

## Development of raft foundation structural design tool for residential buildings

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### ABSTRACT

This study evaluates the structural and geotechnical aspects of raft foundation design for residential buildings, focusing on the influence of soil conditions on moments and shear forces. A comparative analysis between manual calculations and SAFE software revealed deviations due to variations in soil stiffness. Empirical correction factors (CFs) were developed using multiple linear regression to enhance manual design accuracy by incorporating subgrade modulus, raft thickness, and column spacing. These CF were integrated into a Visual Basic for Applications (VBA)-based spreadsheet-based design tool, ensuring compliance with Eurocode standards. The tool demonstrated quantifiable accuracy, achieving percentage errors below 10% for critical positive moment ( $M_{max}$ ) and maximum shear forces ( $V_{max}$ ), particularly in medium to hard soils. Slightly higher errors were observed in soft soils, as CFs were weighted more towards stiffer soils. Discrepancies are present across all soil types for negative moments ( $M_{min}$ ) due to the limitations in conventional slab method assumptions in capturing the location of hogging moments in raft foundations. This outcome indicated the need for further refinement of CFs, possibly through the integration of additional empirical data. As the scope of this study is limited to residential buildings, future work could expand the applicability of this tool to high-rise buildings, which require more complex load distributions and additional soil parameters for accurate soil behaviour modelling. Enhancements could include consideration for various soil types with differing bearing capacities and settlement characteristics under load. Additionally, incorporating differential settlement analysis would improve the representation of raft foundation behaviour and extend the applicability of this tool to more complex geotechnical conditions. Overall, the tool remains a practical and efficient solution for early-stage design and verification against the Finite Element Method (FEM) results.

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## 1. INTRODUCTION

The challenge of inaccurate manual designs is significant in real-world construction projects, where errors in foundation design can lead to serious consequences, including structural instability, increased safety risks, and costly delays. Furthermore, these errors may result in overdesign or underdesign, both of which contribute to unnecessary financial burdens for contractors, engineers, and clients. Therefore, there is a pressing need for an efficient yet accurate tool that can address the limitations of manual calculations while maintaining the reliability of more advanced Finite Element Method (FEM)-based methods.

Existing design approaches face challenges in balancing accuracy and efficiency. Manual calculations simplify soil-structure interaction, potentially leading to design inaccuracies, while the Finite Element Method (FEM)-based tools such as SAFE offer high precision but can be time-

intensive and computationally demanding for preliminary assessments, making this tool less practical for early-stage design. Thus, this study aimed to bridge this gap by developing a spreadsheet-based raft foundation design tool that integrates parametric analysis and regression-based correction factors (CFs). These factors adjust manual calculations to better reflect variations in subgrade modulus, raft thickness, and column configuration, thus improving the correlation with FEM results. The study focused on low-rise residential buildings (one to three stories), following Eurocode 1 load considerations. The raft was modelled as a continuous slab subjected to column and distributed loads, with manual calculations using one-way slab moment and shear coefficients. The SAFE software serves as a benchmark for validation.

The proposed tool enhanced the predictive accuracy of raft foundation design by refining manual calculations through regression-based CFs, while maintaining

computational efficiency. This tool addresses the need for a simpler, more time-efficient alternative to FEM-based tools, particularly during the initial design phase when quick, reliable approximations are crucial. Ultimately, this research provides a practical and cost-effective approach to optimising raft foundation design, improving safety, and reducing project costs, bridging the gap between simplified manual methods and FEM-based results.

The bulk of the literature has examined key aspects of raft foundation design, focusing on rigid and flexible behaviour, soil-structure interaction, and the FEM application. Raft foundations efficiently distribute structural loads, minimising stress concentrations and settlement risks. Tradigo et al. (2015) highlighted the adaptability of flexible rafts to soil stiffness variations, making this design suitable for layered or soft soils. However, studies by Omer and Arbabi (2015) caution that flexible rafts are more susceptible to differential settlement, potentially affecting superstructure integrity. Meanwhile, Chang et al. (2022) demonstrated that soil type significantly influenced stress distribution, altering raft response under loading.

Raft design relies on soil properties such as cohesion, friction angle, and bearing capacity. Leong and Chan (2013) reported that larger rafts experience greater settlement but at a slower rate, influencing raft sizing decisions. In seismic regions, soil-structure interaction is critical, as Venkatesh and Deshpande (2017) found that flexible soils amplified bending moments and shear stresses, requiring design adjustments. In a different study, Sami and Al-Ameri (2023) explored floating piled rafts for soft clay foundations, revealing that increased thickness improved stress distribution and long-term stability.

A critical aspect of raft foundation design is soil-structure interaction, which depends on the modulus of subgrade reaction ( $k$ ). Unlike traditional geotechnical parameters, such as bearing capacity or elasticity modulus, SAFE software models soil behaviour using only  $k$ -values, making the accurate selection essential for reliable design outcomes (Pujadas-Gispert et al., 2018). Pad foundations are common in firm soils and piled foundations in weaker soils, but the former often lead to excessive differential settlement, while the latter are costly and resource-intensive. In contrast, raft foundations offer a balanced alternative, integrating the ground slab and foundation into a single system, optimising material use, construction time, and overall efficiency (Sunesra et al., 2020). Therefore, raft foundations provide an efficient solution for residential buildings by distributing structural loads over a large area, reducing soil stress and settlement risks.

