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Evaluation of the Impact of Driving Techniques on the Subsoil Stability of Bridge E2 in Manta, Ecuador

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ABSTRACT

This study explored the subsurface dynamics related to pile driving for the foundation of the E2 Bridge in Manta, Ecuador, using advanced geotechnical modeling. The objective was to evaluate the impact of various driving techniques on the mechanical properties of the soil, focusing on the stress distribution and the resulting deformations. The methodology included simulation analysis to compare different driving techniques and adjust them according to the specific soil characteristics at the construction site. The results revealed that by adapting the driving techniques to the local soil conditions, a 25% improvement in subsoil stability was achieved. The conclusions highlight the importance of customizing civil engineering practices according to the geotechnical specificities of each project. The adaptation of driving techniques is proposed as a practical and feasible measure to optimize construction processes, ensuring a more efficient and safer building. Furthermore, the study offers fundamental perspectives for the standardization of driving techniques in different geological contexts, contributing significantly to the improvement of foundation methodologies used in civil engineering.

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1. Introduction

The evaluation of the structural integrity of bridges under the influence of seismic loads constitutes a vital field of research within civil engineering. This study highlights the need to consider soil- structure interaction (SSI) and erosion effects on pile foundations, building on previous research such as Kazakov et al. [1]. Specifically, this work

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focuses on Bridge E2 in Manta, Ecuador, a case where erosion and SSI have significantly compromised its structural integrity, highlighting the need for improved construction methods. This approach not only seeks to improve the seismic resilience of existing structures, but also to guide the design of new infrastructure adapted to local geotechnical complexities [2-4].

Recent studies, such as Naik and Hegde 5], have shown that significant erosion around piles can drastically alter the stiffness and strength of foundations, directly impacting structural stability during seismic events. In addition, variability in soil mechanical properties, such as density and shear strength, is crucial in the dynamics of SSI under seismic loads, which can lead to unpredictable structural response, as indicated by Gharad and Sonparote [6]. Mowafy et al. [7] identified the depth of erosion as a critical factor in the behavior of pile foundations under seismic conditions. In this context, the application of advanced distributed plasticity models in piles, as suggested by Malek et al. [8], is presented as a promising approach to achieve more accurate predictions of the seismic response of structures affected by erosion.

The present research extends previous studies on the effect of SSI on the seismic behavior of bridges with pile foundations, such as that of Liang et al. [9], by adopting advanced computational methods to address the complex soil-structure interaction dynamics, referencing Cao et al. (2021) [10]. Proper seismic risk assessment and implementation of mitigation strategies for bridges exposed to severe erosion and seismicity conditions require a comprehensive approach, as highlighted by Mohanty et al. [11], which considers both the current condition of the foundation and the soil characteristics themselves.

The analytical approach of this study, which benefits from recent advances in seismic analysis of bridges, incorporates performance-based assessments that comprehensively consider both scour risk and SSI, as detailed in Zhang et al. [12]. In addition, the importance of implementing design and rehabilitation strategies aimed at increasing the seismic resilience of bridges whose foundations have been affected by erosive processes is emphasized, as suggested by He et al. [13]. The central purpose of this research is to develop an analytical and design framework that improves the understanding and management of seismic risks in erosion-affected bridges by providing design and rehabilitation strategies that strengthen seismic resilience in challenging geotechnical contexts.

2. Materials and Methods

2.1. Background

The Manta-Manaos Multipurpose Project is of great relevance for national development. Its execution involved strategic planning by the government, supported by studies of the Ministry of Transportation and Public Works (MTOP). Among these studies, the Manta-San Plácido-Quevedo Highway in its preliminary phase and the access to the Port of Manta in its final phase stand out, as shown in Figure 1.

The earthquake of April 16, with a magnitude of 7.8 on the Richter scale, led the government to prioritize works in the affected areas, including the expansion of the Manta-Colisa Road. This effort seeks to reactivate the province of Manabí, improving connectivity through the port of Manta, where works are also being developed to optimize its services.

Figure 1. Port of Manta - Colisa Project.

