

# Investigating the impact of soil properties, design errors, and construction defects on foundation failure in residential buildings

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## Abstract:

Foundation failure in residential buildings is a critical issue that often leads to structural instability, economic loss, and, in extreme cases, collapse. This research investigates the impact of three key factors: soil properties, design errors, and construction defects on foundation failure. The study identifies soil properties such as cohesion, internal friction angle, and bearing capacity, as well as foundation settlement, as primary contributors to instability. Design errors, including improper load calculations and inadequate foundation dimensions, further exacerbate these risks, while construction defects and environmental conditions play a secondary yet important role. The methodology adopted involves a comprehensive analysis of design parameters, soil characteristics, and construction practices. This includes the use of Terzaghi's bearing capacity theory, settlement equations, and risk analysis to evaluate the relative impact and risks associated with each factor. Visualizations such as pie charts, line charts, and stacked bar graphs are used to represent the distribution of impact, risk trends, and safety margins across the studied parameters. Results indicate that soil properties and foundation settlement are the most significant contributors to foundation failure, with high-risk levels and minimal safety margins. Design parameters and loading conditions also pose considerable risks, particularly when design errors lead to misaligned structural loads. Construction defects and environmental factors are less critical but still affect long-term foundation durability. The findings underscore the necessity of thorough geotechnical investigations, precise settlement predictions, and robust design practices to mitigate the risks of foundation failure. By addressing the most critical factors i.e. soil properties and settlement, this research provides a framework for improving foundation stability and ensuring the longevity of residential structures.

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## 1. Introduction

Foundation failure is a serious problem that threatens the integrity of residential buildings, frequently resulting in major economic loss, structural instability, and, in extreme situations, catastrophic collapse. Foundation failure can be caused by a variety of sources, including both natural and human faults. Specifically, soil conditions, design mistakes, and building problems are recognized as the leading causes of such collapses. Understanding these elements is critical to increasing the safety and longevity of residential constructions [1].

The stability of a building is heavily influenced by the soil's qualities. Poor soil conditions, such as expansive clays or high groundwater levels, have been frequently recorded to cause differential settlement, excessive lateral displacement, and, eventually, foundation failure [1]. Expansive soils, for example, experience considerable volumetric changes due to moisture variation, which can result in structural stresses that exceed the tolerance of traditional foundations [2].

In addition to soil qualities, design flaws have a substantial impact on the stability of a building's foundation. Errors in estimating load distribution, inaccurate calculations, or wrong foundation type selection frequently result in a mismatch between expected and actual structural requirements, raising the risk of failure [3]. Design flaws are sometimes exacerbated by a lack of proper geotechnical investigation, resulting in designs that fail to account for unique subsurface conditions [4].

Another major cause of foundation failure is construction faults. These flaws might result from poor craftsmanship, faulty concrete curing, insufficient reinforcement, or changes from the specified design during construction [5]. Negligence during construction, such as neglecting to follow material requirements or ignoring sufficient site preparation, can drastically compromise the foundation's structural integrity [6].

The purpose of this study is to look into the combined impact of soil qualities, design flaws, and construction problems on foundation failure in residential buildings. Understanding how these factors interact allows us to

develop more effective ways for preventing foundation failure and enhancing building safety. The aim of this study is to investigate the impact of soil properties, design errors, and construction defects on foundation failure in residential buildings.

## 2. Methodology

### 2.1 Mathematical models

To investigate the impact of soil properties, design errors, and construction defects on foundation failure, a mathematical model can be formulated based on the fundamental principles of soil mechanics, structural analysis, and engineering reliability theory. The model aims to evaluate the load-bearing capacity of the foundation and determine the factors that influence potential foundation failure.

The primary concept behind the model is the equilibrium of forces acting on the foundation system. Specifically, we consider the ultimate bearing capacity of the soil, the applied loads due to structural weight, and any lateral forces. The ultimate bearing capacity,  $q_u$ , of the foundation can be expressed as a combination of the soil's strength parameters, cohesion ( $c$ ), and internal friction angle ( $\phi$ ), as well as the depth ( $D_f$ ) and width ( $B$ ) of the foundation as in equation 1:

$$q_u = cN_c + qN_q + 0.5\gamma BN_\gamma \quad (1)$$

Where  $c$ ,  $\gamma$ , and  $D_f$  represent soil properties and  $N_c$ ,  $N_q$ , and  $N_\gamma$  are bearing capacity factors, dependent on the internal friction angle  $\phi$  [1].

To consider the impact of design errors, the applied load  $q_u$  on the foundation must be compared against the allowable bearing capacity ( $q_a$ ) as in equation 2:

$$q_a = \frac{q_u}{FS} \quad (2)$$

Where  $FS$  is the factor of safety.

Design errors, such as inaccuracies in calculating load or ignoring soil heterogeneity, can lead to an underestimated factor of safety, thus reducing the foundation's reliability [2].