FEM provides a deeper understanding of settlement,

load distribution, and structural response. Meyerhof (2002) demonstrated that controlled settlement enhanced bearing capacity in granular soils. Tabsh and Al-Shawa (2005) introduced a rigidity factor to assess soil pressure sensitivity, while Xiong et al. (2017) demonstrated that accounting for superstructure stiffness and soil plasticity results in a more uniform pressure distribution, reducing differential settlement risks. Other studies also confirmed that increased raft thickness improves load distribution (Anggraini & Sarifah, 2002), while a higher subgrade modulus enhances load transfer and minimises settlement (Dey & Chatterjee, 2023a). In addition, Singh et al. (2023) examined long-term raft deflection and noted maximum deformation at corners. Combining FEM with boundary element methods can improve predictions for soil-raft interaction over rigid bases (Ribeiro & de Paiva, 2015).

Despite extensive research, most studies focused on high-rise buildings and complex piled-raft systems, with limited attention to low-rise residential structures. Key gaps include the lack of practical design tools integrating soil-structure interaction, the exclusion of live loads in many models, and inaccuracies in manual moment and shear force predictions. Thus, the current study addressed these gaps by developing a spreadsheet-based raft design tool tailored for low-rise buildings, incorporating CFs from FEM comparisons to enhance manual calculation accuracy while maintaining efficiency. Moreover, this study improved the reliability and practicality of raft foundation design in residential applications by refining the design methodologies.

## 2. MATERIALS AND METHODS

The modelling and analysis of the raft foundation are based on soil parameters, primarily the modulus of subgrade reaction ( $k$ ), which governs the soil-structure interaction and affects the distribution of moments and shear forces. The CSI SAFE only uses the modulus of subgrade reaction to model the soil-structure interaction, and as such, this study did not account for other geotechnical parameters such as cohesion or friction angle. The study considered three soil categories: soft ( $4410 \text{ kN/m}^3$ ), medium ( $11770 \text{ kN/m}^3$ ), and hard ( $72000 \text{ kN/m}^3$ ), as displayed in Table 1 (Bowles, 2001). These values corresponded to sand layers with varying densities, from loose to dense conditions. The design tool allows users to input soil type and corresponding  $k$  values for consistency with geotechnical standards, which are classified accordingly.

**Table 1:** Modulus of subgrade reaction

Type of Soil	Modulus of subgrade reaction, $k$ ( $\text{kN/m}^3$ )
Hard	72000
Medium	11770
Soft	4410

The raft is modelled as a 12 m × 12 m symmetrical slab, with thicknesses ranging from 200 mm to 400 mm, depending on soil stiffness. These dimensions were chosen for analysis purposes and were intended to represent a typical residential slab. Concrete properties were assumed to be a modulus of elasticity of 25 × 10<sup>6</sup> kPa with a Poisson’s ratio of 0.25, ensuring compatibility with standard concrete design parameters. The applied live load is 1.5 kN/m<sup>2</sup>, consistent with Eurocode 1 (Standardisation, 2002) for residential areas, while the dead load is 1.2 kN/m<sup>2</sup>, representing finishes typically applied in residential building structures.

The raft model is designed for a two-story building (G+1), where the raft supports the load transferred through columns from the first story. The raft was supported by 16 columns, spaced at 4 m intervals, categorised as interior (600 mm × 600 mm), side (600 mm × 300 mm), and corner columns (300 mm × 300 mm), as detailed in Table 2. The column sizes and the assumption of a two-story configuration were chosen for analysis purposes but are reasonable for typical residential buildings.

**Table 2:** Column parameters

Column type	Number of columns on raft	Load (kn)	Dimensions (mm x mm)
Interior	4	172.8	600 x 600
Side	8	86.4	600 x 300
Corner	4	43.2	300 x 300

The column loads are derived from a factored load intensity of 10.8 kN/m<sup>2</sup>, computed using the standard Eurocode load combination.

$$1.4 \times (24 \times 0.2 + 1.2) + 1.6 \times (1.5) = 10.8 \text{ kN/m}^2$$

Where 24 kN/m<sup>3</sup> is the unit weight of concrete, 0.2 m is the slab thickness, while 1.2 kN/m<sup>2</sup> and 1.5 kN/m<sup>2</sup> accounted for additional dead loads and live loads, respectively. This factored load intensity accounted for the first story transferred through the columns to the raft foundation. Each column supported a tributary area based on the location:

- Corner columns: 2 m × 2 m = 4 m<sup>2</sup>
- Side columns: 4 m × 2 m = 8 m<sup>2</sup>
- Interior columns: 4 m × 4 m = 16 m<sup>2</sup>

The tributary area for each column was multiplied by the factored load intensity to determine the corresponding column load, with interior columns experiencing the highest loads due to the larger tributary area.

The spreadsheet-based design tool treated the raft as a continuous slab under distributed loads. Using ultimate

bending moment and shear force coefficients for one-way spanning slabs (see Figure 1), the critical bending moment and shear forces were determined, ensuring computational efficiency and adherence to structural engineering principles. The moment and shear coefficients for one-way slabs were defined based on the effective span, L, with each bay covering an area of at least 30 m<sup>2</sup>. A bay was defined as a strip of slab spanning across the structure between adjacent rows and columns. The total ultimate load was expressed as follows:

$$F = (1.35 G_k + 1.5Q_k) * \text{Span Length} * 1m$$

	End support condition						
	Pinned		Continuous				
	Outer support	Near middle of end span	End support	End span	At first interior support	At middle of interior spans	At interior supports
Moment	0	0.086Fl	-	0.075Fl	-	0.063Fl	-
			0.04Fl		0.086Fl		0.063Fl
Shear	0.4F	-	-	-	-	-	-
			0.46F		0.6F		0.5F

**Figure 1:** One-way slab moment and shear coefficients

SAFE evaluated load distribution and bending behaviour along a critical strip, considering two primary cases: (1) a flat plate, and (2) a flat plate with a thickened under column to simulate real raft behaviour. Additional cases included load redistribution by considering only corner and side columns at full thickness, and a thinner slab with a thickened edge, reinforcing the one-way slab assumption. Table 3 presents the parameters of raft foundation for the abovementioned cases. Meanwhile, the raft model for Cases 1 and 2 is displayed in Figures 2a and b, respectively.

