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Geotechnical stability and optimization of foundation systems in landslide-prone urban areas using coupled numerical models and IoT sensors

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The expansion of urban areas in geotechnically complex regions has led to the imperative for more precise assessments of ground stability and the optimization of foundation design. To this end, a methodological framework was developed that integrates numerical modeling using the coupled Finite Element Method (MEF), real-time monitoring with Internet of Things (IoT) technologies, and stability analysis using the Shear Strength Reduction Method (SRM). This methodology was implemented in five urban sites with contrasting geotechnical conditions, characterized by different types of surface soil and risk levels defined by the probability of increased pore pressure (υω). The advent of IoT sensors has enabled the calibration of critical parameters, including permeability (k), and the detection of critical events that were previously unanticipated, such as earthquake-induced pressure peaks or extreme water variability. The findings indicated that sites A and E exhibited safety factor reductions exceeding 30% under maximum saturation, with critical values falling below 1.05, suggesting the imminent occurrence of a failure condition. In response, the pile length was optimized to achieve an $FS \geq 1.30$, implying increases of 42.00% and 48.33%, respectively. The other sites maintained critical FS above 1.40, without requiring geometric adjustments, allowing the design to focus on compliance with the Limit of Service State (ELS). The efficacy of coupled modeling in simulating dynamic scenarios and validating adaptive structural solutions was demonstrated, while the indispensability of IoT monitoring in adjusting the design based on actual ground conditions was confirmed. The proposed methodological framework is a comprehensive strategy for assessing geotechnical stability in at-risk urban areas. It involves the optimization of deep foundations and the reduction of uncertainty through continuous observation. This approach promotes the development of safer, more efficient, and resilient designs in critical conditions.

Keywords: Geotechnical stability, Deep foundations, Pore pressure, Numerical modeling, IoT monitoring

1. Introduction

The contemporary urban landscape has undergone significant transformations, which can be attributed, in large part, to global population growth. As cities undergo accelerated expansion, they are compelled to extend their conventional boundaries, occupying territories that were historically deemed unsuitable for urban development due to their unfavorable geotechnical conditions. This expansion has led to the urbanization of areas characterized by steep slopes, colluvial soils, anthropic fills, and other low-quality geological formations. This has resulted in a significant increase in the exposure of infrastructures and the population to geotechnical risks. In the context of Latin America, where urban planning is frequently encumbered by the pressures of informal growth, the sustainability of development is closely associated with the capacity to effectively manage the risks inherent to these fragile environments (Ludeña, 2024).

In this framework, the geotechnical stability of the terrain assumes a primary role, as it is a critical factor in ensuring both structural functionality and public safety, as well as the resilience of essential infrastructures. Urban planning and foundation design have historically faced the challenge of adapting to complex and heterogeneous subsurface conditions. The structural integrity of edifices, ranging from single-family residences to skyscrapers, is contingent upon a meticulous characterization of the subsoil. This characterization must encompass not only conventional geotechnical parameters but also the dynamic and transient conditions that impinge upon the stability of the terrain (Quispe & Angulo, 2021; Cutipa, Terrazas, & Ramírez, 2019; Hernández Aguilar & Vega López, 2023).

In regions susceptible to landslides, soil characterization must extend beyond the mere assessment of static bearing capacity. It is imperative to incorporate the analysis of dynamic threats, such as gravitational processes, which can be amplified by external factors, including extreme rainfall, changes in land use, and inappropriate anthropogenic interventions (Manturano-Chipana, Campos-Vásquez, & Rabanal-Chávez, 2025; González & Daniel, 2019). Slope landslides are a particularly salient problem in contemporary civil engineering, given their complexity and significant socioeconomic impact. These landslides emerge from the interplay between adverse geological and geotechnical conditions, compounded by human activities that disrupt the natural equilibrium of the terrain. Examples of such activities include slope cuts or increases in structural load.