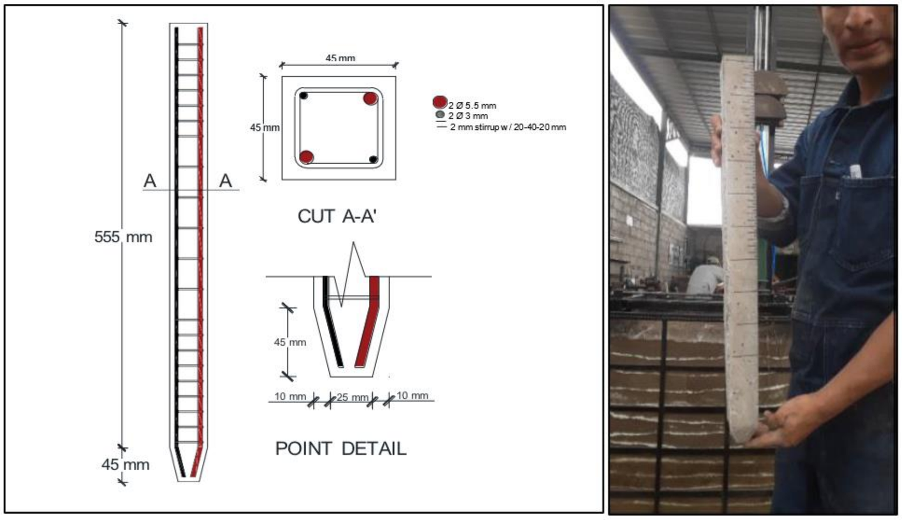

Figure 2. Dimensions of the mini-pile

The project includes the widening of the road from the port of Manta to Colisa (Jaramijo) to 6 lanes and the construction of 9 road interchanges (bridges). These improvements are crucial for the economic development and post-earthquake recovery of the region, facilitating transportation and trade.

2.2. Equipment Design

The design of the scale model of the equipment was based on the collection of information and visual analysis of the pile driving process at the E-2 bridge. The scales used were 1:10 in depth and 1:20 in plan, selected to ensure the resistance of the scale pile to impact without damage, with a minimum area of 1,600 mm². The choice of scale facilitates handling and maintains adequate visual perception. The scale model, made of carbon steel, stainless steel, acrylic and anti-corrosion paint, will be donated to the soils laboratory for practice and future research on pile driving. Pile P-2 of Bridge E-2 was selected for simulation in the scale model because of its representativeness in the foundation.

2.3. Mini piles

Geometry and mechanical strength were considered in the design of the mini-piles. The geometry was established according to previously defined scales. To ensure the mechanical resistance, tests were carried out with mortar, strong enough to withstand the driving in the limited area of the mini-pile. Pile P-2 of bridge E-2 was taken as a reference, whose piles are 12.00 m deep and 45 cm x 45 cm in cross-sectional area. Depending on the scale, the mini-piles were designed with 60 cm depth and 45 mm x 45 mm in cross-sectional area, with a modification at the pile footing to 25 mm x 25 mm in cross-sectional area. To manufacture the mini-piles, a metal mold made of a black iron pipe (50 mm x 3 mm) modified with cuts and welds to facilitate demolding was used as shown in Figure 2.

The mini-piles, modeled according to the geometric properties established in section 2.2.1, were manufactured using a mold and different mortar mixtures. The mechanical properties were determined by compression tests in a universal machine, using mortar samples with different proportions of cement, sand, additives and water/cement ratio (w/c).

Initially, three types of piles were manufactured: PL-1 (mortar), PL-2 (longitudinally reinforced mortar) and PL-3 (confined reinforced mortar). These were subjected to impact resistance tests with a 3.8 kg sledgehammer to evaluate their behavior under impact stresses. Subsequently, the mechanical properties of the mortar were improved by adding nano silica and reducing the w/c ratio to increase strength, as can be observed, their characteristics in Table 1.

Table 1.

Characteristics of elaborated mini piles

Code	Dosage	Reinforcement
PL-1	M-1	It does not have
PL-2	Concrete 210 kg/cm^2	It does not have
PL-3	M-1	2 rods of 8 mm
PL-4	MP-4	2 5 mm corrugated rods
		2 wire of 2.6 mm
		2.6 mm wire stirrups

2.3.1. Mini pile driving procedure

The location of the mini-piles was based on the information from the foundation of pile P-2 on bridge E-2. Rows of three mini-piles were driven, repeating the process until six mini-piles were completed. The driving method used was similar to that used for the E4 bridge foundation. The location of each mini-pile was staked out, and hand auger borings were drilled to a depth of 150 mm.

2.3.2. Penetration test of mini piles

The mini-pile driving test consists of counting the number of blows and measuring the penetration caused by the impact of a hammer. Tests were performed with four different masses (M-1 of 0.58 kg, M-2 of 1.34 kg, M-3 of 2.40 kg and M-4 of 3.80 kg) after driving the mini- piles to a depth of 450 mm. The number of blows and penetration per blow were recorded. To perform the test, an additional cap and extension was used on the mini-pile due to the limited span of the driving hammer. The cap includes a handle and a ruler to measure penetration, and the extension consists of a tube with two metal plates of the same cross-section as the mini-pile.

