Overcoming Limitations in Raft Footing Design: Alternative Approaches to Uniform Modulus of Subgrade Reaction Analysis

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ABSTRACT

Raft footing is a cost and time effective foundation solution for building and infrastructure development. By eliminating the need for deep piling, raft foundation significantly reduces embodied carbon, construction time, capital expenditure and disturbances to surroundings. In current industry practice, the Winkler Spring Model is commonly employed for shallow foundation design. This approach simulates the founding soil as a series of independent spring supports defined by the modulus of subgrade reaction (k_s) for analysis using structural software such as SAFE.

However, the simplified method for estimating k_s and the assumption of uniform subgrade support across the entire raft footing have limitations, often producing unrealistic settlement and differential results. Misinterpreted subgrade values may lead to the rejection of the raft footing option and necessitating to opt for a more costly and time-consuming piling foundations.

This paper explores an alternative approach to estimate the modulus of subgrade reaction (k_s) in a more comprehensive manner using geotechnical finite element software PLAXIS 3D. This method can capture complex subsurface conditions and soil-structure interaction effects, allowing the distribution of k_s to vary spatially across the raft. The outcome provides a more accurate and realistic k_s estimation, ensuring better decision-making in the design of raft footings.

1 INTRODUCTION

Foundation works in Hong Kong are often expensive, time-consuming, and fraught with uncertainty due to the city's complex and varying geological conditions, including deep bedrock, hilly terrain, and extensive reclaimed land. On average, foundation works account for approximately 15% to 25% of the total construction cost, 10% to 25% of the total embodied carbon footprint, and 20% to 25% of the total construction period. Therefore, pursuing sustainable foundation solutions can have a significant impact on the overall efficiency, cost, and environmental footprint of land and infrastructure developments.

To achieve more sustainable outcomes in foundation design, the following strategies are crucial:

- Conducting thorough information search and detailed desktop studies;
- Undertaking sufficient site investigations and laboratory testing;
- Developing a comprehensive geological model;
- Considering alternative foundation systems;
- Applying value engineering to optimize foundation design.

Minimizing subsurface uncertainties is essential to avoid conservative, over-engineered solutions. Selecting an appropriate foundation system tailored to site conditions is equally important.

Raft foundations are often more cost-effective, time-efficient, and environmentally sustainable than piled foundations. They can reduce foundation costs by approximately 50%, embodied carbon footprint by up to 75%, and construction time by around 50%. Furthermore, the minimization of piling activities helps to reduce disturbances such as vibration, noise, and dust, thereby lowering the impact on adjacent structures and

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communities and to alleviate the potential workplace risk associated with plant maneuvering and heavy lifting operation for piling construction.

Given these substantial benefits, it is essential to adopt an appropriate and accurate design approach for raft foundations. Inaccurate or simplified modeling may lead to over-design, causing unnecessary rejection of raft options in favor of piling systems, or under-design, which can compromise structural safety and serviceability.

According to GEO Publication No. 1/2006, raft foundations, being relatively large in size, are typically governed by total and differential settlements rather than bearing capacity. A common design method involves modeling ground support using the Winkler Model, which simulates the soil as a series of independent springs defined by the modulus of subgrade reaction (k_s). As noted by BSI (2004), subgrade reaction models are generally inadequate for estimating total or differential settlements in raft foundations. Finite element analysis or elastic continuum models are recommended to capture the soil-structure interaction in a realistic and reliable manner (French, 1999; Poulos, 2000).

2 CURRENT DESIGN PRACTICE FOR RAFT FOOTING DESIGN

2.1 Determination of Modulus Subgrade Reaction (k_s)

The current practice for raft footing design analysis typically involves the Winkler Model, implemented using structural software such as SAFE. In this approach, the interaction between the foundation and the soil is represented by a series of independent linear elastic springs, each characterized by the modulus of subgrade reaction (k_s). This parameter is crucial for determining foundation performance and is typically linked to the soil's Young's modulus (E_s), Poisson's ratio (υ), and the width of the footing (B).

The most widely adopted formulation for estimating the modulus of subgrade reaction (k_s) is based on Vesic (1961) equation that k_s could be computed using the stress-strain modulus E_s as

$$k_s = \frac{E_S}{B(1-\upsilon^2)} \quad \text{(Eq. 1)}$$

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

While Vesic's equation is simple and widely applied, it often falls short in addressing more complex soil behaviors. For such cases, modified approaches have been proposed. For example, Tse (2024) introduced a refined method that incorporates a conceptual relationship between soil pressure and deformation to better estimate k_s under varying ground conditions.

The estimated k_s values are input into SAFE to model the raft footing. The software then analyzes the structural responses under Ultimate Limit State (ULS) conditions, such as bending moments and shear forces, as well as settlement behavior under Serviceability Limit State (SLS) loading.

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 modulus of subgrade reaction (k_s) and the stiffness of the footing. The k_s is inversely proportional to the width of the footing, resulting in lower k_s values for wider a raft footing. Consequently, it results in larger predicted settlements and differential settlements, which may exceed the allowable design criteria of 30mm total settlement and 1 in 500 differential settlement, as specified in the Code of Practice for Foundations 2017.

2.2 Drawbacks of the Current Practice on Winkler Model with Uniform Modulus of Subgrade Reaction (k_s)

The Winkler Model (WM), which acts soil support as discrete, uniform springs with constant stiffness (k_s), has several critical limitations when applied to raft footing design:

- **Non-intrinsic Property:** The subgrade modulus is not a fundamental soil parameter. Its value depends not only on soil stiffness but also on the foundation dimensions (Poulos, 2000). As footing width increases, k_s decreases, potentially leading to exaggerated settlement predictions, particularly near edges and corners.
- **Lack of Soil Continuum Behavior:** The Winkler Model treats soil as isolated springs with no interaction and the spring only deflects if a pressure is applied to it. Thus unloaded areas in a Winkler soil model do not deflect, and hence there is no stress transmission or interaction within the soil (Poulos, 2000). In reality, soil behavior involves stress redistribution and interaction between adjacent zones. The absence of these effects leads to inaccurate predictions of soil pressure and structural response, especially under non-uniform loads.
- **Neglect of Shear or Lateral Resistance:** The springs in the Winkler Model only resist vertical displacements and so the vertical loading will produce only vertical displacements, and no horizontal displacements, and vice-versa (Poulos, 2000). Shear interactions and edge effects, which are significant in raft foundations, are ignored. This results in overestimation of settlement at corners and underestimation of structural forces.
- **Oversimplified Elastic Medium:** Treating the founding soil as a discrete elastic medium fails to capture complex behaviors such as bulging, arching, or differential stiffness across the foundation. This is particularly problematic in heterogeneous or layered soils which commonly encountered in Hong Kong.
- **Neglect of Time-Dependent Effects:** The Winkler Model does not account for long-term settlement due to consolidation or creep. This can lead to underestimation of differential settlements over time, especially in clayey soils or newly reclaimed land.
- **Incompatibility with Irregular Geometries:** Uniform k_s values do not accurately represent complex raft geometries or varying load conditions. This over-simplification can result in misleading predictions for bending moments, shear forces, and settlement profiles.

