From Empirical Construction to Intelligent Automation: State of the Art in Foundation Design for Single-Family Housing

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ABSTRACT

Single-family housing represents a critical sector in urban development, where the structural safety of foundations is essential to ensure habitability and the service life of buildings. This article presents a narrative review of the state of the art focused on the evolution of strip footing design methodologies, transitioning from empirical methods to advanced computational tools. The limitations of traditional construction practices and the accessibility barriers of current commercial software are analyzed. Likewise, the emerging potential of artificial intelligence and automated calculation is examined as solutions to optimize structural and economic efficiency. The findings suggest the existence of a technological gap in the social housing sector, which can be mitigated through the development of customized, low-cost tools that integrate machine learning techniques.

Keywords: Foundation Design Automation, Artificial Intelligence in Civil Engineering, Structural Safety in Social Housing

INTRODUCTION

General Context

Housing is a fundamental pillar for social development and stability, representing one of the greatest assets for families in urban and peri-urban contexts. In Mexico, the growth of cities has driven the demand for single-family housing, where the choice of the foundation system is decisive for structural safety and building durability. Among the predominant construction systems, strip footings stand out as one of the most widely used solutions due to their constructive simplicity, ease of execution, and, in theory, relatively low cost. However, the apparent simplicity of this type of foundation contrasts with the complexity of soil-structure interaction, which requires rigorous technical analysis that is often overlooked in common practice.

Problem Statement

Despite the structural relevance of foundations, in the single-family housing sector—especially in social housing or self-construction—the design of strip footings faces a problematic dichotomy. On one hand, a significant percentage of projects are developed under empirical practices, based on the builder’s experience or “rules of thumb” that do not consider the specific geotechnical variables of the site nor the actual loads of the building. This often results in undersized foundations, compromising structural safety against differential settlements or soil failures, or oversized foundations, unnecessarily increasing costs in a context where resource optimization is critical.

On the other hand, although there have been significant advances in structural calculation software, the commercial tools available (such as CYPECAD, ETABS, or Robot Structural Analysis) present important entry barriers for their widespread adoption in small-scale projects. These barriers include high license costs, the need for specialized hardware, and a steep learning curve. Consequently, the structural design process remains highly dependent on manual execution and the subjectivity of the designer, introducing variability and potential risk of

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human error. The lack of accessible, automated tools adapted to local regulations to evaluate the structural efficiency of foundations represents an urgent technological gap to address.

Justification of the Review

Given this scenario, it is imperative to understand the evolution of design methodologies to identify where the limitations of current approaches lie and where future solutions should be directed. The analysis of existing literature shows how civil engineering has transitioned from manual analytical methods to computational modeling, and how this transition has left behind sectors with lower economic capacity. Conducting a state-of-the-art review not only serves to diagnose technological stagnation in foundation design for single-family housing but also lays the groundwork to justify the integration of emerging technologies. In this context, automated calculation and artificial intelligence (AI) emerge as viable alternatives to democratize access to safe and efficient structural designs.

Objective of the Article

The objective of this article is to analyze the state of the art in foundation design for single-family housing, examining the evolution from empirical and manual methodologies to the use of specialized software. Through this narrative review, the aim is to identify gaps in accessibility and efficiency of current tools, supporting the need to develop automated systems based on artificial intelligence that optimize the design of strip footings, aligned with sustainability and structural safety principles required by the current housing sector.

METHODOLOGY

This article is developed under a narrative literature review approach (state of the art), which allows synthesizing the historical and technological evolution of structural design methodologies. This approach is the most suitable for identifying trends, knowledge gaps, and the theoretical context necessary to understand the current problem of foundations in single-family housing.

Search Strategy

For information collection, academic databases and recognized scientific repositories in engineering and architecture were consulted, such as Google Scholar, Redalyc, Scopus, Dialnet, and ScienceDirect. The search was limited to articles published in indexed journals, postgraduate theses, and book chapters, prioritizing documents published between 2012 and 2025, to ensure the relevance of information with current regulations and technologies.

The search equation was built using Boolean operators combining the following descriptors or keywords, derived from the base research project: “Structural design,” “Shallow foundations,” “Strip footings,” “Single-family housing,” “Automated structural calculation,” “Engineering software” (CYPECAD, ETABS), “Structural efficiency,” and “Civil engineering.”

Selection Criteria

The selection of documents for this review was carried out through a filtering process based on inclusion and exclusion criteria defined a priori, with the objective of ensuring the relevance of the information to the study’s aim:

Inclusion criteria:

- Theoretical and experimental studies addressing the design, calculation, or analysis of shallow foundations, specifically strip footings.
- Research comparing traditional design methodologies with the use of specialized software.