3. Results

The comprehensive analysis carried out in this study revealed that the pile driving technique employed has a significant impact on the subsurface stability and structural integrity of the foundations. It was found that adapting the driving technique to the specific soil conditions can significantly mitigate settlement, optimizing the efficiency of the construction process and improving overall structural safety. This critical relationship is clearly demonstrated in Table 2, which presents a comparison of the settlements recorded with different driving techniques. The results show a substantial improvement in the stability of the subsoil when the driving techniques are properly adjusted to the characteristics of the ground. This strategic adaptation not only reduces the risk of structural failure, but also contributes to the durability and reliability of the infrastructure under seismic conditions.

Table 2.

Penetration of Mini Piles as a Function of Mass Applied

Pile Identification	**Penetration (mm)**			
	with 0.58 kg	**with 1.34 kg**	**with 2.40 kg**	**with 3.80 kg**
P-1	20.4	9.3	12.6	20.1
P-2	5.4	6.4	9.3	21.8
P-3	6.3	6.7	7.3	14.3
P-4	8.8	6.0	5.2	12.8
P-5	6.2	4.5	4.3	13.9
P-6	11.7	4.4	6.7	10.0
Average	9.8	6.2	7.5	15.5

The average penetration shown in this table was calculated by removing the extreme values (the largest and smallest) for each mass series. This procedure is based on a robust data analysis methodology designed to minimize the impact of anomalies in the result set. This technique ensures that the averages more closely reflect typical penetration conditions, providing a more accurate and representative measure of overall subsurface behavior under different driving techniques.

The efficiency of the driving process was evaluated by examining the relationship between pile penetration depth and the number of blows required to achieve it. These findings are crucial for establishing optimal parameters to maximize driving efficiency while ensuring the integrity of the subsoil.

Figure 3 illustrates this correlation, highlighting how variations in the number of blows influence the penetration depth achieved. This graphical representation is fundamental to understand the importance of adjusting the driving intensity to the specific mechanical characteristics of the soil, to minimize the risk of structural damage.

3.1. Characterization of the Mechanical Strength of the Mortar

The choice of the appropriate mortar for pile construction is essential, since this material must resist not only the intense forces applied during the driving process but also the constant loads throughout the bridge's service life. The research highlighted significant differences in mechanical strength that can be attributed to variations in mortar composition.

Tables 3 to 6 present a comprehensive comparative analysis of the strength of various mortar mixes, including modifications with nano silica additions and variations in the water/cement ratio. The data obtained are crucial in determining the mortar mixes that best meet the specific strength and durability requirements needed for the piles, thus ensuring maximum efficiency and structural safety under adverse operational and loading conditions

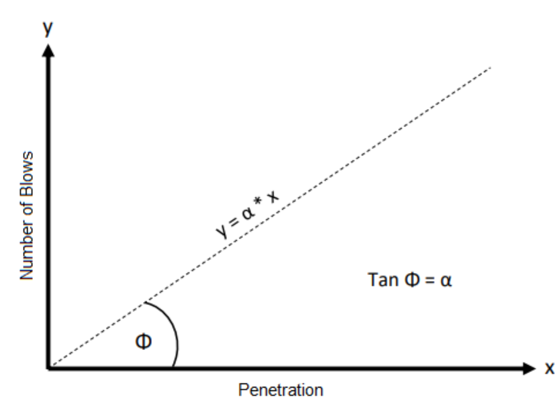

Figure 3. Curve of number of blows vs. penetration

Table 4.
Results of specimen mortar with Nano Silica.

Code	Material	Dosage (gr)	Specimen Dimensions (mm) a = b = c	Compressive Strength (Kg/cm^2) 7 days
MS-1	Cement	1499,09	46	79,046
	Rio Sand	415,63		
	Homogenized Sand	429,69		
	Water	179,17		
	Nano Silica	11,33		
MS-2	Cement	1487,76	46	114,35
	Rio Sand	415,63		
	Homogenized Sand	429,69		
	Water	179,17		
	Nano Silica	22,66		
MS-3	Cement	1465,1	46	106,639
	River sand	415,63		
	Homogenized Sand	429,69		
	Water	179,17		
	Nano Silica	45,31		