**Table 3:** Raft parameters

Case	Parameter	Soft Soil	Medium Soil	Hard Soil
1	Raft thickness (m)	0.4	0.3	0.2
	Beam depth (m)	0.4	0.3	0.2
2	Raft thickness (m)	0.2	0.15	0.1
	Beam depth (m)	0.4	0.3	0.2

A comparative analysis was conducted against SAFE software results to ensure the accuracy of manual calculations for critical moments and shear forces. The percentage error was calculated as follows:

$$\text{Error} = \frac{|\text{SAFE critical value} - \text{Manual critical value}|}{\text{SAFE critical value}} \times 100$$

Consistent trends in the errors led to the introduction of CFs, derived through multiple linear regression analysis. The purpose of this step was to establish empirical relationships that could correct manual calculations for

bending moments and shear forces in the raft foundation model. The CFs (CFMmax, CFMmin, CFVmax) were computed as:

$$CF = \frac{SAFE\ result}{Manual\ result}$$

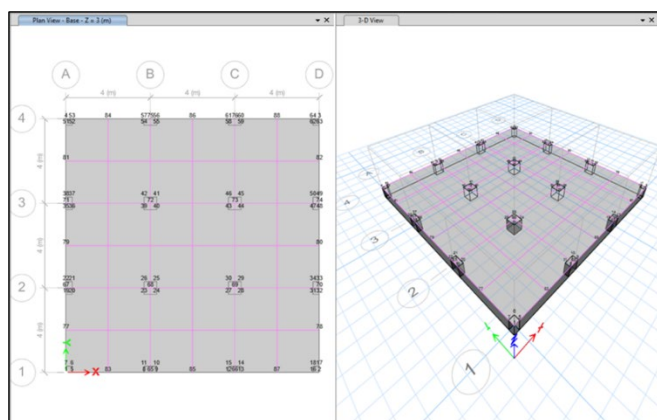


Figure 2a: Raft foundation model for Case 1

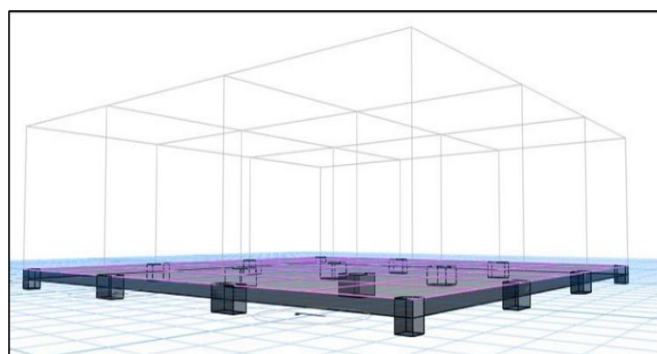


Figure 2b: Raft foundation model for Case 2

The dataset was analysed using Excel's Data Analysis ToolPak for the multiple regression analysis, with CFs as the dependent variable and the independent variables being subgrade modulus, raft thickness, and column spacing. The output provided four coefficients for each CF:

$$CF = a + b(K_s) + c(t) + d(s)$$

Where  $K_s$  is the subgrade modulus,  $t$  is the raft thickness, and  $s$  is column spacing.

The model for  $M_{max}$  yielded a high  $R^2$  value of 0.944, indicating that the predictors explained 94.4% of the variance in the bending moment calculations. The P-value for the intercept (0.072) demonstrated that the intercept was not statistically significant at the 95% confidence level. Likewise, the p-values for the coefficients related to soil modulus (0.773) and raft thickness were also above the typical threshold of 0.05, suggesting limited statistical significance for these individual predictors.

The model for negative moment ( $M_{min}$ ) yielded an

$R^2$  value of 0.496, indicating a moderate fit. The P-value for the intercept (0.415) and coefficients for modulus of subgrade reaction and raft thickness (0.914 and 0.585, respectively) suggested that these predictors did not significantly contribute to the prediction of  $M_{min}$ . Finally, the  $R^2$  value of  $V_{max}$  was 0.490, which was similar to  $M_{min}$  and indicated a moderate fit for the shear force model. The P-values for the intercept (0.170) and the predictors (0.637 for soil modulus, 0.998 for raft thickness) suggested that the influence of these parameters was minimal in predicting shear forces. The regression coefficients  $a$ ,  $b$ ,  $c$ , and  $d$  were embedded into the Visual Basic for Applications (VBA)-based spreadsheet tool, allowing automatic correction of manual results. Subsequently, the values were used to determine reinforcement requirements, ensuring compliance with Eurocode design standards.

$$Corrected\ Manual = Original\ Manual \times CF$$

### 3. RESULTS AND DISCUSSION

The numerical analysis was performed using SAFE software, modelling the raft foundation as a continuous slab subjected to distributed loads. The objective was to extract critical bending moments and shear forces along a representative strip for each case and compare the values against manual calculations. The analysis covered 12 cases, considering variations in soil stiffness (soft, medium, and hard) and raft configurations (Cases 1, 2, 3, and 4). Across all cases, the raft was subjected to uniformly distributed loads (UDL) from dead and live loads and point loads from columns. Each case varied in raft thickness, column configurations, and load distribution. Three different soil types (soft, medium, and hard) were analysed for each case.