Given these limitations, there is a clear need for more advanced and representative modeling approaches, such as finite element methods, that can more accurately simulate soil-structure interaction and the spatial variability of subgrade reactions across the raft footprint.

3 COMPARISON OF WINKLER MODEL (WM) AND FINITE ELEMENT METHOD (FEM)

3.1 Parametric Studies for Raft Footing Design

Two sets of parametric studies were carried out to compare raft footing analyses between the Winkler Model (WM) with a uniform modulus of subgrade reaction using structural software (SAFE) and Finite Element Method (FEM) by using the geotechnical software (PLAXIS 3D). The objectives of these parametric studies were to evaluate the accuracy and limitations of the WM with uniform k_s against FEM in predicting settlement, pressure distribution and structural responses under varying design parameters as follows, refer to Table 1 and Table 2:

1) Loading pattern – Uniform Distributed Load (UDL) vs Point Load (PL), refer to Set A
2) Footing thickness – from 0.5m to 1m, refer to Set B
3) Founding materials – Elastic Modulus from 15,000kN/m^2 to 30,000kN/m^2, refer to Set B
4) Footing sizes – from 5m x 5m to 30m x 30m, refer to Set B

Table 1: Inputs and Results for Set A Parametric Study

Model No.	Footing Size (B x L x D) (m)	Load Pattern	Equ. Pressure(4) (kPa)	Founding E_s (kPa)	Max. Settlement (mm)			Max. Pressure (kPa)		
					WM(1)	FEM(2)	% Diff(3)	WM(1)	FEM(2)	% Diff(3)
Model A1	10 x 10 x 1	1 No. PL	25	15,000	31	25	-21	51	92	45
Model A1a	10 x 10 x 1	3 Nos. PL	25	15,000	30	25	-22	50	87	42
Model A1b	10 x 10 x 1	UDL	25	15,000	30	24	-23	50	89	44

Remark: (1) WM = Winkler Model by SAFE with Uniform k_s
(2) FEM = Finite Element Method by PLAXIS 3D
(3) % Diff = Percentage Difference between WM and FEM results = (FEM -WM)/FEM x 100%
(4) Applied Equivalent Pressure = Total Column Loads / Footing Area

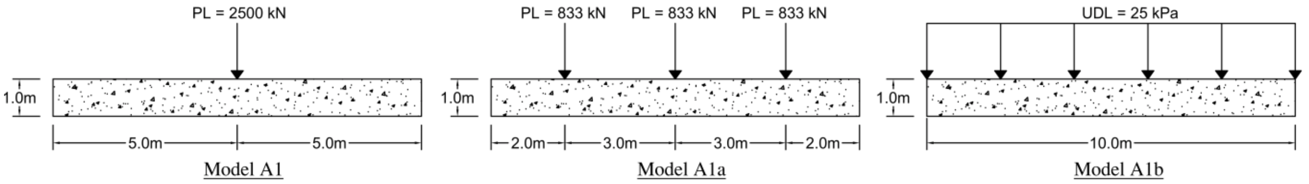
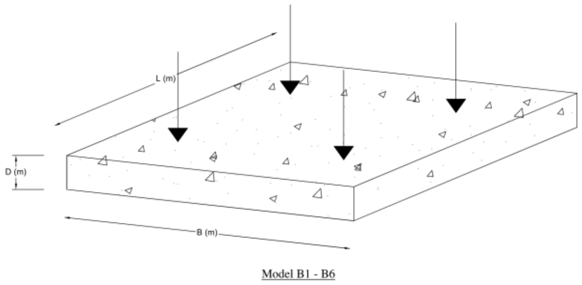


Table 2: Inputs for Set B Parametric Study

Model No.	Footing Size (B x L) (m x m)	Thk. (D) (m)	No. of PL	Equ Pressure$^{(4)}$ (kPa)	Founding E_s (kPa)	Max. Settlement (mm)			Max. Pressure (kPa)		
						WM$^{(1)}$	FEM$^{(2)}$	% Diff$^{(3)}$	WM$^{(1)}$	FEM $^{(2)}$	% Diff$^{(3)}$
Model B1	5 x 5	1	1	100	15,000	38.0	40.3	5.7	125.1	204.0	38.7
Model B1a	5 x 5	0.5	1	100	15,000	35.6	36.2	1.7	117.2	160.4	26.9
Model B1b	5 x 5	1	1	100	30,000	19.1	20.1	5.0	125.8	199.2	36.8
Model B2	10 x 10	1	4	100	15,000	76.0	68.5	-10.9	125.2	242.5	48.4
Model B2a	10 x 10	0.5	4	100	15,000	71.2	61	-16.7	117.4	206.9	43.3
Model B2b	10 x 10	1	4	100	30,000	38.2	34.2	-11.7	125.9	239.9	47.5
Model B3	15 x 15	1	9	100	15,000	114.7	92.3	-24.3	126.0	292.5	56.9
Model B3a	15 x 15	0.5	9	100	15,000	110.8	87	-27.4	121.8	325.0	62.5
Model B3b	15 x 15	1	9	100	30,000	58.0	46.8	-23.9	127.5	279.8	54.4
Model B4	20 x 20	1	16	100	15,000	156.0	116.0	-34.5	128.5	321.8	60.1
Model B5	25 x 25	1	25	100	15,000	208.1	141.8	-46.8	130.1	329.4	60.5
Model B6	30 x 30	1	36	100	15,000	242.3	164.5	-47.3	133.0	355.7	62.6

Remark: (1) to (4) are same as Table 1 above, refer to sketch as shown below for load patterns.