Construction defects are introduced into the model by accounting for potential variations in material properties and workmanship quality. Let  $\delta$  represent a reduction factor that accounts for construction defects, such as inadequate curing or improper reinforcement. The effective bearing capacity ( $q_{eff}$ ) can be written as in equation 3:

$$q_{eff} = \delta q_a \quad (3)$$

The condition for foundation failure is given when the applied load ( $Q$ ) exceeds the effective bearing capacity ( $q_{eff}$ ) as can be seen in equation 4:

$$Q > q_{eff} \quad (4)$$

In probabilistic terms, the reliability index ( $\beta$ ) can be used to quantify the probability of failure ( $P_f$ ). The reliability index is defined as can be seen in equation 5:

$$\beta = \frac{q_{eff} - Q}{\sigma_{total}} \quad (5)$$

Where  $q_{eff}$  is the effective bearing capacity, reduced by construction defect factor  $\delta$ ,  $Q$  is the applied load and  $\sigma_{total}$  represents uncertainties in soil, load, and construction quality as reported in Li, et al. [3].

The probability of failure is related to the reliability index through a cumulative distribution function ( $\Phi$ ) can be seen in equation 6:

$$P_f = \Phi(-\beta) \quad (6)$$

This formulation allows for the evaluation of how variations in soil properties ( $c$ ,  $\phi$ ,  $\gamma$ ), design accuracy ( $FS$ ), and construction quality ( $\delta$ ) influence the likelihood of foundation failure. Some of the variable parameters used in the models' equations as reported in Pinto, et al. [5] include the following:

Variable parameters influencing foundation failure are,

- Soil Properties including cohesion ( $c$ ), angle of internal friction ( $\phi$ ) and unit weight of soil ( $\gamma$ )
- Design Accuracy which involve determining of Factor of Safety ( $FS$ )
- Construction Quality which involve determining of construction tolerance/error ( $\delta$ )

For the research titled "Investigating the Impact of Soil Properties, Design Errors, and Construction Defects on Foundation Failure in Residential Buildings," several design parameters and variables were considered to ensure a comprehensive analysis. These parameters are categorized under three main areas: soil properties, design parameters, and construction-related variables.

Settlement Analysis Equation: The total settlement ( $S_{total}$ ) is the sum of the initial and consolidation settlements as in equation 7:

$$S_{total} = S_i + S_c \quad (7)$$

## 2.2 Design parameters and variables

### 2.2.1 Soil properties

Soil properties play a crucial role in determining the behaviour of foundations. The properties of the soil can significantly impact the stability, settlement, and ultimate capacity of the foundation. Therefore, accurate determination of soil properties is essential for reliable design and analysis of foundations. As suggested by Pinto, et al. [5], the following soil properties are essential for foundation design:

- Cohesion ( $c$ ): Represents the adhesive force between soil particles. Values could range from 0 to 50 kPa, with typical values for clay soils between 20 and 40 kPa [5].
- Internal Friction Angle ( $\phi$ ): Determines the shearing resistance of the soil. Values can range from 15° to 40°, depending on the type of soil (e.g., sandy soils tend to have higher friction angles) [5].
- Unit Weight ( $\gamma$ ): Soil density per unit volume; typically it ranges from 16 to 22 kN/m<sup>3</sup> depending on the soil type [5].
- Elastic Modulus ( $E_s$ ): Represents soil stiffness, ranging from 10 to 100 MPa depending on soil types (clays versus dense sands).

- e. Soil Bearing Capacity ( $q_u$ ): Bearing capacity could be between 100 and 500 kN/m<sup>2</sup>.
- f. Soil Plasticity Index (PI): Used to determine the soil's ability to expand or shrink, with values ranging from 0 (non-plastic) to 40 or more.
- g. Water Table Depth: The depth of the groundwater level affects the effective stress on the foundation. Depths range from 1 m to 10 m below the foundation base.

## 2.2.2 Design parameters

Design parameters are crucial in determining the safety and performance of a foundation. These parameters are used to calculate the bearing capacity, settlement, and stability of the foundation. According to Schmidt, et al. [6], the following design parameters are essential for foundation design:

- a. Foundation Type: this could be either
  - i. Shallow Foundations: Types such as strip footing, pad footing, and raft foundation.
  - ii. Deep Foundations: Types like pile foundation. Pile length ranging from 5 m to 20 m.
- b. Foundation Depth ( $D_f$ ): Depth of foundation below ground level, ranging from 1 m to 5 m for shallow foundations.
- c. Width of Foundation (B): The width of the footing could range between 0.5 m to 3 m.
- d. Factor of Safety (FS): Common values range between 2.0 and 3.5, depending on the risk associated with the construction site.
- e. Load Intensity ( $q$ ): The distributed load applied by the structure, ranging from 100 to 500 kN/m<sup>2</sup>.
- f. Material Properties:
  - i. Concrete Compressive Strength ( $f_c$ ): Hypothetical values from 20 MPa to 40 MPa.
  - ii. Reinforcement Yield Strength ( $f_y$ ): Typical values could range from 250 MPa to 500 MPa.