The phenomenon of climate change has been demonstrated to exacerbate the risks by intensifying the frequency and severity of extreme hydrometeorological events. These events have been shown to modify the subsurface flow regime and increase water infiltration into the soil. These processes have the effect of altering pore pressure, thereby reducing the shear resistance of the soil. This, in turn, compromises the stability of slopes and foundations. Conventionally, the assessment of slope stability has been predicated on limit equilibrium analysis (ELA), a methodology that, while instrumental in estimating the safety factor (FS), is encumbered by substantial limitations. These limitations stem from the inability of ELA to adequately account for the nonlinear response of the soil, the true distribution of stresses, and the hydromechanical coupling.

The mechanics of unsaturated soils have demonstrated that variations in pore pressure directly affect the effective stress and, consequently, the shear strength of the soil, in accordance with the Terzaghi principle. In transient conditions, the flow of water modifies the effective stress state and stiffness of the massif. This modification cannot be accurately captured by traditional methods, which tend to generate estimates of FS that may be excessively conservative or, in the worst case, not representative of critical failure conditions.

In this context, the design of structural elements, such as foundation slabs, necessitates the use of more sophisticated models that coherently integrate the soil-structure interaction. Consequently, contemporary geotechnical engineering has embraced coupled numerical models that facilitate the concurrent resolution of equations governing mechanical equilibrium and water flow. These models employ methodologies such as the Finite Element Method (FEM) or the Finite Difference Method (FDM), underpinned by Biot's theory of poroelasticity (Achá et al., 2024). The selection of an appropriate constitutive law, such as the Modified Mohr-Coulomb model or Modified Endochrony (CEM), is essential to capture phenomena such as dilation and the dependence of shear stress on the trajectory of stresses, fundamental aspects in the dynamic and seismic response of the soil-foundation system (Morales Zúñiga et al., 2025).

These models facilitate the evaluation of the static bearing capacity and stability against settlements. Additionally, they enable a comprehensive understanding of soil deformation and failure under variable load and saturation conditions, a crucial aspect for the design of deep foundations, such as piles and piles (Olivera & Villarreal, 2023; Mendoza, 2021). However, the precision of numerical predictions is constrained by the inherent variability in geotechnical parameters, such as cohesion (C̓), friction angle (Ǿ), and permeability (k). These parameters, when determined through spot tests, do not always accurately reflect the actual conditions of the soil massif.

Confronted with this limitation, the convergence of these technologies with the emerging technologies of the Fourth Industrial Revolution has precipitated a paradigm shift. The Internet of Things (IoT) has been employed in geotechnical monitoring, facilitating the continuous and real-time collection of field data. This transformation of a system of static parameters into a dynamic observation environment is a significant development. The implementation of low-cost, high-performance sensor networks, including vibrating wire piezometers, in-place inclinometers (IPI), extensometers, and GNSS sensors, facilitates high-frequency data capture, which is imperative for slope stability assessment (González & Daniel, 2019).

Beyond their role as early warning systems, these devices facilitate the reverse calibration of numerical models through the integration of observed data on displacement, deformation, and pore pressure. This iterative process of parameter tuning and optimization results in the development of the Geotechnical Digital Twin, which is a virtual and dynamic replica of the soil mass that evolves based on real environmental and operational conditions. This instrument signifies a substantial enhancement in the assessment of stability, as it facilitates not only the determination of the condition of the terrain, but also the prediction of its future behavior with a noticeably diminished margin of uncertainty.

The primary objective of a comprehensive stability assessment is to ensure the structural integrity and economic viability of civil engineering projects. In urban areas with high susceptibility to landslides, foundation solutions often require deep systems, such as piles or micropiles, to transfer structural loads to more stable strata (Camacho Angarita & Gutiérrez Aguilera, 2023). However, the conventional approach, predicated on elevated safety factors to mitigate uncertainty, frequently results in oversizing and superfluous expenditures (Pérez, 2020). Consequently, a thorough and heuristic optimization of foundation geometries is imperative, taking into account variables such as the depth and diameter of the structural elements (Marco, Perez, & Gabarda, 2021).