3.2 Findings from the Parametric Studies

- **Load Pattern Effect:** Set A parametric study investigated the effect of varying load pattern on the accuracy of WM. The study transitioned from a single point load to a uniformly distributed load (UDL), maintaining constant equivalent pressure. As shown in Table 1, the load pattern had minimal influence on the estimated maximum settlement and bearing pressure using WM.

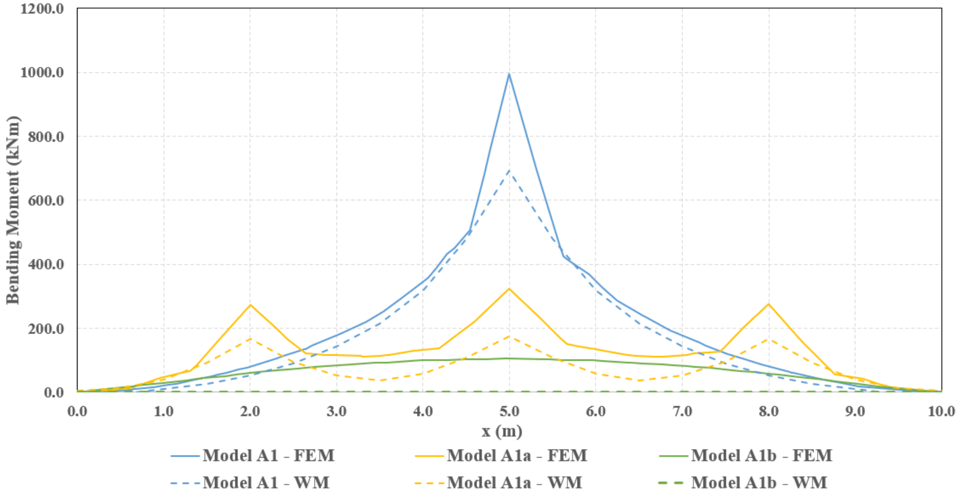


Figure 1: Bending Moment Diagram of Raft Footing under Different Load Patterns

However, significant discrepancies were observed in the estimation of bending moments. Figure 1 demonstrates that as loading became more distributed, the divergence between FEM and WM predictions increased. Notably, under the UDL, the WM predicted zero bending moment, underscoring its limitations in modelling structural response under distributed loads.

- **Footing Thickness and Founding Material Effect:** Comparative analysis was conducted on Models B1, B1a, B1b, B2, B2a, B2b, B3, B3a, and B3b to explore the influence of footing thickness and founding material stiffness. As illustrated in Figure 2, varying the modulus of elasticity (E_s) of the founding material had a limited effect on WM accuracy. Even when the E_s was doubled from 15MPa to 30MPa, the differences in the estimated maximum settlement and pressure remained relatively consistent.

  On the other hand, the study highlighted that the effect of footing thickness was more pronounced. The thickness of the footing demonstrated a more significant impact on the accuracy of the Winkler Models. This indicates that WM sensitivity is more influenced by the rigidity of the raft than the stiffness of the supporting soil.

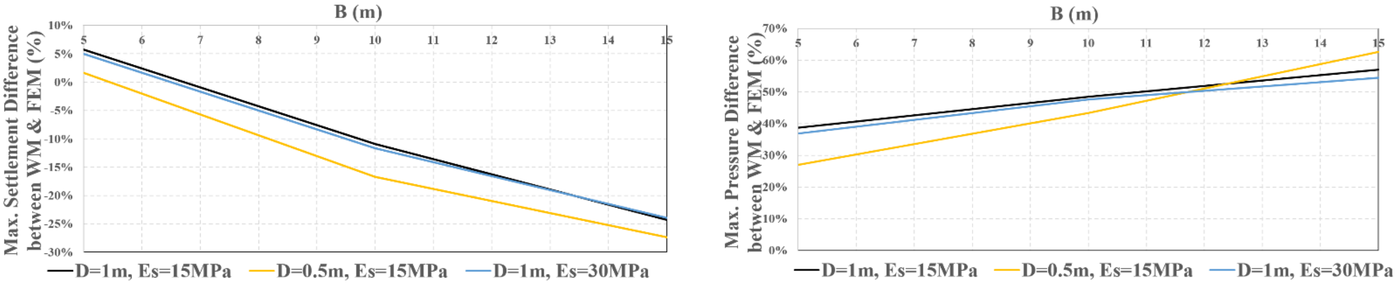


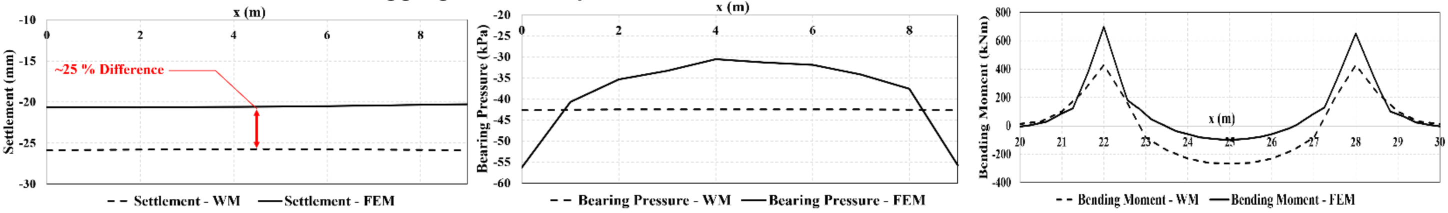
Figure 2: Difference between WM and FEM under Different Footing Thickness and Founding Material

- **Footing Size Effect:** As shown on Figure 5 below, it is evident that there is an inverse proportionality between the accuracy of the WM and the sizes of footing. The accuracy of the WM decreases as the footing size increases, leading to significant impacts on settlement and pressure estimations. The study revealed that as the footing size reaches 10m, the differences in maximum settlement and pressure estimations exceed 10% and 50%, respectively, highlighting the substantial impact of footing size on the suitability for application of Winkle Model on footing design.