## 2.2.3 Construction defects variables

Construction defects can significantly impact the performance and safety of a foundation. These defects can arise from various sources, including poor workmanship, inadequate quality control, and insufficient design details. As reported by Merah [7], construction defects can be categorized into several variables that affect the foundation's behaviour. These variables include:

- a. Material Quality Deviation ( $\delta_m$ ): A reduction factor that represents deviation from specified material properties, ranging from 0.7 to 1.0, where 1.0 means perfect compliance.
- b. Workmanship Quality Factor ( $\delta_w$ ): This factor accounts for the quality of workmanship, with values ranging from 0.75 to 1.0, where lower values indicate poor quality.
- c. Improper Curing Time: Time for which concrete curing is done improperly, affecting strength. Range could be between 3-7 days (versus the ideal 28 days)
- d. Reinforcement Position Deviation: Distance of deviation from the intended reinforcement position, ranging from 0 to 50 mm.

- e. Concrete Cover Thickness Variation: The variation in cover thickness, ranging from 20 mm to 60 mm, impacting durability and fire resistance.

## 2.2.4 Environmental conditions

Environmental conditions play a significant role in the behaviour and performance of foundations. Factors such as temperature, rainfall, and groundwater levels can impact the soil's mechanical properties, leading to changes in the foundation's behaviour. Based on the work of Pinto, et al. [5], the following environmental conditions can affect the behaviour of foundations:

- a. Temperature Variation: Temperature extremes, ranging from -10°C to 40°C, could affect soil properties and the curing process of concrete.
- b. Seasonal Moisture Content: The seasonal changes in soil moisture content, affecting soil properties such as cohesion and friction angle, with a variation of  $\pm 20\%$ .

## 2.2.5 Loading conditions

Loading conditions play a crucial role in determining the behaviour and performance of foundations. Various types of loads, including dead loads, live loads, wind loads, and seismic loads, can impact the foundation's stability and safety. According to Das [8], the following loading conditions should be considered in foundation design:

- a. Dead Load ( $W_d$ ): Load due to the self-weight of the building structure. Values ranging from 200 to 1000 kN.
- b. Live Load ( $W_l$ ): Additional loading from occupants and movable items, ranging from 50 to 200 kN, based on building usage.
- c. Lateral Loads ( $W_{lat}$ ): Loads due to wind or seismic effects, ranging from 20 to 100 kN, depending on regional conditions.

## 2.2.6 Probabilistic variables:

Reliability analysis enables engineers to quantify the probability of failure and ensure that the foundation meets the required safety standards. Consistent with Das [8], the following probabilistic variables are essential for reliability analysis in foundation design:

- a. Uncertainty in Soil Properties ( $\sigma_s$ ): Represents variability in soil parameters due to spatial heterogeneity, ranging from 10% to 30% of nominal values.
- b. Uncertainty in Load ( $\sigma_q$ ): Represents uncertainties in loading conditions, potentially ranging from 5% to 15%.
- c. Uncertainty in Construction Quality ( $\sigma_c$ ): Represents workmanship and material quality uncertainty, ranging from 5% to 20%.

## 3. Results

Table 1 summarizes the design and variable used in this research and their ranges for comprehensive analysis. Furthermore, Figure 1 The analysis of the hypothetical parameters highlights the critical role of soil properties, design considerations, construction quality, and

environmental conditions in determining foundation stability. Each parameter introduces specific risks to the foundation, and mitigating these risks requires a comprehensive understanding of the underlying principles. By conducting detailed geotechnical investigations, careful design, and strict quality control during construction, the potential for foundation failure can be minimized, ensuring long-term stability and safety for residential buildings.

These visualisations help to demonstrate the relationship between important variables and the outcomes ensuring long-term stability and safety for residential buildings. All the design parameters and variables are summarized in Tables 1 and 2.

Table 1: Summary of Design Parameters and Variables

Parameter	Variable	Range
Soil Cohesion ( $c$ )	$c$	0 - 50 kPa
Internal Friction Angle ( $\phi$ )	$\phi$	15° - 40°
Unit Weight ( $\gamma$ )	$\gamma$	16 - 22 kN/m <sup>3</sup>
Elastic Modulus ( $E_s$ )	$E_s$	10 - 100 MPa
Factor of Safety (FS)	FS	2.0 - 3.5
Material Quality Factor ( $\delta_m$ )	$\delta_m$	0.7 - 1.0
Foundation Depth ( $D_f$ )	$D_f$	1 - 5 m
Width of Foundation (B)	B	0.5 - 3 m
Concrete Compressive Strength ( $f_c$ )	$f_c$	20 - 40 MPa
Reinforcement Yield Strength ( $f_y$ )	$f_y$	250 - 500 MPa

The values stated here above are representative and intended to provide a basis for simulating different scenarios of foundation performance in the context of soil properties, design accuracy, and construction quality. These parameters are essential for developing the mathematical model and conducting subsequent analyses to identify the root causes of foundation failure. Other values and variables considered in the research are as stated below:

### 3.1 Foundation settlement analysis

The foundation settlement analyses conducted and the results obtained include the following and coincide with the result obtained by [5]:

- Initial Settlement ( $S_i$ ): Represents immediate settlement after the application of loads, calculated using elastic theory. The values obtained range from 5 mm to 20 mm.
- Consolidation Settlement ( $S_c$ ): Long-term settlement due to the expulsion of water from clay layers. The consolidation settlement may vary from 10 mm to 50 mm, depending on the soil type and drainage conditions.
- Differential Settlement ( $\Delta S$ ): Represents uneven settlement across the foundation, leading to structural damage. Range obtained was between 5 mm and 30 mm.
- Total Allowable Settlement ( $S_{all}$ ): The maximum permissible settlement for foundation stability, typically in the range of 20 mm to 50 mm, depending on building type.