Case 1: The raft was modelled as a flat plate with supporting columns in 4 m intervals, with loads applied based on actual tributary areas (see Figure 2a). Interior columns carried the highest loads, while edge and corner columns supported lower loads. This case reflected realistic load distribution in a fully continuous slab.

Case 2: The raft thickness was reduced by half, making the structure a flat plate with a thickened under column to evaluate the contribution to load transfer and bending resistance (see Figure 2b). This case assessed the influence of a thinner slab and stiffer beam system on raft behaviour while maintaining the same tributary area-based load distribution as Case 1.

Case 3: The same methodology as Case 1 was used in this condition, but only the corner columns were considered in the critical strip analysis. The interior and edge columns were removed, and the loads from these removed columns were redistributed as a UDL across the slab. This design

maintained similar overall loading conditions but changed the structural response by forcing the slab to span larger distances without intermediate column support, providing further validation for the one-way slab assumption (see Figure 3a)

Case 4: Similar to Case 2. The raft thickness was halved, and only the corner and edge beams remained. The loads from the removed interior and edge columns were redistributed as UDL to maintain a consistent total load (see Figure 3b).

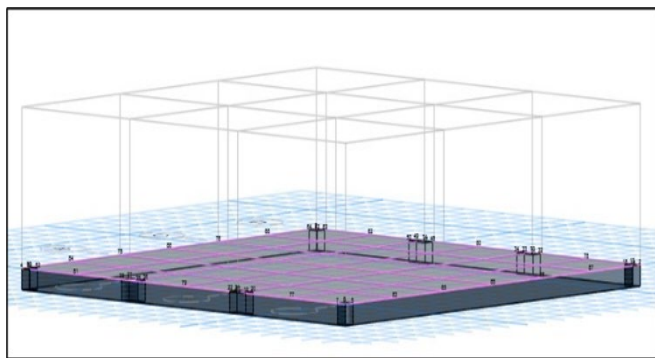


Figure 3a: Raft foundation model for Case 3

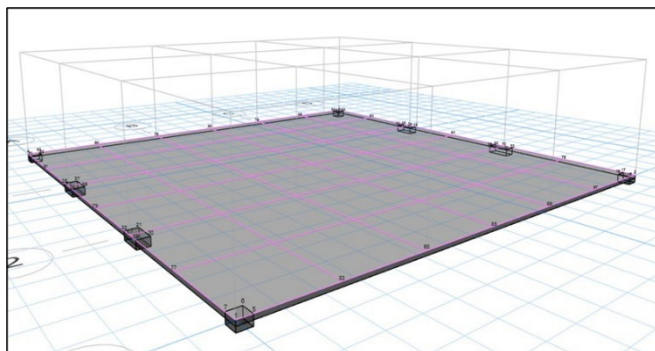


Figure 3b: Raft foundation model for Case 4

The strip bending moment (M) and shear force (V) values were extracted from SAFE for each case. Critical bending moments were obtained at mid-span (negative moment, Mmin) and supported the positive moment (Mmax), while critical shear (Vmax) was taken near column faces. These results served as a benchmark for validation manual calculations using one-way slab coefficients. Table 4 summarises the difference in percentage error between manual design calculations and SAFE software results.

The comparison between SAFE results and manual calculations revealed distinct trends across different soil types, emphasising the limitations of the manual method and the influence of soil stiffness on structural response. Table 4 presents the results for Case 1, where the raft foundation was analysed using a uniform thickness across all soil types.

The manual method overestimated SAFE results in soft soil and underestimated the values in medium and hard soils for the critical Mmax. The differences in Mmax

predictions between manual and SAFE analyses due to soil stiffness are consistent with Dey & Chatterjee (2023b). Similarly, Koltuk & Topçu (2025) highlighted the trend of underestimation of Mmax in stiffer soils compared to FEM models.

Table 4: Percentage error for Case 1

Soil Type	SAFE (kNm/m)	Manual (kNm/m)	Error
Mmax			
Soft Soil	30.57	32.21	5.35%
Medium Soil	30.02	28.80	4.05%
Hard Soil	34.42	25.40	26.20%
Mmin			
Soft Soil	36.18	38.34	5.96%
Medium Soil	37.05	34.29	7.44%
Hard Soil	31.76	30.24	4.79%
Vmax			
Soft Soil	62.24	63.90	2.66%
Medium Soil	65.67	57.15	12.97%
Hard Soil	64.34	50.40	21.66%

Notes: Mmin = Negative moment, Mmax = Positive moment, Vmax = Critical shear

The highest percentage error was observed in hard soil at 26.20%, whereas medium soil had the lowest deviation at 4.05%. These outcomes suggested that the manual method provided a reasonable approximation in medium soil, but did not fully capture the load distribution effects in hard soil. Numerical studies conducted by Jeong et al. (2024) demonstrated that analytical simplifications tend to diverge from finite element results as soil stiffness increased, particularly affecting load distribution and corresponding internal moments, which supported the higher errors recorded for hard soils in this study.

The significant underestimation of Mmax in hard soil indicated that the manual method assumed a more uniform stiffness distribution than the value captured in the SAFE analysis, leading to a lower moment prediction. Conversely, the manual method slightly overestimates SAFE results in soft soil, possibly due to the assumption of a stiffer response than the actual occurrence in highly compressible soils. Earlier studies explained that manual methods tend to overestimate moments in soft soils due to the assumption of a stiffer response than the actual value in compressible soils (K. David et al., 2015; Zhong et al., 2025).