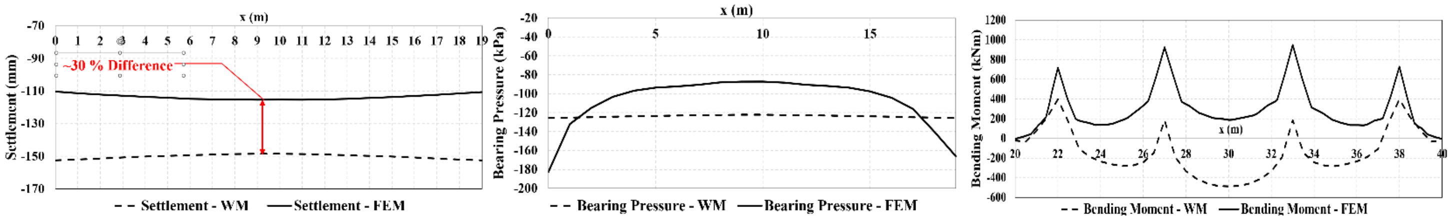
  Furthermore, the comparative study on Model B2, B4, and B6 examined the profiles of parameter concerning settlement, pressure, and bending moment diagrams. The findings indicate that for footings wider than 10m, the WM tends to overestimate settlement, with decreasing accuracy as the footing size increases. A notable discrepancy was also observed in settlement profiles by WM and FEM, where WM predicted greater settlement at the edge compared to the center portion, showcasing an opposite trend to FEM as the footing size increased.

  Regarding pressure estimations, significant differences were noted between WM and FEM profiles. WM returned a uniform pressure profile due to its simple assumption of a uniform soil subgrade, leading to pressure under-estimation at the edge compared to the hogging pressure profile of FEM.

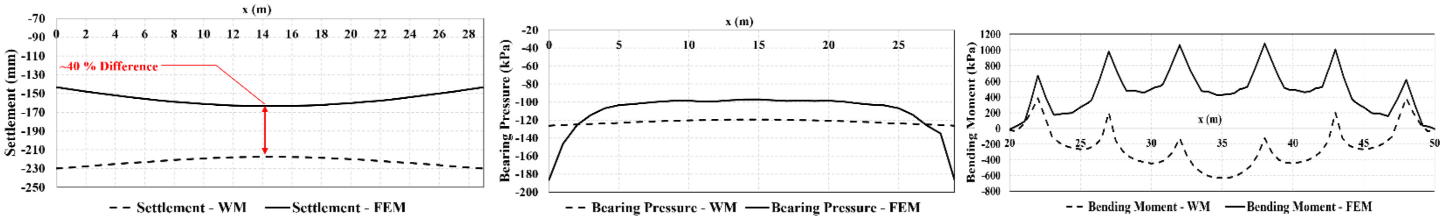
  In terms of bending moment diagrams, discrepancies between WM and FEM increased with larger footing sizes as well as the number of column loads. While WM initially showed reasonable agreement with FEM for a 10m x 10m footing, this agreement diminished as the footing size increased to 30m x 30m, resulting in an underestimation of sagging moment by WM.



Model B2 – 10m x 10m x 1m Raft Footing



Model B4 – 20m x 20m x 1m Raft Footing



Model B6 – 30m x 30m x 1m Raft Footing

Figure 3: Comparison of WM and FEM results - Settlement Profiles (Left Graphs), Bearing Pressure Profiles (Middle Graphs) and Bending Moment Profiles (Right Graphs) under Different Footing Sizes

- **Spatial Location Effect:** The relationship between the position of a footing (center, edge, and corner) and the accuracy of settlement estimation using WM was also examined, the percentage difference in settlement estimated by WM and FEM was analyzed grid by grid. The findings, illustrated in Figure 4, revealed that the difference in settlement by WM and FEM increased radially from the center towards the edge of the raft footing, reaching peak values at the corners. Moreover, as presented in Figure 5, results from Model B1 – B6 were compared to also take footing size effect into account. The accuracy difference between the center, edge, and corner progressively increases as the size of the footing expands. The trend suggests that while the footing size increases, the discrepancy in settlement estimation between the different spatial locations (center, edge, and corner) becomes more pronounced.

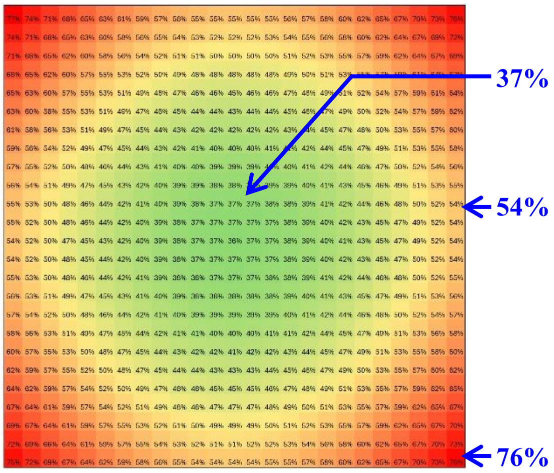


Figure 4: Distribution of Percentage Difference of Estimated Settlement by WM and FEM (Model B5)

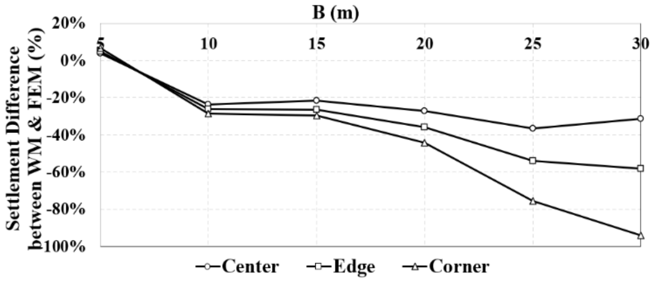


Figure 5: Settlement Difference between WM and FEM at Center, Edge and Corner under Different Footing Sizes

- **Effect of Shear Strength Parameters:** Since shear strength parameters of the founding material such as friction angle (ϕ) and cohesion (c) are not explicitly accounted for in Winkler Model, it is crucial to understand the effects of ϕ and c on settlement and bearing pressure estimation under FEM. Based on a series of FEM sensitive analyses, it is found that higher shear strength parameters could contribute to a reduction in settlement with ranged of 2% to 12% but increased in maximum bearing pressure locally at the edges and corner. However, the reduction trend of settlement with the higher shear strength parameters cannot be well established.