The methodology proposed in this study addresses this optimization through the use of coupled numerical models, previously calibrated with data obtained through IoT technologies. This integration enables the simulation of the behavior of the ground with high precision against different types of foundations, ranging from flexible or rigid surface solutions to combined systems such as plate-piles (Pérez, 2020; Olivera & Villarreal, 2023; Camac et al., 2023). The implementation of the Shear Strength Reduction Method (SRM), incorporated within the MEF framework, on the calibrated model facilitates the determination of the actual FS of the slope, considering both the presence and absence of the proposed foundation. This approach enables a comprehensive evaluation of the structural implications on the system's overall stability.

Consequently, the design is optimized under dual criteria: The primary objective is to guarantee that the outcome exceeds the target design threshold, even in critical saturation and load scenarios. A secondary objective is to minimize the length, diameter, or number of foundation elements. This approach enables substantial savings in materials and construction time, a significant consideration in the context of large-scale infrastructure projects (Hernández Aguilar & Vega Lopez, 2023). Innovative solutions for foundation problems on highly plastic cohesive soils, for example, demonstrate the constant need to adapt engineering to the specific geological challenge, and advanced modeling is the vehicle to validate these adaptations (Castro-Sandoval, MeloPabón, & Angulo-Blanquicetz, 2019).

The article proposes an advanced methodological framework that seeks to overcome the limitations of traditional Geotechnical Engineering in the evaluation of the stability of urban slopes. The primary objective of this study is to establish and validate a robust procedure for the holistic evaluation of geotechnical stability and the optimization of foundation design. This will be achieved by synergistically integrating hydromechanical coupled numerical models with the continuous observation provided by a network of IoT sensors.

2. Materials and methods

The Finite Element Method (FEM) or the Finite Difference Method (FDM) technique is employed to solve the equations that govern the behavior of the soil. The model is predicated on the total or partial coupling of the equations of water flow and mechanical equilibrium, in accordance with Biot's theory of poroelasticity.

2.1. Coupled Numerical Models

The constitutive equation for the mechanical behavior of soil should be modeled using criteria such as the modified Mohr-Coulomb or the modified Endochrony (CEM) model. The criteria facilitate the measurement of the dependence of shear stress on stress trajectory and dilation.

$$\tilde{\mathrm{N}}\times(\mathbf{s}\text{¢}) + b = 0 \quad \text{(Equilibrio Mecánico)}$$

$$\P$$

$$\underline{\quad}(\mathbf{r}_w n)+\tilde{\mathrm{N}}\times(\mathbf{r}_w v) = 0 \quad \text{(Continuidad de Masa) } \P t$$

Where **δ1** is the tensor of effective stresses, **b** is the body forces, **ρω** is the density of the fluid, **η** is the porosity, and **ϒ** is the Darcy velocity.

The solution of this coupled system allows to obtain the spatial and temporal distribution of effective stresses (δ1), pore pressures (υω) and displacements (υ).

2.2. Integration of IoT Sensors for Geotechnical Monitoring

The IoT monitoring system is conceived as a wireless network of low-cost, high-performance sensors, strategically located at the study site. Key instruments include:

- Vibrating wire piezometers: To measure the interstitial water pressure (υω).
- In-Place *Inclinometers* (IPI) and Extensometers: To detect subsurface displacements and strain profiles.

- Low-cost GNSS sensors: To monitor surface displacements.
- Soil moisture sensors: To map the saturation distribution.

The data is transmitted to a *cloud* platform for processing, visualization and, fundamentally, for the real-time calibration of the numerical models.

Reverse calibration is performed by adjusting key geotechnical parameters (e.g., cohesion (C̓), friction angle (Ǿ), and permeability (***k***)) until the model accurately reproduces the observed pore pressure and displacement data.

2.2. Foundation System Optimization

The calibrated model is used to simulate the effect of different foundation geometries and typologies (e.g. Piles, micropiles, offset slabs) under the predicted critical load and stability scenarios. Optimization is guided by two main criteria:

1. Ensure an objective Safety Factor (***FS***) against global or local failure.
2. Minimize the costs and constructive impact of the solution.