- Articles discussing the challenges of single-family housing, social housing, or self-construction in urban contexts.
- Publications in Spanish and English.

Exclusion criteria:

- Documents focused exclusively on deep foundations (piles, drilled shafts) or on high-rise buildings whose design mechanics are not comparable to single-family housing.
- Opinion articles without technical or scientific support.
- Documents that do not present a clear methodology of analysis or bibliographic review.

Table 1 summarizes the inclusion and exclusion criteria applied in the selection of documents for this review.

Table 1. Inclusion and Exclusion Criteria for Literature Selection

Criteria Type	Description
Inclusion Criteria	- Theoretical and experimental studies addressing the design, calculation, or analysis of shallow foundations, specifically strip footings. - Research comparing traditional design methodologies with the use of specialized software. - Articles discussing single-family housing, social housing, or self-construction in urban contexts. - Publications in Spanish and English.
Exclusion Criteria	- Documents focused exclusively on deep foundations (piles, drilled shafts) or high-rise buildings whose design mechanics are not comparable to single-family housing. - Opinion articles without technical or scientific support. - Documents lacking a clear methodology of analysis or bibliographic review.

Analysis Procedure

Once the relevant documents were identified—including previous references collected in the research protocol—a critical reading of the abstracts was conducted, followed by a full-text review. The information was organized and synthesized into an analysis matrix that allowed categorization of the findings into three main thematic axes for the development of the article:

- **Traditional and empirical methods:** Identification of manual practices and associated risks.
- **Current computational tools:** Analysis of advantages, disadvantages, and access barriers (cost/licenses).
- **Need for optimization:** Identification of the technological gap that justifies new solutions.

Evolution of Design Methodologies: State of the Art

Structural design of foundations has undergone a significant transformation in recent decades, moving from manual and approximate procedures to high-precision computational models. This evolution responds to the increasing complexity of seismic-resistant regulations and the need to optimize resources in construction. Below, the three predominant stages in the context of single-family housing are analyzed.

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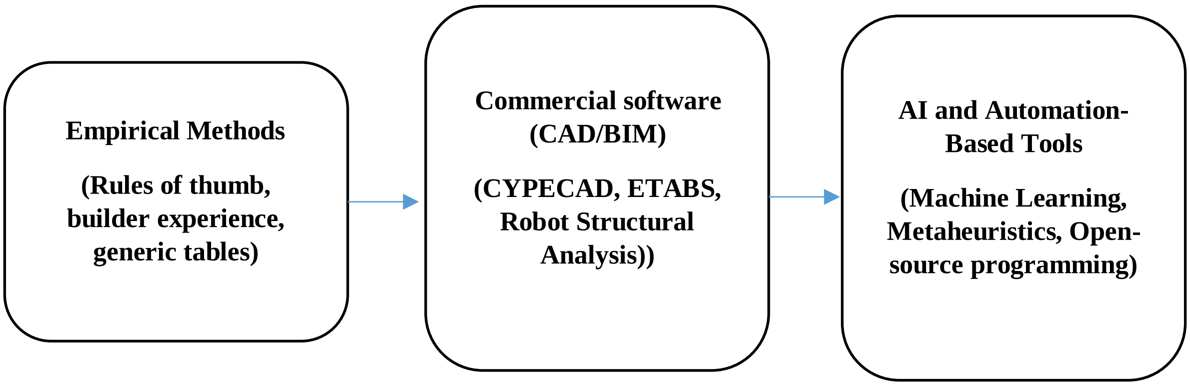

Figure 1. Evolution of foundation design methodologies for single-family housing. The diagram illustrates the transition from empirical methods (rules of thumb, builder experience, generic tables) to commercial software (CYPECAD, ETABS, Robot Structural Analysis), and finally to AI and automation-based tools (machine learning, metaheuristics, open-source programming).

Traditional and Empirical Methods

Historically, the design of strip footings in single-family housing, especially in self-construction and social housing sectors, has relied on empirical methods. These practices are based on the builder's experience, the use of "rules of thumb," or the application of generic tables that do not consider the variability of soil properties.

Although these methods offer an initial advantage in terms of speed and low design cost, they present critical deficiencies in structural safety. The absence of rigorous analysis of bearing capacity and differential settlements often leads to undersized foundations, prone to failure during seismic events or changes in soil conditions. The persistence of empiricism is a documented problem in various contexts, where the lack of technical supervision results in severe pathologies in buildings. Recent studies highlight that geotechnical uncertainty, combined with the lack of precise data, makes empirical methods unsafe to guarantee the service life of housing.