### 3.2 Structural load distribution and interaction

This section presents the analysis of structural load distribution and interaction between the foundation and the

superstructure. The work done here involves: Calculation of vertical loads (dead loads, live loads, and superimposed loads) and their distribution to the foundation. It also involves analysis of load transfer mechanisms between the foundation and the superstructure and evaluation of structural interaction effects, such as soil-structure interaction and pile-soil interaction. It also involves determination of the resulting stresses and deformations in the foundation and superstructure. The analysis is based on the principles of structural mechanics and soil-structure interaction, and utilizes relevant codes and standards, such as ACI 318 and ASCE 7.

#### a. Load Transfer Mechanism:

- Load transferred from superstructure to foundation can be modelled based on tributary areas, moment distribution, and load concentration.
- Applied load per column ( $P_c$ ) could range from 200 kN to 500 kN.

#### b. Load Spread Angle:

- Load distribution angle through the foundation to soil ( $\theta$ ), typically ranging from 25° to 35°, influencing load spread and contact pressure.

### 3.3 Geometric variables

This represents the analysis of geometric variables that affect the behaviour and performance of the foundation. The work done here involves: Definition and calculation of key geometric parameters, such as foundation width, length, and depth. Analysis of the effects of geometric variability on foundation behaviour including: settlement, tilt, and structural integrity. It also involves evaluation of the impact of geometric non-uniformities such as foundation irregularities and soil in homogeneities.

According to [7], quantification of the uncertainties associated with geometric variables and their influence on foundation reliability include:

#### a. Foundation Geometry:

- Footing Area ( $A_f$ ): Values ranges from 0.5 m<sup>2</sup> to 3 m<sup>2</sup>.
  - Shape Factor ( $S_f$ ): Determines the correction factors for circular, rectangular, or strip footings.
- Slenderness Ratio (H/B): Ratio of foundation height to width, affecting stability under lateral loads. Values ranges from 1.0 to 3.0.

### 3.4 Soil-structure interaction (SSI)

The analysis of SSI parameters influenced the behaviour of the foundation. The work done here involves: Identification and quantification of SSI parameters, such as soil stiffness, damping, and density. It also involves analysis of the effects of SSI on foundation behaviour, including settlement, vibration, and dynamic response and evaluation of the impact of SSI on structural integrity, including stress and strain distributions.

According to [8], determination of the SSI parameters that are critical to foundation design and performance include:

- Stiffness of Foundation ( $K_f$ ): Represents the resistance offered by the foundation. Values can be



between 50 MN/m to 200 MN/m, based on foundation type and soil condition.

- b. Soil Modulus of Subgrade Reaction ( $k$ ): Indicates how the soil resists deformation. Hypothetical values range from 10 MN/m<sup>2</sup> to 50 MN/m<sup>2</sup> for different soils.

### 3.5 Risk assessment and sensitivity

This entails a comprehensive risk assessment and sensitivity analysis to identify and evaluate the critical variables influencing foundation design and performance.

- a. Design Error Impact Factor ( $E_d$ ): A dimensionless factor that quantifies the risk associated with errors in the design process, typically ranging from 0.8 to 1.0 [7].
- b. Sensitivity Coefficients:
  - i. Soil Property Sensitivity ( $S_{soil}$ ): Indicates the influence of soil variability on foundation performance, ranging from 0.1 to 0.5 [7].
  - ii. Load Sensitivity ( $S_{load}$ ): Represents the sensitivity of the structure to load variations, ranging from 0.2 to 0.6 [7].
- c. Probability of Defects ( $P_d$ ): Represents the probability of occurrence of construction defects, ranging from 0% to 15%, based on quality control measures [7].

### 3.6 Groundwater influence.

This section involves the analysis and quantification of groundwater influence parameters that affect the foundation's behaviour and performance, including:

- a. Pore Water Pressure ( $u$ ): Influences the effective stress in soils, typically ranging from 10 kPa to 30 kPa, depending on groundwater levels and soil permeability [12].

- b. Capillary Rise Height ( $h_c$ ): Values ranging from 0.5 m to 2 m, depending on soil type, which impacts moisture content at the foundation level [12].

### 3.7 Mathematical expressions

This represents the development and formulation of mathematical expressions that incorporate the various parameters influencing the foundation's behaviour, allowing for a quantitative analysis and prediction of its performance.

- a. Bearing Capacity Equation (Terzaghi's Model): The ultimate bearing capacity is influenced by cohesion, unit weight and the surcharge load at the base can be seen from equation 1:

$$q_u = cN_c + \gamma D_f N_q + 0.5\gamma B N_\gamma$$

- b. Settlement Analysis: The total settlement ( $S_{total}$ ) is the sum of the initial and consolidation settlements as in equation 7:

$$S_{total} = S_i + S_c$$

Where  $S_i$  depends on the elastic modulus of the soil and applied load and  $S_c$  is derived from consolidation theory, depending on the compression index and overburden pressure.