The ***FS*** is calculated using the Shear Strength Reduction Method (SRM), a technique integrated into the MEF, which progressively reduces the resistance parameters until the limit state is reached.

3. Results

The proposed methodological framework, predicated on the integration of the coupled Finite Element Method (MEF), real-time monitoring through Internet of Things (IoT) technologies, and the Shear Resistance Reduction Method (SRM), was implemented in five selected urban environments. Each site exhibits distinct geotechnical characteristics, delineated by the presence of varied surface stratums, and is subject to varying degrees of geotechnical risk. The risk classification was established on the basis of the probability of increased pore pressure (**υω**), which is a key indicator of susceptibility to ground instability processes.

3.1. Characterization of Critical Sites and Scenarios

The geotechnical conditions and risk scenarios associated with the five urban sites selected for the application of the methodological framework (Table 1) will be examined. Each site exhibits a predominant soil type, characterized by distinct mechanical properties, as evidenced by the values of cohesion (c′) and internal friction angle (Ǿ). Consequently, the depth of the water table is reported as a pivotal indicator of saturation, which varies from surface conditions (0.50 m) to deep levels (8.00 m). The urban risk scenarios were classified according to conditioning factors such as seismicity, rainfall intensity, terrain morphology, and water variability. The application of these parameters in conjunction enables the establishment of a comparative framework for the evaluation of the ground's response to critical load and infiltration conditions. This, in turn, facilitates the selection of foundation strategies that are adapted to each specific context.

3.2. Variation of the Safety Factor (FS) in the face of Saturation

The Shear Resistance Reduction Method (SRM) was employed for analysis at each of the five urban sites under two contrasting conditions: the baseline condition, corresponding to the terrain's usual operating state, and the critical condition, defined by the maximum saturation level recorded by the IoT sensors. This comparison enabled the evaluation of the sensitivity of each site to the variation of pore pressure (**υω**) and its impact on geotechnical stability.

The findings indicate that sites A and E exhibit the greatest vulnerability to water-induced instability, exhibiting safety factor reductions exceeding 30%. Specifically, the E site exhibited a substantial decline in FS below 1.05, attributable to the synergy of diminished internal friction (φ′ = 18.50°) and notable surface saturation. This value indicates an imminent failure condition, which necessitates the urgent implementation of mitigation measures.

Table 2 provides a synopsis of the diminution of the safety factor at each site, emphasizing the prevailing conditions that elucidate the erosion of stability. It has been observed that, while site D exhibits practically constant

Table 1: Geotechnical parameters and risk scenarios

Place	Dominant Soil Type	Cohesion (c′) (kPa)	Ǿ (Degrees)	Water table (reference)	Associated urban risk
To	Sensitive Clays	15.00	8.50 p.m.	Surface (0.50 m)	**Very High** (High Seismicity)
B	Slime Sands	5.00	32.10	Medium (3.00 m)	**High** (heavy rainfall)
C	Marl (Soft Rock)	35.00	28.00	Deep (8.00 m)	**Medium** (Very High Slopes)
D	Colluvial Deposits	10.00	24.00	Variable (IoT Monitoring)	**Low** (Slow Slides)
And	Organic Slimes	12.00	18.50	Surface (1.50 m)	**Very high** (high water variability)

Table 2. Safety Factor Reduction (ΔFS)

Place	***FS*** **Reference**	FSCritic	ΔFS(%)	Determining Condition
To	1.55	1.08	30.32%	Increase in uw due to a mild earthquake
B	1.72	1.45	15.69%	Leaching and friction loss
C	1.98	1.65	16.67%	Material fatigue due to high height
D	1.40	1.38	1.43%	Very intrinsically stable slope
And	1.51	1.01	33.11%	High φ′ angle sensitivity

Table 3. Optimized Pile Length (Lopt) and Gain in FS

Place	***FS*** **Critical**	Base Length (m)	Lopt (m)	***FS*** **Optimized**	ΔL(%)
To	1.08	10.00	14.20	1.33	42.00%
B	1.45	8.00	8.00	1.45	0.00%
C	1.65	18.00	18.00	1.65	0.00%
D	1.38	7.50	7.50	1.38	0.00%
And	1.01	12.00	17.80	1.30	48.33%

stability due to its favorable geomorphological configuration, the other sites manifest specific vulnerabilities associated with factors such as seismicity, leaching, material fatigue, and hydraulic sensitivity.