The manual calculations were slightly higher than the SAFE results for all the critical Mmin across all soil conditions, with percentage errors ranging from 4.79% in hard soil to 7.44% in medium soil. The manual method slightly

overestimated  $M_{min}$  because simplified soil assumptions do not fully capture the nonlinear behaviour of soft and stiff soils (Saeed, 2022). This outcome suggested that the manual method tends to overestimate  $M_{min}$  due to the simplified approach, which does not fully capture the effects of soil flexibility and moment redistribution. In softer soils with more significant deformation, the manual method provides a reasonable approximation. However, the discrepancy remains in hard soil, likely due to the assumption of full continuity in design coefficients, which did not entirely align with the moment redistribution behaviour observed in the SAFE model.

The percentage error for maximum shear ( $V_{max}$ ) was highest in hard soil (21.66%) and lowest in soft soil (2.66%). This trend indicated that as soil stiffness increased, the accuracy of the manual method decreased. The increasing percentage error in maximum shear with higher soil stiffness aligns with the findings of Omer et al. (2022), who reported that shear forces tend to be amplified with increasing soil modulus in raft foundation analysis. This result indicated the limitations of simplified manual assumptions in stiffer soil conditions. The discrepancy in hard soil arises because the manual method assumes a simplified shear distribution, whereas SAFE captured the actual load distribution more accurately. The significant error in hard soil suggested that the manual method did not fully account for variations in soil stiffness, leading to an underestimation of shear forces. In soft soil with significant deformation, the manual method aligns more closely with the SAFE results, likely due to the assumption of a more distributed load transfer.

**Table 5:** Percentage error for Case 2

Soil Type	SAFE (kNm/m)	Manual (kNm/m)	Error
<b><math>M_{max}</math></b>			
Soft Soil	30.81	25.40	17.55%
Medium Soil	32.38	23.70	26.82%
Hard Soil	29.99	22.00	26.66%
<b><math>M_{min}</math></b>			
Soft Soil	21.97	30.24	37.64%
Medium Soil	23.64	28.22	19.35%
Hard Soil	16.33	26.19	60.40%
<b><math>V_{max}</math></b>			
Soft Soil	46.20	50.40	9.10%
Medium Soil	51.16	47.02	8.09%
Hard Soil	47.55	43.65	8.19%

**Notes:**  $M_{min}$  = Negative moment,  $M_{max}$  = Positive moment,  $V_{max}$  = Critical shear

In Case 2, a thinner raft was used to evaluate the effects of reducing slab thickness on moment and shear

calculations (see Table 5). This case simulated a more realistic raft foundation, where the edges were thicker than the interior to enhance load distribution and minimise differential settlement. Notably, these percentage errors were generally higher than in Case 1, indicating that the one-way slab method did not fully reflect the interaction between variable thickness sections in the raft. SAFE, through FEM, accounted for the influence of edge stiffening on overall structural response, whereas the manual method simplified the raft as a uniform thickness element, leading to notable discrepancies.

The manual calculations consistently underestimated the critical  $M_{max}$  of SAFE across all soil types. The highest percentage error was observed in medium soil (26.82%), followed closely by hard soil (26.66%) and soft soil (17.55%). Significant underestimation in medium and hard soils suggested that as raft thickness decreased, the one-way slab method became less reliable as the variations in stiffness and deflection behaviour were not fully captured. These effects were accounted for in the FEM-based SAFE model, contrasting the manual method that applied simplified assumptions that did not capture the redistribution of bending moments effectively.

The percentage errors for critical  $M_{min}$  varied significantly across soil types. The manual method overestimated  $M_{min}$  in all cases, with the most extreme deviation occurring in hard soil (60.40%), followed by soft soil (37.64%) and medium soil (19.35%). The drastic overestimation in hard soil suggested that the manual method assumed greater fixity and restrained the realistic values observed in the SAFE results. In contrast, the lower error in medium soil indicated that the method provided a more reasonable approximation in conditions where raft stiffness was balanced with soil flexibility. Nonetheless, the manual method did not reflect the redistribution of  $M_{min}$  in soft and hard soils, particularly when raft thickness was reduced.

The percentage errors of maximum shear ( $V_{max}$ ) remained within an acceptable range, with deviations of 9.10% in soft soil, 8.09% in medium soil, and 8.19% in hard soil. These results indicated that while moment predictions were highly sensitive to raft thickness and soil conditions, shear forces were less affected by these factors. The manual method estimated shear forces directly based on tributary area loads, which aligns relatively well with the SAFE results. This outcome suggested that shear force calculations in the manual approach remained reasonably reliable even when raft thickness was reduced, whereas moment calculations required additional refinement.

Overall, the results indicated that the manual method provided reasonable approximations for medium soil conditions, but the accuracy deteriorated in soft and hard soils,

particularly for moment calculations. The errors in soft soil arose from the inability to account for soil-structure interaction effects in the manual method, while overestimating stiffness and restraint in hard soil, leading to higher predicted moments. The discrepancies were more pronounced when raft thickness was reduced, reinforcing the need for CFs in the manual approach, particularly for Mmax and Mmin. Implementing CFs into the VBA-based design tool will improve accuracy, making manual calculations more reliable and comparable to FEM-based SAFE results. The CFs were developed for this purpose based on the percentage error observed for each soil type.