The Era of Commercial Software (CAD/BIM) and Structural Analysis

With the rise of technology, civil engineering adopted specialized software tools that allowed modeling structural behavior with greater accuracy. Current literature shows widespread use of platforms such as CYPECAD, ETABS, and Robot Structural Analysis for building analysis.

Authors such as Huaraca Ramos (2018) have conducted comparative analyses using Robot Structural Analysis and ETABS to evaluate the behavior of self-built housing, demonstrating that the use of these tools is essential to detect structural pathologies ignored by empirical methods. Likewise, De Alba Quintero et al. explored architectural modeling through software such as Cype Architecture, integrating geometric design with structural calculation.

In the geotechnical and seismic-resistant field, software precision becomes vital. Recent studies, such as Salcedo Quispe (2025), emphasize the importance of using advanced software for the analysis of clay soils and the design of connected foundation beams. Similarly, Vilema Condo (2014) and Ore Cardenas et al. (2022) used CYPECAD to ensure safety against seismic loads and to evaluate behavior in saturated soils, respectively.

However, the adoption of these technologies is not without challenges. Sacks et al. (2018) point out that, although Building Information Modeling (BIM) and structural software have improved coordination, problems of interoperability and the need for highly skilled labor persist.

In addition, Ahmed et al. (2022) emphasize in their studies on single-family housing that, although software increases precision, the learning curve and license costs remain significant barriers for widespread implementation in small-scale projects. This confirms that current technology is efficient but not necessarily accessible or democratic.

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Towards Optimization and Artificial Intelligence

Faced with the limitations of cost and accessibility of commercial software, recent scientific literature points to a new era based on automated calculation and artificial intelligence (AI). The integration of machine learning algorithms and evolutionary computation allows optimizing structural design, seeking not only safety but also economic efficiency—an essential aspect in social housing.

In this context, Shahin (2015) and Zhang et al. (2021) conducted comprehensive reviews on the application of machine learning techniques in geotechnical engineering, concluding that these tools are superior to empirical methods for predicting soil bearing capacity and foundation behavior. Specifically, Sadrossadat et al. (2020) demonstrated that artificial neural networks can predict the load capacity of strip and isolated footings with high precision, minimizing the need for costly field tests and reducing the margin of human error.

Likewise, structural optimization through metaheuristics has gained ground. Kaveh and Javadi (2022) proposed advanced algorithms for the design of shallow foundations, achieving significant reductions in concrete and steel volume, which directly translates into cost savings. This line of research supports the premise of the present project: automation is not only a matter of convenience but a technical tool to maximize structural efficiency.

Therefore, the trend observed in the state of the art suggests that the future of foundation design for single-family housing lies in the development of customized tools, based on open-source code (such as Python) and enhanced by AI. These solutions would overcome the economic barriers of commercial software, offering professionals and students the ability to perform optimal, safe, and regulation-compliant designs without incurring high licensing costs, thus filling the gap identified in current methods.

Table 2 summarizes the comparative characteristics of empirical methods, commercial software, and AI-based tools in foundation design.

Table 2. Comparative Analysis of Foundation Design Methodologies

Aspect	**Empirical Methods**	**Commercial Software (CAD/BIM)**	**AI and Automation-Based Tools**
Cost	Low initial cost; no licenses	High license fees and hardware requirements	Low-cost if open-source; scalable solutions
Accessibility	Widely used in self-construction	Limited to trained professionals and firms	Potentially accessible to students and small projects
Precision	Low; based on rules of thumb	High; detailed structural and geotechnical modeling	Very high; predictive models and optimization algorithms
Risks	Structural failures due to under/oversizing	Barriers of adoption; steep learning curve	Dependence on data quality and algorithm calibration
Examples	Local builder practices, generic tables	CYPECAD, ETABS, Robot Structural Analysis	Neural networks, metaheuristics, Python-based open-source tools

DISCUSSION

The findings derived from the literature review reveal a significant disparity between technological advances in structural engineering and their practical application in single-family social housing. The critical analysis of these methodologies suggests that the central problem does not lie in the lack of technical knowledge, but rather in the inefficiency of technology transfer mechanisms to the housing construction sector. The discussion is structured around three fundamental axes: the paradox of accessibility, the potential of structural efficiency through algorithms, and the need for contextualized automation.