3.3. Foundation Optimization (Pile Design)

Based on the results obtained from the SRM analysis under critical saturation conditions, an optimized pile length (Lopt) was defined for each of the five evaluated sites (Table 3). The design criterion adopted consisted of guaranteeing an optimized safety factor (*FSopt) equal to or greater than 1.30, even in scenarios of maximum pore pressure recorded by the IoT monitoring system.*

Geometric optimization was particularly relevant at sites A and E, where conditions of low shear strength and surface saturation demanded significant increases in pile length. In site A, an increase of 42.00% was required with respect to the base length, while in site E the increase reached 48.33%, both cases being necessary to reach the established safety threshold. On the other hand, sites B, C and D had *critical FS values higher than 1.40, so it was not necessary to modify the length of the* foundation elements. In these cases, the design focused exclusively on compliance with the Limit of Service State (ELS), i.e. on ensuring load capacity without exceeding admissible deformations, an aspect that is not detailed in this section for the sake of brevity.

3.4 Role of IoT Monitoring in Design Adaptation

IoT Monitoring provided the data for k calibration and control failure detection at sites A and E.

- Site A (Sensitive Clays): The IoT network detected a peak in **υω** induced by a moderate magnitude earthquake that the initial model did not consider. This forced the recalculation of the *FSCritic*, justifying the large increase in Lopt (42.00% longer).

- Site E (organic silt): The high water variability prevented the establishment of a constant water table. Continuous reverse calibration was essential, adjusting k weekly, allowing the *optimized FS* of 1.30 to remain in force.

This evidence demonstrates that the integration of IoT monitoring is indispensable for modern geotechnical engineering in areas of variable risk, allowing the adaptation of the structural design (such as pile length) *post-calibration* of the model.

4. Discussion

The findings, derived from the implementation of the proposed methodological framework, which integrates the coupled Finite Element Method (FEM), real-time monitoring using Internet of Things (IoT) technologies, and the Shear Resistance Reduction Method (SRM), demonstrate the efficacy of integrating advanced numerical modeling with continuous observation to address the geotechnical complexity of urban environments at risk. This multidisciplinary approach enables the circumvention of the limitations of conventional methods of stability analysis, which are typically predicated on static assumptions and geometric simplifications that fail to adequately capture the hydromechanical dynamics of the soil (Achá, Moscoso, & Gonzales, 2024; Morales Zuñiga et al., 2025).

The comprehensive characterization of the five selected sites enabled the identification of substantial variations in the mechanical parameters of the soil, including cohesion (c′) and the angle of internal friction (φ′), as well as in the depth of the water table. These variations influenced the behavior in critical saturation scenarios. This geotechnical heterogeneity, prevalent in rapidly expanding urban regions, has been previously documented in various studies. These studies underscore the necessity to adapt foundation solutions to the specific characteristics of the local subsoil (Quispe & Angulo, 2021; Cutipa, Terrazas, & Ramírez, 2019; Camac et al., 2023).

The reduction of the safety factor under conditions of maximum pore pressure (**υω**) was particularly severe at sites A and E, where drops of more than 30% were recorded. These findings corroborate the assertion posited by Ludeña (2024) regarding the structural fragility of Latin American urban areas, particularly with regard to the heightened vulnerability to hydrometeorological and seismic events. The presence of soils characterized by low internal friction and shallow water tables has been demonstrated to significantly amplify this vulnerability. In contrast, site D exhibited virtually constant stability, thereby validating the significance of geomorphological configuration as a component of natural resilience. This finding aligns with the research conducted by González and Daniel (2019) on marginalized areas vulnerable to gravitational processes.