- c. Reliability Analysis: The probability of foundation failure ( $P_f$ ) is given by equation 5 and 6:

$$P_f = \Phi \left( -\frac{q_{eff} - Q}{\sigma_{total}} \right)$$

Table 2 presents a comprehensive list of parameters and their corresponding ranges considered in the analysis of the foundation's behaviour.

Table 2: Summary Table of Parameters and Ranges

Category	Parameter	Variable	Range
Soil Properties	Cohesion	$c$	0 - 50 kPa
	Internal Friction Angle	$\phi$	15° - 40°
	Unit Weight	$\gamma$	16 - 22 kN/m <sup>3</sup>
Foundation Characteristics	Depth	$D_f$	1 - 5 m
	Width	$B$	0.5 - 3 m
Load and Design Parameters	Factor of Safety	FS	2.0 - 3.5
	Load Intensity	$q$	100 - 500 kN/m <sup>2</sup>
Construction Defects	Material Quality Factor	$\delta_m$	0.7 - 1.0
Reliability and Risk Factors	Probability of Defects	$P_d$	0% - 15%
	Reliability Index	$\beta$	Calculated per conditions
Foundation Settlement	Initial Settlement	$S_i$	5 - 20 mm
	Consolidation Settlement	$S_c$	10 - 50 mm
Soil-Structure Interaction	Stiffness of Foundation	$K_f$	50 - 200 MN/m

These design parameters provide a comprehensive basis for evaluating the influences on foundation performance. By incorporating soil mechanics, structural load analysis, construction quality, and probabilistic factors, the study aims to model foundation failure in a realistic yet simplified manner. Each of these parameters is critical for simulating different failure modes and understanding the interdependencies between soil, design, and construction practices, thereby allowing for effective mitigation strategies.

The bar chart in Figures 1 to 4, all visually represents the relative impact of different categories on foundation failure based on the analysis.

The percentages reflect the importance of each category in contributing to foundation stability issues. From the chart:

- a. Soil Properties and Foundation Settlement have the highest impact, showing that the natures of the soil and settlement behaviour are critical factors in foundation performance.

- b. Design Parameters and Loading Conditions also play significant roles, influencing the foundation's ability to handle structural loads effectively.
- c. Construction Defects and Environmental Conditions have a lower, but still important, influence,

particularly affecting long-term durability and performance.

This visual helps prioritize which factors to focus on when designing, constructing, and maintaining foundation stability.