The CF was determined systematically using Eq. 4, as the ratio of the SAFE result to the manual calculation. This process was applied to each soil type for Cases 1 and 2, ensuring that the CFs effectively reduced errors across all conditions while maintaining consistency in the variation patterns of bending moments and shear forces.

$$CF_{Mmax} = 1.530358 + (6.87566E - 07 \times K_s) - (1.472737 \times t)$$

$$CF_{Mmin} = 0.629654 + (6.90265E - 07 \times K_s) + (1.103351 \times t)$$

$$CF_{Vmax} = 1.048113 + (1.93703E - 06 \times K_s) + (0.002869 \times t)$$

Multiple linear regression has been effectively used to relate foundation CF to key soil parameters, providing a practical tool to improve manual design accuracy (Bery, 2022). A multiple linear regression analysis was performed in Excel to establish mathematical relationships between the CFs and the key soil parameters. The values included were subgrade modulus (Ks), raft thickness (t), and the resulting CFs for critical positive bending moment (CFMmax), critical negative bending moment (CFMmin), and maximum shear force (CFVmax). Table 6 summarises the CF values for each case along with other parameters for the regression analysis.

**Table 6:** Dataset for regression analysis

Soil Type	Ks	Spacin g	CFMmax x	CFMmin	CFVmax
Soft	4410	0.2	4	1.212893701	0.726537698
Medium	1177	0.15	4	1.366451477	0.837866761
Hard	7200	0.1	4	1.363518182	0.623447881
Soft	4410	0.4	4	0.949189693	0.943755869
Medium	1177	0.3	4	1.042225694	1.08040245
Hard	7200	0.2	4	1.354984252	1.050343915

**Notes:** Ks = Subgrade modulus, t = Raft thickness, CFMmax = Correction factors for critical positive bending moment, CFMmin = Critical negative bending moment, CFVmax = maximum shear force

The manual values were recalculated using the regression equations to validate the effectiveness of the CF and were integrated into the spreadsheet-based design tool using VBA programming. The revised values were compared with SAFE results, and the percentage error was reassessed, as shown in Table 7a for Case 1 and Table 7b for Case 2. The user interface was structured into two main sections. Figure 4 demonstrates the output comparison for Mmax, Mmin, and Vmax between Corrected Manual and SAFE for Case 1 and Case 2.

**Table 7a:** Output comparison between Corrected Manual and SAFE for Case 1

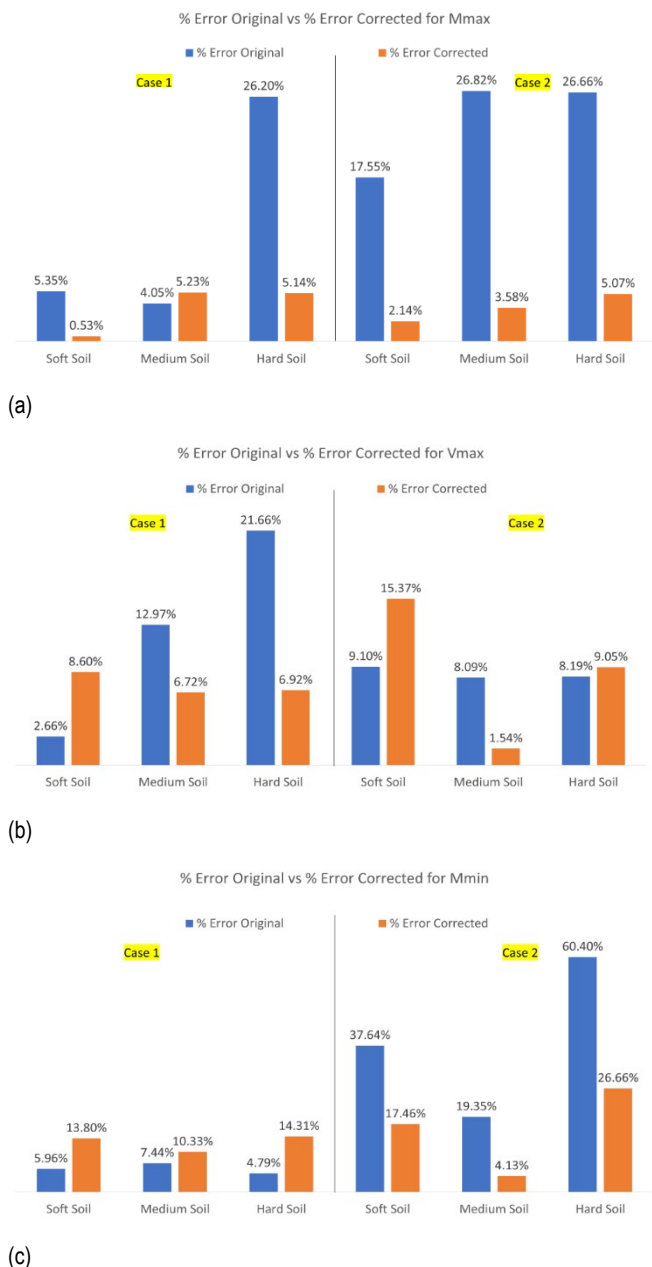
Soil Type	Manual Original	Manual Corrected	SAFE	% Error Original	% Error Corrected
Mmax (kNm/m)					
Soft	32.21	30.41	30.57	5.35%	0.53%
Medium	28.80	31.59	30.02	4.05%	5.23%
Hard	25.40	32.65	34.42	26.20%	5.14%
Mmin (kNm/m)					
Soft	38.34	41.18	36.18	5.96%	13.80%
Medium	34.29	33.22	37.05	7.44%	10.33%
Hard	30.24	27.22	31.76	4.79%	14.31%
Vmax (kN/m)					
Soft	63.90	67.60	62.24	2.66%	8.60%
Medium	57.15	61.25	65.67	12.97%	6.72%
Hard	50.40	59.88	64.34	21.66%	6.92%

