUITABLE MATERIAL FOR COMPRESSIBLE LAYER

Expanded Polystyrene (EPS), shown in Plate 1, which has a long history of application for construction which can be a suitable type of material for compressible layer to be placed under footing. The proposed compressible layer should be soft enough to minimize the load transferring from the footing to founding materials. The lowest grades of EPS can be considered, and their elastic modulus varies from 1,450kPa to 2,200kPa, while the density varies from 11kg/m^3 to 13.5kg/m^3. The material properties of the EPS are presented in Table 5 below for reference. The advantage of EPS is easy handling and easy installation due to its light weight, and it is not reactive with concrete. Similar usages of EPS were commonly applied for construction, such as joint filler for movement joints and horizontal sleeving layer along pile shaft and basement walls.

Table 5: Material Properties of Expanded Polystyrene

Grade	**Density (kg/m^3)**	**Min. Flexural Strength (kPa)**	**Min. Elastic Modulus (kPa)**	**Compressive Stress at 1% deformation (kPa)**	**Compressive Stress at 10% deformation (kPa)**
L	11	60	1,450	14	50
SL	13.5	150	2,200	23	70

Plate 1: Compressible Layer beneath Footing

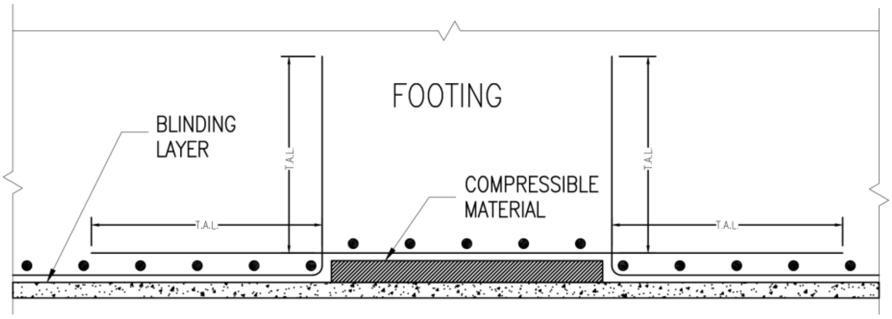

Figure 9: Typical Installation Detail of Compressible Layer

Referring to Plate 1 and Figure 9, the compressible materials were placed on top of the blinding layer and were embedded into the footing. The structural design of the footing should take into account of the relative thinner design depth, along with the structural detailing required for lapping the reinforcement.

Expanded Polystyrene (EPS) possesses several advantageous properties that make it as an ideal construction material. Firstly, EPS is an inert and organic material, meaning it will not decay over time. This property ensures its longevity and durability, making it suitable for long-term use without the risk of rotting. Additionally, EPS is resistant to pests such as ants, termites, and rodents, as it lacks any nutritional value for these organisms. This further enhances its durability and makes it widely used for construction and insulation purposes. Moreover, EPS is not susceptible to damage from the normal range of climate conditions, including temperature fluctuations and moisture exposure. This resilience ensures its stability and performance under various environmental conditions. When specified and installed correctly, EPS can be relied upon as a durable and long-lasting material, providing lasting benefits as compressible layer.

The required thickness of compressible layer shall be determined based on the following:

- The expected deformation of the compressible layer under construction load during the curing of wet concrete, s_1;
- The expected deformation of the compressible layer under working load, s_2;
- The residual thickness of compressible layer deducting the above-mentioned deformation(s_1+s_2);

To estimate the deformation induced by the wet concrete during construction (s_1), it can be calculated by dividing the wet concrete self-weight pressure by the elastic modulus of the compressible layer as shown in Table 5. The stress within the compressible layer under anticipated working conditions can be determined using a Finite Element model, such as Plaxis, facilitating the estimation of the deformation of the compressible layer (s_2).

To ensure the proper performance of the compressible layer, it is recommended that the proposed thickness of the compressible layer should be a least two time of the estimated accumulated deformation (s_1 + s_2).

7 CONCLUSIONS

The compressible layer has a long history of application in construction industry, mainly for movement joints, horizontal sleeving for piles and basement walls to control load transfer and spreading. This paper proposed the use of compressible layer underneath portion of raft footing in order to control the loaded width of the footing. By reducing the loaded width of the footing, the subgrade reaction modulus of the footing would be increased. This yields several advantages, including the reduction of settlement and differential settlement, which in turn has significant implications for the overall performance of the foundation.

In addition, this paper suggested a modified method for the estimation of the subgrade modulus. The modified method allows for the considerations of diverse geological and depth conditions as well as excavation of the overburden soil. Utilizing the modified subgrade modulus in SAFE analysis results in more realistic and accurate Serviceability Limit State (SLS) outcomes, particularly in settlement and differential settlement assessment.

This paper presents a parametric study and two case studies to elucidate the calculation procedures and practical applications of the compressible layer in footing design. These examples showcase the effectiveness of the proposed approach in real-world construction projects.

PUBLISHER'S NOTE

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