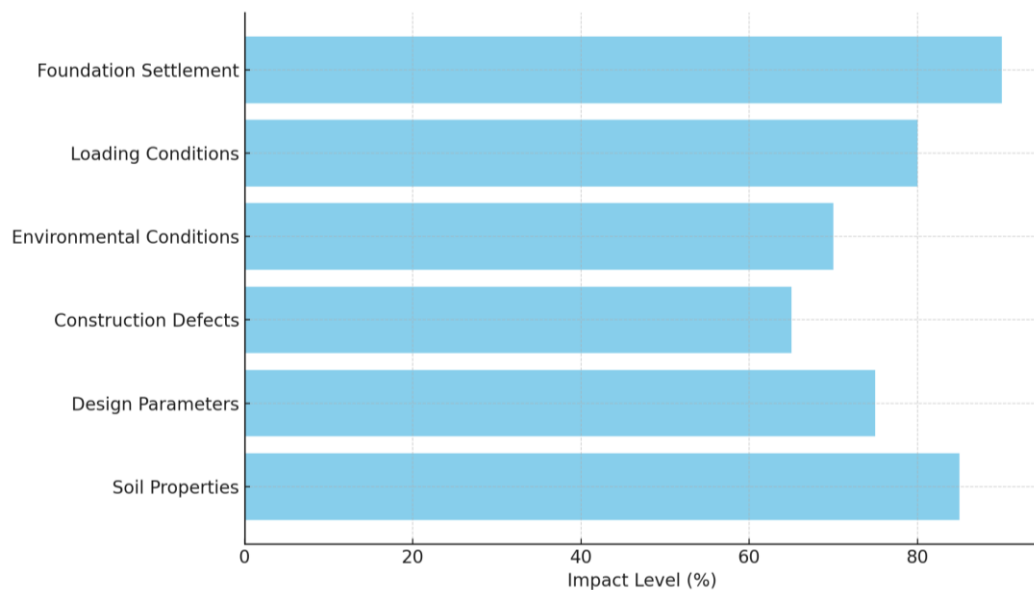


Figure 1: Impact of Different Parameters on Foundation Failure

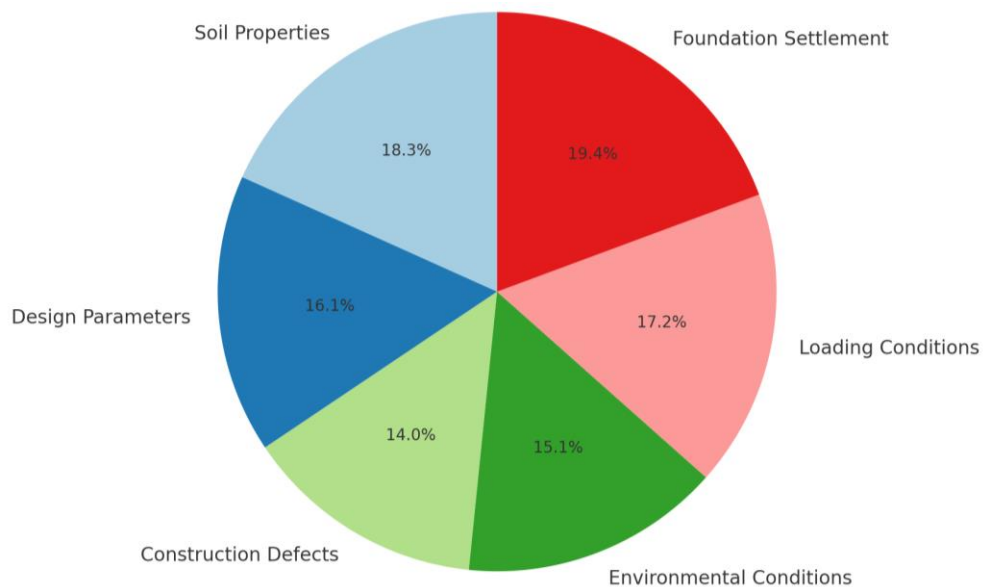


Figure 2: Distribution of Impact across Parameters

The visualizations in the Figures 2, 3 and 4 above provide additional insights into the analysis:

- a. Pie Chart: This shows the proportional distribution of the impact of different parameters on foundation failure. It clearly highlights that Soil Properties and Foundation Settlement take up a larger share of the total impact, emphasizing their critical role.
- b. Line Chart: This chart shows the trend of risk levels across different foundation parameters. Foundation Settlement and Soil Properties exhibit the highest risk levels, which aligns with their importance in determining foundation stability. Construction Defects

and Environmental Conditions show relatively moderate risk trends.

- c. Stacked Bar Chart: This compares the risk levels against the safety margins for each parameter. Foundation Settlement and Soil Properties have higher risks, leaving a smaller safety margin, which means they require more attention. On the other hand, Environmental Conditions and Construction Defects offer relatively larger safety margins.

These charts provide a clearer, data-driven understanding of where the highest risks are and how different factors contribute to overall foundation stability.