**Notes:** Mmin = Negative moment, Mmax = Positive moment, Vmax = Critical shear

**Table 7b.** Output Comparison between Corrected Manual and SAFE for Case 2

Soil Type	Manual Original	Manual Corrected	SAFE	% Error Original	% Error Corrected
Mmax (kNm/m)					
Soft	25.40	31.47	30.81	17.55%	2.14%
Medium	23.70	31.23	32.38	26.82%	3.58%
Hard	22.00	31.52	29.99	26.66%	5.07%
Mmin (kNm/m)					
Soft	30.24	25.81	21.97	37.64%	17.46%
Medium	28.22	22.68	23.64	19.35%	4.13%
Hard	26.19	20.68	16.33	60.40%	26.66%
Vmax (kN/m)					
Soft	50.40	53.28	46.20	9.10%	15.37%
Medium	47.02	50.37	51.16	8.09%	1.54%
Hard	43.65	51.85	47.55	8.19%	9.05%

**Notes:** Mmin = Negative moment, Mmax = Positive moment, Vmax = Critical shear



**Figure 4:** Output Comparison for (a) Mmax, (b) Mmin, and (c) Vmax between corrected manual and SAFE values for Case 1 and Case 2

The manual values were recalculated using the regression equations to validate the effectiveness of the CF and were integrated into the spreadsheet-based design tool using VBA programming. The revised values were compared with SAFE results, and the percentage error was reassessed, as shown in Table 7a for Case 1 and Table 7b for Case 2. The user interface was structured into two main sections. Figure 4 demonstrates the output comparison for Mmax, Mmin, and Vmax between Corrected Manual and SAFE for Case 1 and Case 2.

The comparison between the corrected manual calculations and SAFE software results demonstrated that the applied CFs significantly enhanced the accuracy of the spreadsheet-based design tool. This improvement aligns with

earlier studies that derived empirical CF by comparing analytical predictions to finite element results to enhance the reliability of simplified foundation design (Pantelidis, 2021). As shown in Tables 7a and b., the most consistent improvement was observed in the Mmax estimation. Mmax values corrected using the empirical equation align closely with SAFE results across all soil types in Cases 1 and 2. In Case 1, the Mmax error in soft soil reduced from 5.35% to 0.53%, while the values in hard soil dropped from 26.30% to 5.14%. Similarly, Mmax error in soft soil reduced significantly from 17.55% to 2.14%, and in medium soil from 26.82% to 3.58% in Case 2. These results confirmed that the CF effectively captured the influence of subgrade stiffness and raft thickness, yielding more reliable estimates for flexural demand under various soil conditions.

Minimum Mmin exhibited more variability, with consistently higher errors across all soil types, even after applying the CF. This overestimation arose primarily from the simplified one-way slab moment distribution approach used in manual calculations, which assumed that hogging moments occurred directly at slab supports, as is typical in conventional floor systems. However, raft foundations behave differently due to the distribution of soil pressure beneath the slab. In raft foundations, hogging moments develop due to the varying pressure distribution from the soil, with significant moments typically occurring at the end spans rather than supports. This discrepancy between the conventional slab assumption and the actual behaviour of raft foundations led to an overestimation of Mmin in manual calculations.

In Case 1, the Mmin error increased after applying the CF for soft and hard soils, indicating that the correction was not fully effective in accounting for this fundamental behaviour difference. While the corrections reduced Mmin errors significantly in Case 2, residual discrepancies remained. These discrepancies suggested that the one-way slab moment distribution approach did not fully capture the complexity of moment behaviour in raft foundations. Further refinement of the CF, such as introducing additional empirical data, could improve the accuracy of these effects in preliminary design.

The CFs generally reduced discrepancies of maximum shear forces (Vmax) with SAFE results, particularly in medium and hard soils. Nonetheless, soft soil exhibited mixed behaviour, with errors increasing after correction. In Case 1, the error increased slightly from 2.66% to 8.60%, and in Case 2, from 9.10% to 15.37%. These outcomes can be attributed to the CF being derived from a single regression equation that was applied across all soil types. The CF was primarily weighted towards reducing hard soil error in Case 1, which exhibited the largest deviation in the original manual

calculations. As a result, the correction strategy of the model led to a higher adjusted value for Vmax. This discrepancy indicated that a more tailored CF is necessary for each soil type to account for these unique behaviours and improve the accuracy of Vmax predictions in such conditions.

The spreadsheet-based design tool for raft foundations was developed in this study to automate the calculation process, ensuring efficiency and accuracy in structural design. The tool integrated user inputs, soil classifications, load calculations, structural analysis, and reinforcement design according to Eurocode standards. The implementation was carried out using Excel formulas and VBA to automate complex computations and enhance user interaction.