- **Overall Findings:**

- Accuracy of the Winkler Model with uniform k_s (WM) in settlement estimation decreases as the footing size increase and becomes inaccurate (difference > 10%) when the size of raft footing exceeds 10m x 10m.
- Accuracy of the WM is affected by the thickness/rigidity of footing, in which a less rigid footing returns less accurate result.
- Simplified nature of the WM can result in overly conservative estimation of settlement along the edges and corners of raft footings.
- Accuracy of the WM in settlement estimation radially decreases from the center of the raft footing.
- The WM tends to underestimate the localized bearing pressure along the outer sides.
- The WM becomes inaccurate in estimating bending moment when the load pattern is distributed in nature.
- As the footing size expands with increasing number of column loads, the WM under-estimates the sagging moment and over-estimates the hogging moment, leading to potential under-design of steel reinforcement.

4 SUGGESTED METHODS FOR RAFT FOOTING DESIGN

4.1 Method A: Finite Element Method (FEM) using PLAXIS 3D

Three-dimensional finite element analysis on raft footing design can be conducted using PLAXIS 3D which models entire foundation system and associated geology underneath. Unlike software SAFE which simulate the founding condition based on modulus of subgrade reaction as individual spring support, PLAXIS 3D can simulate the founding condition with intrinsic soil properties including friction angle, cohesion and Young's Modules, etc. Most importantly, it takes into consideration the interaction of soil mass, especially those soil supports beyond the footing footprint, and provide a more realistic estimation on settlement, bearing pressure and structural responses of raft footings.

However, PLAXIS 3D normally requires longer computational time and higher demand on computer power. Furthermore, PLAXIS 3D is less suitable for structural design tasks due to its geotechnical focus especially it is not good at performing analysis under multiple load combinations and detailed reinforced concrete design.

4.2 Method B: Back-calculated k_s from PLAXIS 3D into SAFE

An alternative is to adjust modulus of subgrade reaction (k_s) in WM by adopting the data inferred from PLAXIS 3D. Initially, a PLAXIS 3D model is constructed under a dominant load case, preferably a combination of dead load and live load. The raft footing is virtually segmented into 1m x 1m grids (or smaller for increased precision). Each grid is assigned with its unique subgrade modulus which is back-calculated from the force and settlement within the same grid by PLAXIS 3D. The actual analysis of raft footing is subsequently conducted by Winkler Model in SAFE with the adjusted k_s.

The method numerically simulates the distribution of k_s and applied it in Winkler Model. Not only it can provide more realistic results, but also enable analysis under multiple load combinations, facilitating the structural design of the foundation.

However, the method still requires three-dimensional finite element analysis, leading to long computational time and resources demand. Additionally, since the adjusted subgrade modulus is calculated under one specific load case, the accuracy may be compromised when subjected to different load combinations.

4.3 Method C: Empirical Zoning and Adjusting of k_s Values into SAFE

An empirical method can be used to distribute k_s across the raft. Hans-Georg (2006) suggested multiplying k_s by factors of 1.75 and 3.5 at the edge and corner respectively for a strip width of 0.1B as illustrated in Figure 6 below.

$$k_{s,e} \cdot A_e + k_{s,r} \cdot A_r + k_{s,m} \cdot (A - A_r - A_e) = k_s \cdot A \quad \text{(Eq. 2a)}$$

$$k_{s,r} = 3.5 \cdot k_{s,m} \ , \ k_{s,e} = 1.75 \cdot k_{s,m} \qquad \text{(Eq. 2b)}$$

where k_{se}, k_{sr}, k_{sm} = subgrade modulus at edge, corner and center respectively, k_s = overall subgrade modulus and A_e, A_r, A = area of edge, area of corner and total area respectively.

According to Figure 3 above, the resulting settlements from WM and FEM not only deviate in terms of shape but also in magnitude. It is observed that WM with k_s derived by Eq. 1 has overestimated the resulting settlement. Considering Eq. 2a and Eq. 2b only caters for the distribution of k_s. This paper introduces an empirical coefficient (N), derived by comparing k_s from Eq. 1 and the average k_s back-calculated from PLAXIS 3D (Method B) based on the size of a square raft footing as described in Figure 7. This adjustment helps align WM results with those from FEM. k_{se}, k_{sr} and k_{sm} are derived from k_s x N and subsequently applied by zone in SAFE.

While this method offers a convenient alternative to obtain relatively realistic results using WM with simplifies modeling and shortens computation time, it is less accurate for irregular footings or complex soil conditions.

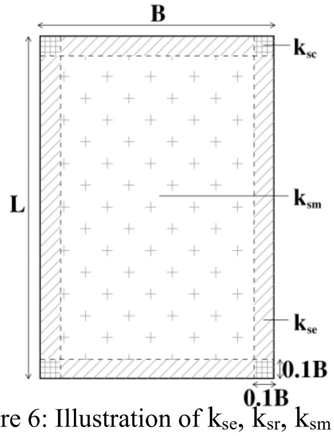


Figure 6: Illustration of k_{se}, k_{sr}, k_{sm}

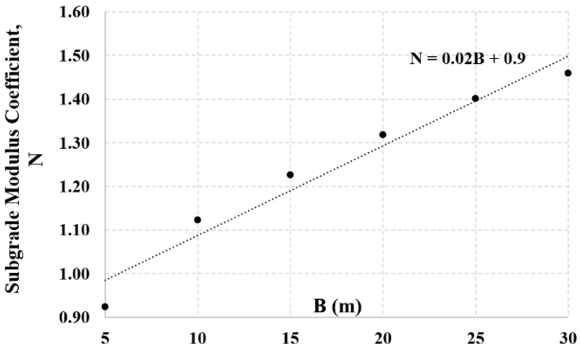


Figure 7: Subgrade Modulus Coefficient, N

4.4 Results Comparison of Method A, Method B and Method C

A comparative study was conducted on Model B5 to examine the accuracy of Method B and Method C. Settlement, bearing pressure and bending moment obtained from the methods are compared. The settlement profiles and bending moment estimations derived from both Method B and Method C exhibit a good level of agreement with the results obtained from the FEM (Method A). As for bearing pressure, while there is a reasonable agreement between the results of FEM and Method B, result from Method C deviates from FEM. The comparison of the advantages and disadvantages of the three suggested methods are listed in Table 3 below:

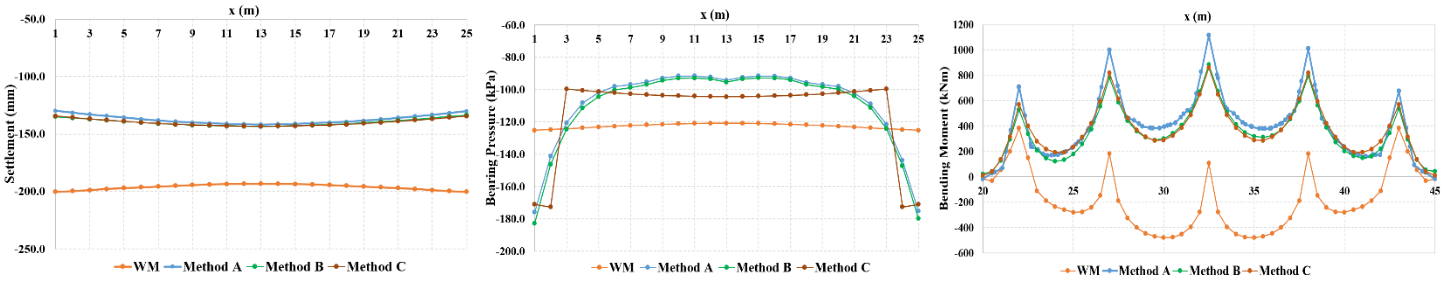


Figure 8: Settlement, Pressure and Bending Moment Comparison of Method A, B and C

Table 3: Summary of Advantages and Disadvantages of Suggested Methods

	Advantages	**Disadvantages**
Method A (FEM)	1. Most accurate, especially dealing with complicated footing shape, load pattern and geology	1. Very long computational time 2. Less suitable to compute for large amount of load combinations

	Advantages	Disadvantages
		3. Limited structural design capability
Method B (Back-calculated k_s)	1. Moderately accurate 2. Support multiple load combinations and R.C. design	1. Require FEM modelling 2. Accuracy may reduce for varied load case
Method C (Empirical ks)	1. Generally aligns with FEM results 2. Short computational time (no FEM model) 3. Support multiple load combinations and R.C. design	1. Least accurate 2. Not suitable for complex footings load or varied geology

Given the uncertainties in k_s estimation, sensitivity analyses are recommended under Method B and Method C for both 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 75% to 150% of the estimated subgrade modulus for bearing capacity and structural checking under Method B and Method C.

5 CAES STUDIES FOR RAFT FOOTING DESIGN

5.1 Case Study 1 – Mixed Foundation Types for a Multi-deck Car Park in Complex Geological Site

The project involved the construction of a new multi-deck car park in Australia. The site was geologically complex, situated on the boundary between two geological formations: Tertiary Older Volcanic (comprising Basalt and Tuff) and Werribee Formation (consisting of Clayey Sand and Silty/Sandy Clay). Site investigation works were conducted in two stages with boreholes and geophysical survey (Multi-channel Analysis of Surface Waves Method). Based on the site investigation works, shallow competent Basalt rock could be found at the northern portion of the site while Silty Clay/Clayey Sand with no bedrock could be founded within 30m depth below ground at the southern portion. The longitudinal geological cross section of the site is shown in Figure 9 below.

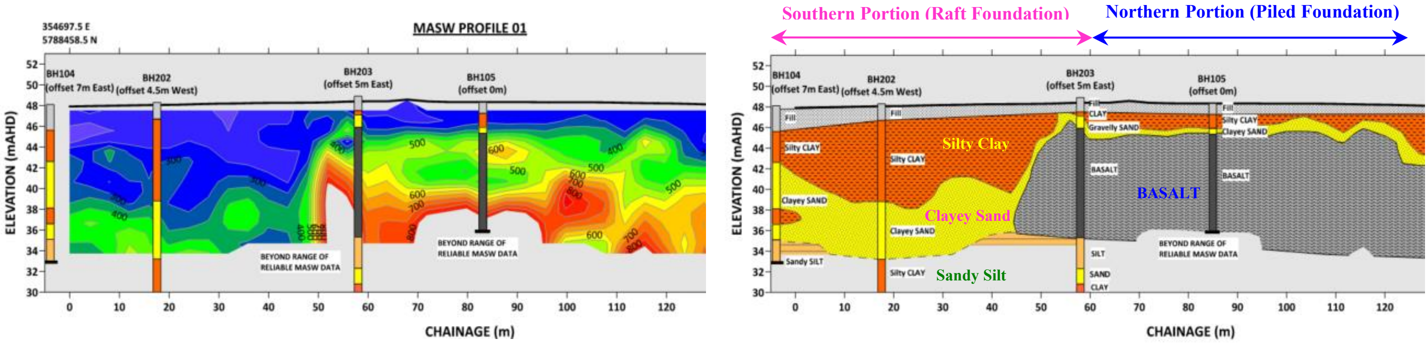


Figure 9: Long Sections show the Geophysical Survey Profile (Left) and Inferred Geological Profile (Right)

Due to highly variable subsurface conditions, a mixed foundation approach was proposed to optimize cost, construction time and manage geotechnical risks from underground uncertainties. For the northern portion of the site with Basalt rock, piled foundation system (600mm to 900mm diameter bored piles) was proposed with slab on grade slab for the ground floor which was cheaper and faster for shallow bedrock situation. For the southern portion of the site with no bedrock encountered, 500mm thick raft footing (35m x 96m) was proposed to prevent deep foundation requirements.

To manage anticipated differential settlement across the two foundation types, structural movement joints (M.J.) were incorporated into the design. However, the initial analysis using the Winkler Model in SAFE with a uniform modulus of subgrade reaction (i.e. $k_s = 2250\text{kN/m}^3$ estimated by Vesic Equation) predicted settlement at the raft footing corners of approximate 50mm, while adjacent pile-supported areas settled only 5mm. This resulted in an estimated differential settlement of 45mm across the M.J. – an unacceptable high value.

To better represent the actual soil–structure interaction, a Finite Element Method (FEM) analysis was conducted using PLAXIS 3D. The raft footing was modeled as a plate element, and variable subsurface conditions were captured through real and dummy boreholes. The results showed maximum settlement of 40mm at the center of the raft under core wall loads, while corner settlement was significantly reduced to approximately 12 mm. This yielded a differential settlement of just 7 mm across the M.J.—substantially less than that predicted by the initial SAFE model.