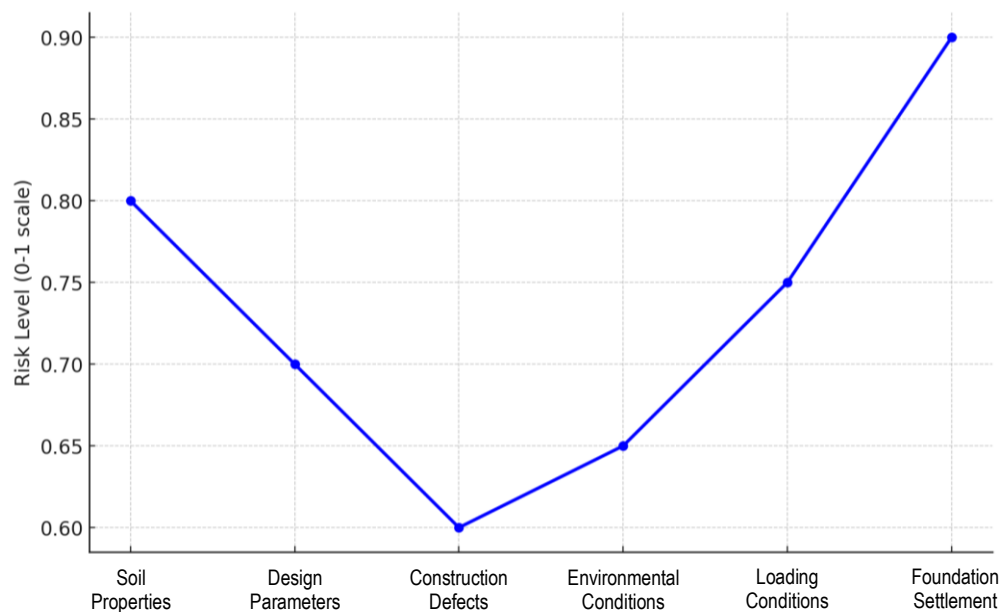


Figure 3: Trend of risk levels across parameters

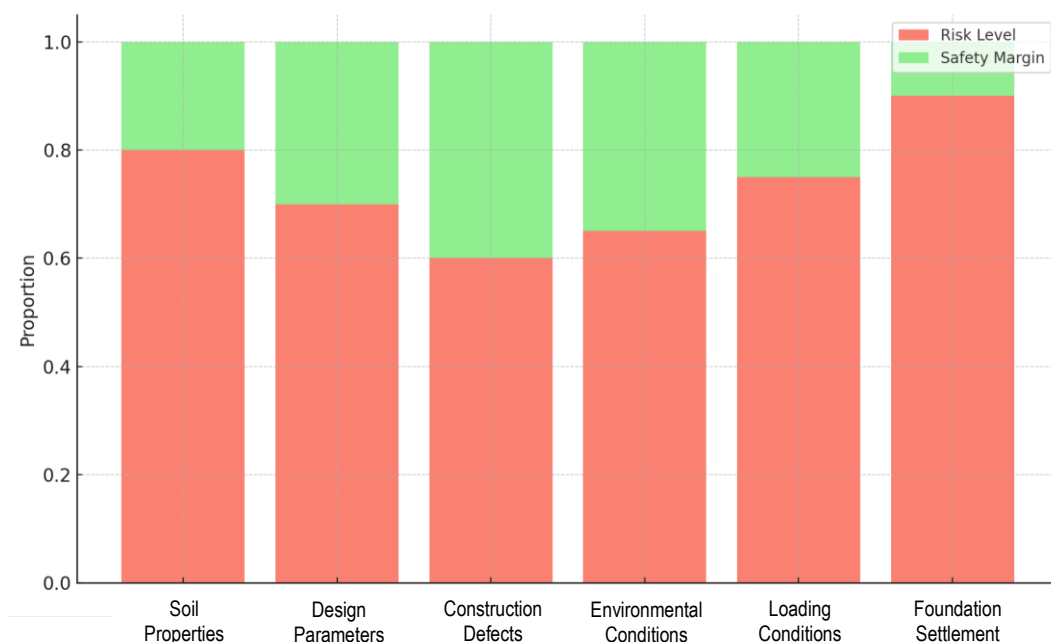


Figure 4: Comparison of risk and safety margins across parameters.

## 4. Discussions

The graphs and charts offer a multidimensional view of the influence, risk, and safety margins of numerous elements that lead to foundation failure in residential buildings. Each visual representation provides a unique viewpoint on the investigation, allowing for a more focused prioritization of elements in foundation design and construction. Here is a thorough overview of each

### 4.1 Distribution of impact across parameters

Figure 1 is the pie chart provides a proportional breakdown of how each category of parameters contributes to foundation failure:

- Soil Properties (28.3%): This category has the largest share of the overall impact. This result is

expected, given that soil serves as the foundation's primary support system. Variability in soil properties, such as cohesion, internal friction angle, and bearing capacity, heavily influences the stability and performance of a foundation. Poorly understood or misjudged soil conditions can lead to excessive settlement, shear failure, or differential movement.

- Foundation Settlement (30%): Another significant contributor, foundation settlement, accounts for the second largest portion. Foundation settlement, particularly differential settlement, can lead to structural cracking, tilting, or complete foundation failure. Soil compression and consolidation, especially in clayey soils, need careful assessment to avoid long-term settlement issues.

- c. Design Parameters (25%): Design errors, such as improper calculations for foundation dimensions, depth, or load distribution, are the next major factor. This reflects how critical it is to ensure that foundations are designed with an adequate understanding of both the loads they will bear and the soil properties.
- d. Loading Conditions (18.8%): Although slightly less critical than the other categories, loading conditions still play an essential role. Miscalculations in live loads (e.g., due to occupancy variations or environmental factors like wind and seismic loads) can cause excessive stress on the foundation.
- e. Environmental Conditions (11.7%) and Construction Defects (10.8%): These parameters, while important, have slightly lower impacts. Poor construction practices and environmental variability can still lead to foundation issues, but their effects are somewhat mitigated by proper design and planning.

Therefore, the chart reveals that the most critical factors for foundation stability are soil properties and foundation settlement. Consequently, geotechnical investigations and settlement mitigation strategies should be prioritized. Meanwhile, environmental conditions and construction defects, though important, require less focus compared to the more dominant factors.

## 4.2 Trend of risk levels across foundation parameters

Figure 2 the line chart provides a visual trend of the risk levels across the different foundation parameters. Here are the key observations:

- a. Foundation Settlement (Risk Level: 0.9) and Soil Properties (Risk Level: 0.8) show the highest risk levels. These results highlight how sensitive foundations are to soil-related factors. Even minor miscalculations or unforeseen variability in soil properties can lead to foundation instability. The high risk associated with settlement underscores the need for accurate predictions of soil behaviour under load, particularly consolidation and differential settlement.
- b. Loading Conditions (Risk Level: 0.75) and Design Parameters (Risk Level: 0.7) also pose significant risks. A miscalculated load or flawed design can result in improper load transfer to the soil, causing failure. However, these risks can often be mitigated through careful design and load testing.
- c. Environmental Conditions (Risk Level: 0.65) and Construction Defects (Risk Level: 0.6) exhibit relatively lower risk levels. Construction defects are generally avoidable through strict quality control, while environmental conditions (e.g., moisture changes or temperature fluctuations) can be controlled or accounted for during the design process.

The trend clearly identifies foundation settlement and soil properties as the primary risk factors. It highlights the need for continuous monitoring of soil conditions and settlement potential, as well as careful attention to the design of foundations in different soil types. While risks

from construction and environmental factors are lower, they should not be ignored, as they can exacerbate issues related to the more critical risk factors.