INPUT DATA	
<b>Foundation Information</b>	
Base Dimension, B	12 m
Footing Length, L	12 m
Raft Thickness, t	0.4 m
Concrete Cover, cc	0.04 m
Column Spacing, s	4 m
<b>Soil Information</b>	
Modulus of Subgrade Reaction, $K_s$	4430 kN/m <sup>3</sup>
Soil Layer Type	Sand
<b>Load Information</b>	
Corner Column Load	43.2 kN
Edge Column Load	86.4 kN
Interior Column Load	172.8 kN
Dead Load (DL)	1.2 kN/m <sup>2</sup>
Live Load (LL)	1.5 kN/m <sup>2</sup>
<b>Material Properties (Concrete &amp; Steel)</b>	
Concrete Strength (f <sub>ck</sub> )	30 MPa
Steel Yield Strength (f <sub>yk</sub> )	420 MPa
Steel Bar Size	12 mm
Concrete Unit Weight	25 kN/m <sup>3</sup>

Figure 5: User input data Interface of the spreadsheet-based design tool for raft foundations

In the input data section (see Figure 5), users provide key parameters, including foundation dimensions, soil properties, column loads, and material properties.

The output data section in Figure 6 contains automated computations that generate key results, such as equivalent column loads per unit area, force per unit width, moments, shear forces, and reinforcement details. The tool includes built-in safety checks to ensure design compliance.

The VBA programming was integrated into the tool to automate key calculations. The soil type was classified automatically based on the modulus of subgrade reaction (Ks), distinguishing between soft, medium, and hard soil conditions. Load calculations were dynamically updated based on user inputs, determining self-weight, total dead load, and ultimate load per unit area. Structural analysis computations were performed based on established moment and shear coefficients, where CF was applied according to soil properties and raft thickness. The force per unit width is calculated using the ultimate load per unit area and column spacing. The lever arm and required steel area are determined

using Eurocode formulas for the reinforcement design, ensuring that the provided reinforcement meets or exceeds the required area. The tool also automates bar selection and performs checks to verify the adequacy of the reinforcement provided.

OUTPUT DATA		
<b>Automated Parameters</b>		
Soil Type	Soft	
Correction Factor for Mmax	0.9443	
Correction Factor for Mmin	1.07404	
Correction Factor for Vmax	1.0578	
<b>Structural Analysis Results</b>		
Corrected Critical Positive Moment (Mmax)	30.41159884 kNm/m	
Corrected Critical Negative Moment (Mmin)	41.17863489 kNm/m	
Corrected Maximum Shear (Vmax)	67.59360546 kNm/m	
<b>Reinforcement Design</b>		
Effective Depth, d	350 mm	
Moment Ratio, k	0.008275265	
Lever Arm, Z	347.4269905 mm	
Required Steel Area (As_req)	239.5560567 mm <sup>2</sup> /m	
No. of Bars Required	4	
Provided Steel Area (As_provided)	314.16 mm <sup>2</sup> /m	
<b>Equivalent Column Load Per Unit Area</b>		
Corner Column Contribution, q <sub>corner</sub>	10.8 kN/m <sup>2</sup>	
Edge Column Contribution, q <sub>edge</sub>	10.8 kN/m <sup>2</sup>	
Interior Column Contribution, q <sub>interior</sub>	10.8 kN/m <sup>2</sup>	
<b>Safety Checks</b>		
Zmax = 0.954d	333.9 m	
Lever Arm Check (Z <= Zmax)	Exceeded, use Zmax	Pass/Fail
Steel Area Check (As_provided >= As_req)	Within Range	Pass/Fail
Force per Unit Width, F	127.8 kN	

Figure 6: Output data section of the spreadsheet-based design tool for raft foundations

Overall, the results demonstrated that the spreadsheet-based design tool provides reasonable accuracy in predicting maximum Mmax and shear forces, particularly for medium and hard soils. Nevertheless, inconsistencies in Mmin estimations suggested that further adjustments may be needed to refine the CF. While SAFE remains essential for final verification, the spreadsheet tool serves as an efficient and practical alternative for preliminary design, allowing engineers to rapidly assess raft foundation behaviour across different soil conditions.

#### 4. CONCLUSION

This study analysed the impact of soil stiffness on raft foundation behaviour, revealing that Mmax and shear forces were well captured by the spreadsheet-based design tool. Enhanced with empirical CF, the tool produced results that aligned closely to those of the SAFE software, with discrepancies remaining below 10%. Despite that, there is a need for refinements in Mmin, particularly in hard soil conditions. The tool provides a practical solution to improve manual calculations, bridging the gap between simplified hand calculations and detailed numerical models. Furthermore, the tool allows for rapid preliminary assessments, particularly in the early-stage design of raft foundations, where time and cost savings are critical. Reduction in computational effort also enables practitioners to quickly generate results, identify design issues, and consider various scenarios, allowing for faster decision-making and potentially minimising the need for extensive, time-consuming software modelling in the early

stages of projects. While SAFE software remains essential for final verification, the spreadsheet tool represents a significant advancement, particularly in speed and efficiency.

It is important to note that CSI SAFE primarily uses the modulus of subgrade reaction to model soil-structure interaction, which defines the scope of this study by not accounting for other geotechnical parameters such as cohesion or the friction angle. Additionally, the focus of this study is limited to low-rise residential buildings. Therefore, the applicability of this tool could be expanded to more complex foundation systems, such as those used in high-rise buildings. The expansion would require the tool to have the ability to model more complex load distributions and integrate additional soil parameters to accurately capture soil behaviour. Additionally, future work should focus on refining the CF for  $M_{min}$ , possibly through a more detailed regression analysis. This enhancement could lead to separate CF equations for each soil type, better accounting for hogging moments in raft foundations. In summary, the tool developed in this study offers a valuable alternative to traditional methods despite the limitations, providing an efficient, cost-effective approach for early-stage raft foundation design. Further improvements in accuracy and expanded capabilities can make this tool a powerful resource for practitioners in the field.

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