The optimization of the pile length according to the *critical FS allowed the establishment of adaptive design criteria* . At sites A and E, it was necessary to increase the length by more than 40% to achieve an *optimal FS ≥ 1.30, demonstrating that the structural design must respond dynamically to the hydraulic conditions* of the ground. This need for geometric adjustment has been addressed by authors such as Camacho Angarita and Gutiérrez Aguilera (2023), who propose the plate-pile system as a viable alternative in contexts of high loads and excessive settlements. Likewise, Marco, Perez, and Gabarda (2021) highlight the importance of applying heuristic optimization algorithms to improve structural efficiency without compromising safety.

At the other sites, where the *FScritical exceeded the safety threshold, no geometric adjustments were required, allowing the design to focus on Service Limit State (ELS) compliance. This approach, focused on load capacity without exceeding admissible deformations, has been widely discussed in the technical literature as a strategy to avoid oversizing foundations (Pérez, 2020; Bardales & Benites, 2021; Olivera & Villarreal, 2023).*

The role of IoT monitoring in the calibration of key parameters, such as permeability (k), was found to be crucial. Additionally, its application enabled the detection of events that were not foreseen by the initial models. At Site A, the detection of a moderate earthquake-induced pore pressure peak necessitated the recalibration of the model and the re-sizing of the foundation. This finding aligns with the observations reported by Hernández Aguilar and Vega Lopez (2023), who document the necessity to modify foundation designs in response to unanticipated seismic occurrences. At site E, the high water variability necessitated continuous reverse calibration, thereby enabling structural stability to be maintained within the prescribed safety margins. This approach to dynamic adjustment was first put forward in a 2019 study by Castro-Sandoval, Melo-Pabón, and Angulo-Blanquicetz, who proposed it as a novel solution for foundations in the context of highly plastic cohesive soils.

The IoT system's capacity to deliver real-time data facilitated the transformation of a static model into a predictive tool, aligning with the methodologies proposed by González and Daniel (2019) concerning the implementation of geomatic techniques within urban prediction models. The integration of sensors, including piezometers, inclinometers, and extensometers, in conjunction with reverse calibration algorithms, facilitates the creation of geotechnical digital twins that are able to adapt to actual environmental and operational conditions. This technology signifies a substantial advancement in the realm of geotechnical risk management. It facilitates not only the assessment of the state of the land but also the prediction of its future behavior, thereby reducing the associated uncertainty.

The implementation of coupled MEF has enabled the accurate simulation of the soil-structure interaction under transient conditions of saturation, a finding that has been validated in studies such as that of Achá, Moscoso, and Gonzales (2024), who applied parametric analyses for isolated foundations. The selection of appropriate constitutive laws, such as the Modified Mohr-Coulomb model or Modified Endochrony, was key to capturing phenomena such as dilation and the dependence of shear stress on the trajectory of stresses, fundamental aspects in the seismic response of the soil-foundation system (Morales Zuñiga et al., 2025).

Similarly, the analysis of piles subjected to lateral loading, as exemplified by Mendoza's (2021) study, underscores the necessity to consider the dynamic interaction between the ground and the structural elements, particularly in contexts characterized by high hydraulic variability. The employment of numerical modeling has enabled the assessment of not only static bearing capacity but also deformation and failure potential under variable load conditions. This is of paramount importance for the design of deep foundations in dense urban areas.

The preliminary characterization of the sites, which was based on parameters such as cohesion, internal friction, and water table, was essential for establishing differentiated risk scenarios. This methodology aligns with the approaches proposed by Camac et al. (2023) in soil microzoning and by Pelkowski (2023), who emphasizes the significance of empirical correlations in evaluating surface conditions. The classification of urban risk according to the probability of increased pore pressure enabled the prioritization of interventions and the adjustment of design strategies to each specific context.

From a sustainability perspective, the methodological framework contributes to efficiency in the use of materials and resources by avoiding the unnecessary oversizing of foundations. This perspective aligns with the principles of sustainable development in urban areas, as proposed by Ludeña (2024), and with the recommendations of Ramírez and Alonso (2011) on the execution of foundations in complex urban environments.