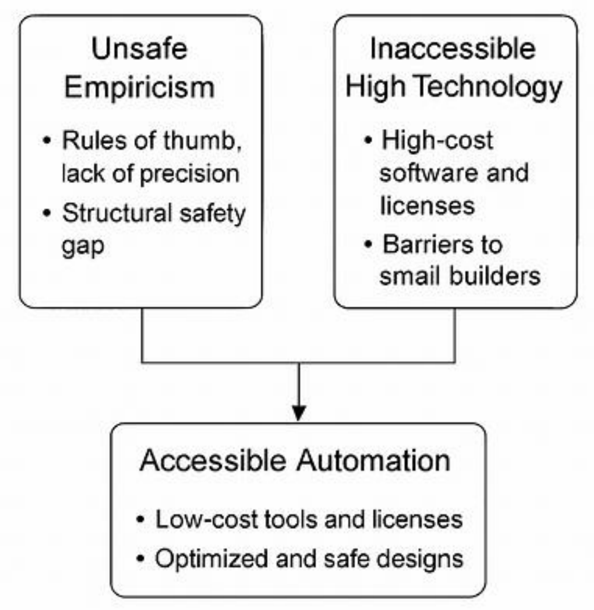

Figure 2. Conceptual scheme of the technological gap in foundation design. The diagram illustrates the contrast between unsafe empiricism (rules of thumb, lack of precision, structural safety gap) and inaccessible high technology (high-cost software, barriers to small builders), proposing accessible automation (low-cost tools, optimized and safe designs) as a bridging solution.

The examination of available tools reveals a concerning contradiction in the current market. On one hand, there is high-precision software capable of modeling complex behaviors with great accuracy, ensuring regulatory compliance. On the other hand, these platforms present entry barriers—economic and related to the learning curve—that make them unattainable for small builders and social housing projects.

This situation generates a "structural safety gap": those with resources have access to optimized and safe designs, while lower-income sectors are forced to rely on empirical or simplified practices, exposing themselves to failure risks. The literature consulted indicates that the problem is not the lack of technology per se, but its democratization. Current commercial software is designed for large corporate projects and complex buildings, leaving a void in the single-family housing market. In this context, the proposal to develop low-cost automated systems is not merely a technical improvement, but a necessary measure to balance access to structural safety in society.

Beyond accessibility, comparative analysis shows that traditional manual calculation methodologies are reaching a limit of optimization. Manual designs tend to be excessively conservative (oversizing elements to compensate for uncertainty) or, conversely, risky due to lack of knowledge of real geotechnical variables. Both scenarios negatively impact housing economics: the former due to high material costs and the latter due to latent repair or collapse costs.

In contrast, the integration of optimization algorithms and machine learning represents a qualitative leap. The reviewed studies consistently demonstrate that advanced computational techniques, such as metaheuristics and neural networks, are capable of processing a greater number of geotechnical and structural variables to find footing configurations that use exactly the necessary material—no more, no less. This suggests that adopting these tools not only improves safety but also has the direct potential to reduce foundation costs, making quality housing viable in resource-limited contexts.

Finally, reflection on existing tools points to the need for solutions that are not only powerful but also relevant. The vast majority of available structural software follows a "black box" logic or requires expert interpretation of results, distancing the average user from the design process. In addition, these programs are often generic, designed for international standards that do not always align with specific regulations or local construction practices.

Therefore, the natural evolution of structural design should aim toward contextualized automation. This implies the development of customized tools that integrate the power of artificial intelligence with accessible interfaces and algorithms calibrated to local regulations and conditions. The approach based on open programming environments and personalized scripts emerges as the most coherent response to break dependence on costly licenses. This strategy allows the creation of "tailor-made" tools that empower both engineers and students, ensuring that the transition to digital design is inclusive and effective for the reality of single-family housing.

In conclusion, the analysis of methodological evolution suggests that the sector is stuck between unsafe empiricism and inaccessible high technology. The only viable path to move toward a sustainable and safe housing model is the implementation of intermediate systems: automated, intelligent, and accessible tools that optimize resources and bridge the current technological gap.

CONCLUSIONS

The state-of-the-art review presented in this article allows us to conclude that the structural design of foundations for single-family housing is currently at a turning point. It has been shown that empiricism, although accessible, is unsustainable under modern regulations and represents a latent risk for safety. At the same time, commercial software, while technologically superior, presents economic and technical barriers that restrict it to a niche of users, excluding the vast majority of social housing and self-construction projects.

The literature consistently demonstrates that artificial intelligence tools and optimization algorithms are not merely a technological trend, but a proven technical resource to improve structural efficiency and reduce material costs. Therefore, the integration of these technologies into open programming environments is proposed as a viable solution to close the accessibility gap.

The future of foundation design lies in the democratization of technology through automation, thus ensuring safer, more efficient housing aligned with sustainable development goals.

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