Based on the results of PLAXIS 3D, iterations with the structural SAFE model had converged at a vertical subgrade modulus of 2250kN/m^3 at the center of the raft slab, 8000kN/m^3 along the perimeter (2 m wide edge, i.e. k_s for edges is about 3.5 times of k_s for center) of the raft slab and 4000kN/m^3 between those two areas. An excerpt from the PLAXIS 3D output shown in Figure 10 presents the estimated raft slab displacements under SLS load case. The results of adjusted k_s SAFE model, which showed consistent settlement values as per PLAXIS 3D model, are presents in Figure 11. Once iterations were complete, the design bearing pressures had been reviewed within the allowable bearing capacity of the founding soil. The structural performance of the raft footing and the M.J. had been assessed under the estimated settlement by considering sensitivity of 75% to 150% of the adjusted k_s values.

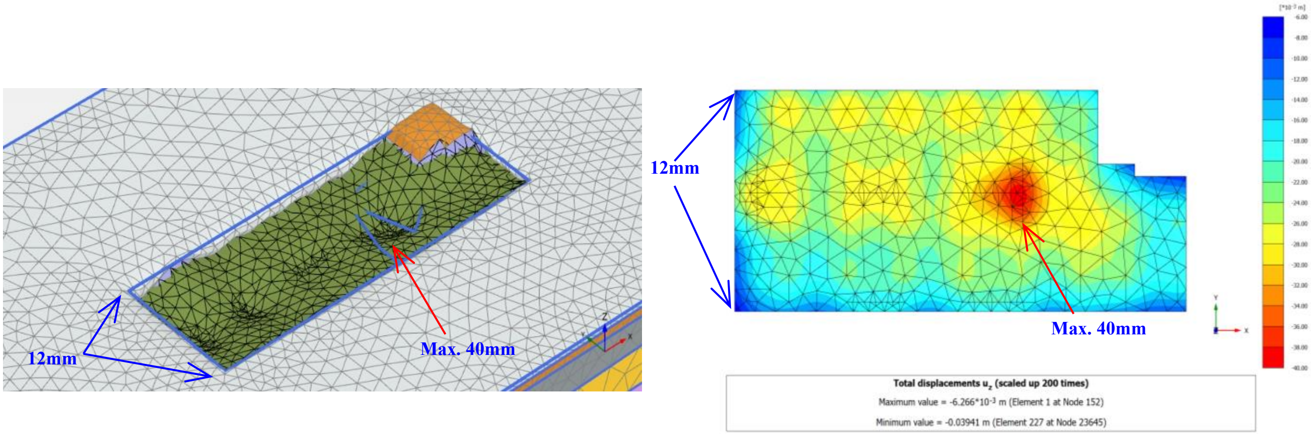


Figure 10: PLAXIS 3D Outputs – 3D View Deformed Shape (Left) and Settlement Contour of Raft Footing (Right)

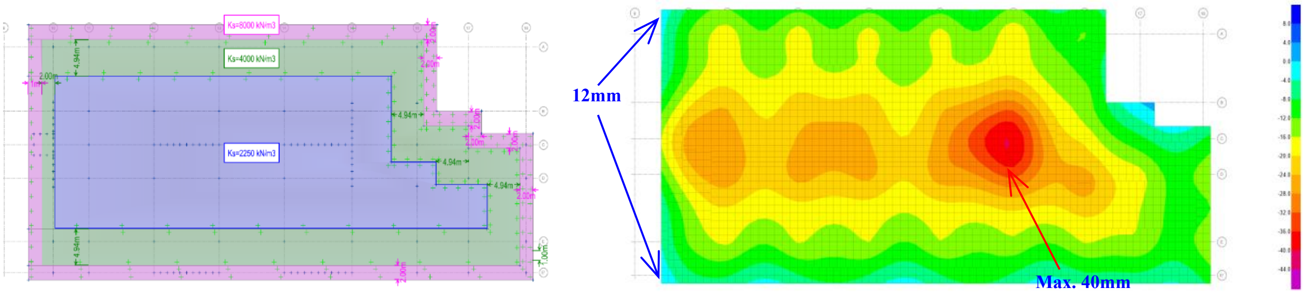


Figure 11: SAFE Model Results – Inputs for k_s (Left) and Settlement Contour of Raft Footing (Right)

5.2 Case Study 2 – Raft Footing on Pulverized Fuel Ash (PFA) in Reclaimed Land

The project involved constructing a plant room on the reclaimed land. The proposed raft footing (size of 23m x 27m x 0.6m thick) was founded on approximate 7m thick of loose PFA fill with silty fine sand and its SPT'N values were less than 5 blows. The design loading of the plant room was relative light with average pressure of 45kPa. Even though the raft footing founding materials were loose in nature, the required bearing capacity could still be achievable based on the bearing capacity equation as per CoP Foundations 2017 because of significant contribution of 23m large width (B) of the raft footing.

The estimated modulus of subgrade reaction (k_s) was 1,650kN/m^3 by hand calculation of settlement assuming 45° load spread pressure on various layers of soil. Winkler Model (WM) by structural software of SAFE was conducted with uniform k_s (adopted 1,650kN/m^3) underneath the entire raft footing footprint. The results revealed that maximum settlement was 33mm at raft footing edge which was marginally over the acceptable limit of 30mm under CoP of Foundations 2017. The SAFE input and output graphs are shown in Figure 12 below.

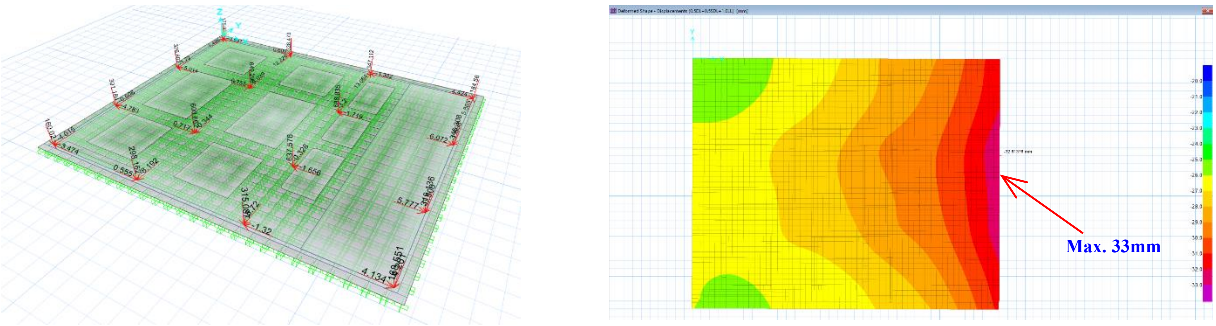


Figure 12: WM (SAFE) Results – Inputs with uniform k_s (Left) and Settlement Contour of Raft Footing (Right)

As discussed previously, Winkler Model with uniform k_s often over-estimates the settlement of raft footing, especially along the edges and corners. To improve accuracy, further analyses using Method B and Method C analyses (referenced in Section 4 of this paper) were conducted to compare with the results of FEM model by PLAXIS 3D (Method A). PLAXIS 3D input and output graphs are shown in Figure 13. The comparison of the results of the following are presented in Figure 14.