Finally, the geometric design of foundation elements, such as double footings or rigid slabs, must consider not only conventional geotechnical parameters but also the dynamic response of the system, as suggested by Pérez-Giraldo and Yepes-Tumay (2021) in their studies on electrical transmission towers. Pérez (2020) examined the correlation between structural design and one-dimensional soil consolidation. The findings of this study underscore the necessity of integrating numerical models with field data to achieve efficient and safe solutions.

Conclusions

The integration of numerical modeling with IoT monitoring has emerged as a robust tool for geotechnical evaluation and design in highly complex urban areas.

Pore pressure (**υω**) is a critical indicator for the classification of geotechnical risk, and its real-time monitoring allows for the anticipation of imminent failure conditions.

The optimization of pile length based on the critical foundation soil strength (FS_(critical)) enhances structural efficiency without compromising safety, particularly in low-strength, high-saturation soils.

The dynamic calibration of geotechnical parameters using IoT sensors enables the adaptation of structural design to changing conditions, thereby reducing uncertainty and enhancing the resilience of infrastructures.

The proposed methodological framework can be replicated in other urban contexts, thus providing a solid basis for the development of geotechnical digital twins. These digital twins are intended to facilitate predictive risk management and informed decision-making in infrastructure projects.

Conflict of interest

The authors have no conflict of interest to declare.

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References

1. Achá, M., Moscoso, Álvaro, & Gonzales, G. (2024). Análisis paramétrico de la interacción suelo-estructura en una cimentación aislada por el método de elementos finitos. *Revista Investigación & Desarrollo*, *24*(1), 5-20. https://doi.org/10.23881/idupbo.024.1-1i

2. Aguilar, M. A. H., & Lopez, R. S. V. (2023). Solución geotécnica para el suelo de cimentación de las 7 torres de la villa panamericana. *Perfiles de Ingeniería*, *19*(19). https://doi.org/10.31381/perfilesingenieria. v19i19.5792
3. Bardales, N. H. M., & Benites, G. D. E. (2021). Influencia de la resistencia del suelo mejorado en el diseño de losa de cimentación mediante un modelo de interacción suelo-estructura. *INGENIERÍA Ciencia Tecnología E Innovación*, *8*(2), 135-148. https://doi.org/10.26495/icti.v8i2.1916
4. Camac, E., Matamoros, F., De la Cruz, D., & Fano, J. (2023). Microzonificación de suelos para cimentación estable de viviendas unifamiliares en el barrio Santa Rosa del distrito de Lircay-Huancavelica. *Revista Científica Ciencias Ingenieriles*, *3*(1), 27–43. https://doi.org/10.54943/ricci.v3i1.222
5. Camacho Angarita, L y Gutiérrez Aguilera, P. (2023). El sistema placa-pilote como alternativa de cimentación para estructuras con grandes cargas y asentamientos excesivos. Universidad Cooperativa de Colombia, Villavicencio, Facultad de Ingenierías, Ingeniería civil. Disponible en: https://doi.org/10.16925/gclc.40
6. Castro-Sandoval , A., Melo-Pabón, C. A., & Angulo-Blanquicetz, G. (2019). Soluciones innovadoras para problemas de cimentación sobre suelos cohesivos altamente plásticos . *Sostenibilidad, Tecnología Y Humanismo*, *10*(1), 54-62. https://doi.org/10.25213/2216-1872.9
7. Cutipa, B. H., Terrazas, R. F., & Ramírez, W. M. (2019). Estudio geotécnico con fines de cimentación para tres asociaciones de vivienda en Tacna. *CIENCIA & DESARROLLO*, *24*, 74-84. https://doi.org/10.33326/26176033.2019.24.788
8. González, R., & Daniel, Ó. (2019). Metodología y técnicas de la geomática aplicada en modelos de predicción real en zonas urbanas marginadas vulnerables a procesos gravitacionales, alcaldía Álvaro Obregón, Cdmx, México.
9. Hernández Aguilar, M. A. ., y Vega Lopez, R. S. . (2023). Solución geotécnica para el suelo de cimentación de las 7 torres de la villa panamericana. *Perfiles de Ingeniería*, *19*(19), 91-108. https://doi.org/10.31381/perfilesingenieria.v19i19.5792
10. Ludeña, L. M. (2024). Evaluación crítica del desarrollo sostenible en zonas urbanas de Latinoamérica: revisión sistemática. *Visión de Futuro*, *28, No 2 (Julio – Diciembre)*, 146-162. https://doi.org/10.36995/j. visiondefuturo.2024.28.02.005.es
11. Manturano-Chipana, R. K., Campos-Vásquez, N., & Rabanal-Chávez, E. H. (2025). Proceso de Cimentación Profunda para la mejora Capacidad Portante del Suelo en Edificaciones en Perú. *Ciencia y TecnologíA.*, *24*(1), 19-28. https://doi.org/10.70414/cyt.v24i1.128
12. Marco, J. L. T., Perez, A. H., & Gabarda, V. A. (2021). HEURISTIC OPTIMIZATION OF THE FOUNDATION OF a DYNAMICALLY STRESSED ROTATING MACHINE USING THE LATE ACCEPTANCE HILL CLIMBING (LAHC) ALGORITHM. *DYNA*, *96*(5), 498-504. https://doi.org/10.6036/9762
13. Mendoza, J. M. (2021). *Análisis de pilotes y pilas de cimentación sometidos a carga lateral*. https://doi.org/10.47807/unison.146