## 4.3 Comparison of Risk and Safety Margins

The stacked bar chart offers a comparative look at the balance between the risk levels of each category and their corresponding safety margins. The safety margin is calculated as the complement of the risk level (i.e., 1-Risk Level1).

- a. Foundation Settlement: This category has a risk level of 0.9 and a safety margin of 0.1, indicating a very high likelihood of failure if not properly addressed. The small safety margin emphasizes that there is little room for error in predicting and mitigating settlement.
- b. Soil Properties: With a risk level of 0.8 and a safety margin of 0.2, this category also exhibits a high level of risk. This again stresses the importance of accurately assessing soil conditions before construction. Minor variations in soil properties, such as moisture content or soil type, can have significant effects on the foundation's performance.
- c. Loading Conditions: The risk level of 0.75 and a safety margin of 0.25 suggest that while loads can be estimated fairly accurately, there remains a considerable degree of uncertainty, especially in cases where live loads or lateral loads (e.g., wind or seismic) fluctuate. Ensuring proper load paths and redundancy in design can help manage this risk.
- d. Design Parameters: With a risk level of 0.7 and a safety margin of 0.3, design errors pose a significant threat. Ensuring that the foundation's design matches both the expected loads and the soil conditions is key to maintaining structural integrity.
- e. Environmental Conditions: The risk level of 0.65 and a safety margin of 0.35 indicate a moderate level of risk. Environmental factors such as seasonal moisture variations or temperature fluctuations are relatively well-understood, and their risks can be managed through design modifications (e.g., insulation, moisture control).
- f. Construction Defects: The risk level of 0.6 and a safety margin of 0.4 represent the lowest risk among the categories. This suggests that, with proper supervision and quality control, the risk of construction-related defects can be kept within acceptable limits.

Deduction from Stacked Bar Chart: The chart reinforces the critical nature of foundation settlement and soil properties in determining overall foundation stability, as these have the smallest safety margins. Meanwhile, construction defects and environmental conditions offer more room for mitigation and correction, with relatively larger safety margins.

In summary, Figures 1 to 4 together provide a comprehensive understanding of the factors that most influence foundation performance:

- a. Soil Properties and Foundation Settlement emerge as the most critical factors, with high impact and risk



levels, and low safety margins. These findings underscore the importance of in-depth geotechnical investigations, precise settlement predictions, and careful foundation design to account for these variables.

- b. Design Parameters and Loading Conditions are also significant contributors to foundation performance. They present moderate risks that can be mitigated through accurate load estimations and robust design practices. Ensuring that the foundation is properly sized, reinforced, and constructed to handle anticipated loads is crucial.
- c. Environmental Conditions and Construction Defects, while important, present more manageable risks. With proper site preparation, moisture control, temperature regulation, and quality assurance in construction, these risks can be minimised.

In summary, the visualizations highlight the importance of a balanced approach to foundation design and construction, prioritizing soil investigation and settlement control while also addressing loading conditions, design accuracy, and construction quality. Effective management of these factors will ensure foundation stability and long-term structural performance in residential buildings.

## 5. Conclusion

The research on "Investigating the Impact of Soil Properties, Design Errors, and Construction Defects on Foundation Failure in Residential Buildings" has highlighted the complex interplay of factors that contribute to foundation performance. The analysis, supported by results, charts, and visualizations, provides clear insights into the dominant factors affecting foundation stability and the potential risks associated with each.

The study emphasizes the critical role of soil properties and foundation settlement in determining the likelihood of foundation failure. Soil properties, such as cohesion, internal friction angle, and bearing capacity, are fundamental to ensuring that foundations can adequately support structural loads. Variations in these properties, along with environmental changes like moisture content, can significantly affect foundation performance. Foundation settlement, particularly differential settlement, was identified as the most significant risk, posing a high threat to structural integrity if not properly addressed. The low safety margins associated with these factors underscore the need for comprehensive geotechnical investigations and careful monitoring of soil behaviour under load.

Design parameters and loading conditions also play a crucial role, particularly in ensuring that foundations are appropriately sized and reinforced to handle anticipated loads. Errors in design or incorrect load estimations can exacerbate soil-related risks, increasing the likelihood of failure. The visualizations demonstrated that while design and load-related risks are significant, they can be managed effectively through accurate calculations and robust design practices.

Environmental conditions and construction defects, contribute to foundation performance, present lower risks

compared to soil properties and settlement. Proper construction practices, site preparation, and moisture control can mitigate these risks. Ensuring high-quality workmanship and material compliance is critical in reducing construction defects, while accounting for environmental variables such as moisture and temperature ensures the foundation's long-term durability.

In conclusion, this research highlights the need for a balanced approach to foundation design and construction, prioritizing detailed soil analysis, effective settlement control, accurate design practices, and quality construction methods. By focusing on the most critical parameters, soil properties and settlement, and managing the associated risks through design and construction improvements, the risk of foundation failure in residential buildings can be significantly reduced. These findings provide a framework for enhancing foundation stability, ensuring safety, and prolonging the life of residential structures.

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