- WM – Winkler Model by SAFE with uniform k_s of 1,650kN/m^3 across whole footing footprint
- Method A – FEM Model by PLAXIS 3D
- Method B – Back-calculate k_s from PLAXIS 3D and then Winkler Method (MW) by SAFE where k_s ranged from 1,980kN/m^3 to 6,263kN/m^3.
- Method C – Adjust and Zone k_s Values by Empirical Method and then Winkler Method (WM) by SAFE, i.e. soil subgrade modulus of the center portion, i.e. overall subgrade modulus ($k_{s\text{-overall}}$) = 1,650kN/m^3 x 1.37 (Subgrade Modulus Coefficient from Figure 7 with width of 23m) = 2,260kN/m^3, where k_{sm}, k_{se} and k_{sr}, = 1,582kN/m^3, 2,769kN/m^3 and 5,538kN/m^3 = subgrade modulus at center, edge and corner, respectively.

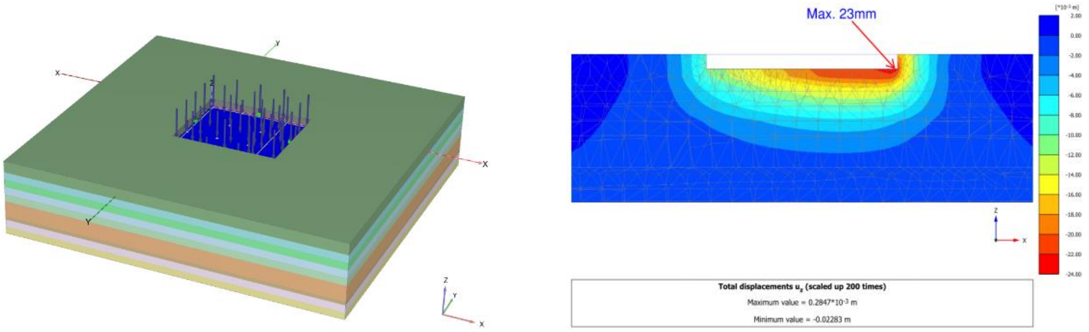
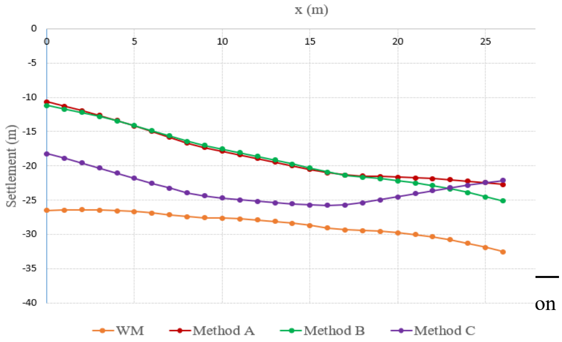


Figure 13: FEM (PLAXIS 3D) Results – Input Graph (Left) and Cross Section Output of Raft Footing Settlement (Right)



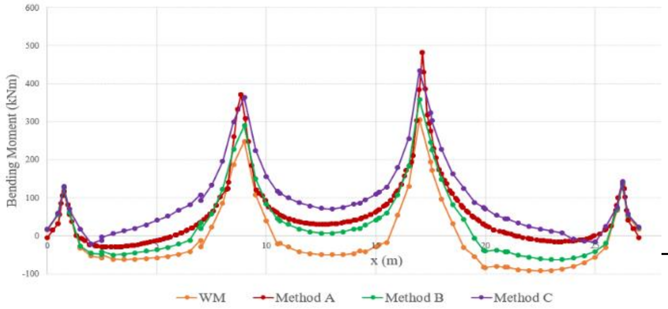


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Figure 14: Comparison of the Results with Various Design Methods: Settlement Profile (Left) and BM Profile (Right)

Based on the comparison of the analyses results of various design method, the maximum settlements are 23mm, 25mm and 27mm for Methods A, B and C respectively, which are within the acceptable limit of 30mm. In addition, the bending moment (BM) diagrams are generally in line whereas Winkler Model (WM) by SAFE with uniform k_s shown the under-estimate of the hogging moment while over-estimate of the sagging moment.

6 CONCLUSIONS

Raft footing remains a practical and sustainable alternative to piled foundations, especially in urban developments where cost efficiency, construction time, and environmental impact are critical concerns. However, the traditional reliance on the Winkler Spring Model with a uniform modulus of subgrade reaction (k_s) often proves inadequate in capturing the complex behavior of soil-structure interaction. This is particularly evident in large or irregular shaped raft on heterogeneous ground conditions, where oversimplified assumptions may lead to the premature rejection of raft footing as viable option.

In comparison, the Finite Element Method (FEM) using PLAXIS 3D (referred to as Method A) accounts for the interaction between soil elements and provides a more realistic and accurate prediction of raft behavior. Nevertheless, PLAXIS 3D requires significantly higher computational effort and resources, and it is less suitable for structural design tasks due to its geotechnical focus.

To bridge the gap between geotechnical accuracy and structural practicality, two additional methods—Method B and Method C—have been developed based on the Winkler Model (WM) within SAFE. Method B involves back-calculating k_s values from FEM results and applying them in a grid layout across the raft footprint. Method C employs an empirical zoning approach to vary k_s based on ground conditions and geometry without the need for FEM. Both methods provide improved accuracy over the uniform k_s model and the results align well with FEM outcomes.

Method C offers a simplified and practical approach suited for projects with relatively uniform geology and regular raft geometry. In contrast, Method B, while requiring preliminary FEM analysis, offers a higher level of precision and is better suited for projects with complex soil profiles, foundation shapes, and load distributions.

Ultimately, by adopting suitable analysis methods, designers can unlock the full potential of raft footing systems – maximizing sustainability benefits, optimizing foundation performance, and ensuring resilience in increasingly complex construction environments.

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