14. Morales Zuñiga, H. R., Ramírez Cabrera, W. J., Guerrero Zuñiga, M. C., Morales Miranda, A. D., & Morales Miranda, S. A. (2025). Estudio del Comportamiento Sísmico de la Interacción Suelo-Cimentación en una Estructura de Acero-Parte 1. *Ciencia Latina Revista Científica Multidisciplinar*, *8*(6), 5914-5946. https://doi.org/10.37811/cl_rcm.v8i6.15293
15. Olivera, R., & Villarreal, G. (2023). Interacción Suelo-Estructura para edificaciones con platea de cimentación por los modelos estático y dinámico. *Memoria Investigaciones En Ingeniería*, (25), 137–171. https://doi.org/10.36561/ING.25.9
16. Pelkowski, J. (2023). CIMENTACIÓN DE LA FÓRMULA EMPÍRICA DE ÅNGSTRÖM REFERENTE A LA RADIACIÓN ATMOSFÉRICA EN SUPERFICIE. *Revista De La Academia Colombiana De Ciencias Exactas, Físicas Y Naturales*, *33*(129), 513-528. https://doi.org/10.18257/raccefyn.33(129).2009.2380
17. Pérez, S. P. M. (2020). CORRELACIÓN EN COSTOS DE UN DISEÑO DE UNA CIMENTACIÓN SUPERFICIAL RÍGIDA y FLEXIBLE CONSIDERANDO LA CONSOLIDACIÓN UNIDIMENSIONAL. *Revista Científica Epistemia*, *4*(3), 15-37. https://doi.org/10.26495/re.v4i3.1310
18. Pérez-Giraldo, M., y Yepes-Tumay, J. D. (2021). Diseño geométrico de una zapata doble para cimentación aplicada en torres de transmisión eléctrica. *Revista Ingenio*, *18*(1), 17–24. https://doi.org/10.22463/2011642X.2385
19. Pérez-Giraldo, M., y Yepes-Tumay, J. D. (2021). Diseño geométrico de una zapata doble para cimentación aplicada en torres de transmisión eléctrica. *Revista Ingenio*, *18*(1), 17–24. https://doi.org/10.22463/2011642X.2385
20. Quispe, B. M. C., & Angulo, M. A. (2021). Metodología para la caracterización de suelos con fines de cimentación. *Prospectiva Universitaria*, *15*(1), 111-116. https://doi.org/10.26490/uncp.prospectivauniversitaria.2018.15.861
21. Ramírez, L.E., & Alonso, D.R. (2011). Ejecución de las cimentaciones de la estación Mercat, para la Línea T2 del metro de Valencia. Problemática de las grandes profundidades de ejecución en zonas urbanas.