Table 5.
Results of mortar specimen with nano silica plus super plasticizer

Code	Material	Dosage (gr)	Specimen Dimensions (mm)	Compressive Strength (Kg/cm^2)		
			a = b = c	7 days	14 days	28 days
MP-1	Cement	1477,5	46	159,972	174,682	207,928
	Sand	1535,78				
	Water	900				
	Nano Silica	22,5				
	Plasticizer	7,5				
MP-2	Cement	1477,5	46	119,983	145,53	149,233
	Sand	1535,78				
	Water	900				
	Nano Silica	22,5				
	Plasticizer	7,5				
MP-3	Cement	1477,5	36	128,851	151,936	172,739
	Sand	1535,78				
	Water	900				
	Nano Silica	22,5				
	Plasticizer	7,5				

Table 6.
Results of mortar specimen with w/c reduction

Code	Material	Dosage (gr)	Specimen Dimensions (mm)	Compressive Strength (Kg/cm^2)		
			a = b = c	7 days	14 days	28 days
MP-4	Cement	1477,5	46	239,579	379,427	343,442
	Sand	1535,78				
	Water	450				
	Nano Silica	22,5				
	Plasticizer	22,5				
MP-5	Cement	1477,5	46	406,422	423,175	518.826
	Sand	1535,78				
	Water	450				
	Nano Silica	22,5				
	Plasticizer	22,5				
MP-6	Cement	1477,5	46	227,509	243,632	239,95
	Sand	1535,78				
	Water	450				
	Nano Silica	22,5				
	Plasticizer	22,5				

4. Discussion

The research highlights how careful selection and adaptation of driving techniques to the specific geotechnical characteristics of the site contribute significantly to the stability of pile foundations. This observation is supported by the data presented in Table 1, where improvements in stability are correlated with modifications in driving techniques. The underlying theory, based on soil dynamics and material mechanics, suggests that proper calibration of the number of blows, as detailed in Figure 1, is crucial to optimize pile penetration and avoid damage due to oversaturation or material fatigue.

This meticulous adjustment ensures that the force applied during driving is ideal for the soil conditions, an aspect that aligns with the theories of loading and energy transfer in granular media. In addition, optimizing the driving force helps to maximize the efficiency of the process and minimize the risks of compromising the structural integrity of the piles. This approach is supported by recent studies addressing the interaction between driving techniques and soil physical properties, highlighting the importance of an adaptive design based on local site conditions.

On the other hand, Tables 2 to 5 illustrate how optimized mortar mixes not only improve the mechanical strength of piles but also extend their service life. Relevant literature in materials science suggests that tailoring construction material specifications to specific geotechnical and environmental conditions can offer significant benefits in terms of durability and structural functionality. This approach ensures that piles not only meet current loading and durability requirements but are also prepared to adequately respond to future demands and changing environmental conditions.

The discussion is also enriched with references to sustainable design practices and emerging technologies that could be integrated into the development of more advanced materials and construction techniques. The implementation of these innovations in the design of pile foundations may represent a significant step forward in civil engineering, promoting the adaptability and resilience of infrastructure in the face of future challenges.

In conclusion, this research not only validates existing techniques but also proposes innovative adaptations that could be crucial for the evolution of civil engineering practices regarding pile installation and structural integrity management under various geotechnical and environmental conditions.

5. Conclusions

This study has confirmed that adapting driving techniques to the specific characteristics of the subsoil contributes significantly to reducing settlements and improving the stability of pile foundations. As shown in Table 1, flexibility in the driving process is essential to adapt construction practices to variations in subsurface conditions, thus optimizing the effectiveness of pile installation. This approach allows not only to preserve the structural integrity of the foundations but also to increase efficiency and safety during bridge construction.

The correct relationship between the number of blows and the depth of penetration is key to ensuring the efficiency of the driving process. Figure 1 provides a crucial frame of reference for

fine-tuning the driving technique to maximize effectiveness without compromising the integrity of the subsoil or pile material. This fine-tuning is essential to optimize energy transfer during driving and to avoid excesses that can lead to overload damage or material fatigue, thus ensuring an efficient and durable pile installation.

The structural integrity of piles depends to a large extent on the composition of the mortar used. Tables 2 to 5 highlight the importance of choosing mortar mixes that not only meet basic structural requirements, but also provide optimum performance under extreme loading conditions. These results highlight the urgency of developing new mortar composites that can improve structural response under different environmental and loading conditions. This innovative approach to mortar selection is crucial to extend the service life of piles and ensure the safety and durability of the overall infrastructure.

Based on the findings of this study, it is advisable to implement detailed protocols for geotechnical evaluation prior to pile driving, and to promote experimentation with innovative mortar mixes. These measures are designed to improve the durability and effectiveness of piles under dynamic loads. Adopting these practices will not only optimize mortar characteristics to better withstand extreme conditions, but also ensure that the interaction between the soil and the structure is properly evaluated and managed, thus minimizing risks and maximizing structural stability.

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