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BRIDGE FOUNDATION DESIGN INTEGRATING GROUND IMPROVEMENT TECHNIQUES IN CHALLENGING SOIL

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Abstract: This study investigates the optimal design of bridge foundations incorporating ground improvement techniques in challenging soil conditions, employing a case study methodology. Bridge foundations primarily serve to transfer forces applied by the bridge to the underlying soil, and ground improvement techniques enhance soil properties, particularly in complex environments. Challenging soil conditions pose substantial difficulties in designing and constructing bridge foundations, requiring engineers to employ specific methodologies to ensure stability and long-term resilience. These solutions are crucial in areas with weak or unstable soil incapable of supporting large structures like bridges. This study aims to conduct a thorough comparative analysis to evaluate the suitability of Controlled Modulus Columns (CMC) for a roadway project in north-central Java, where soil conditions present significant challenges. By collecting and analyzing secondary data from various sources, including literature, case studies, and empirical research, the study assesses ground improvement techniques' effectiveness, efficiency, and performance in similar soil and geotechnical conditions. The objective is to determine whether CMCs are the most beneficial approach for enhancing the stability and performance of the highway or if alternative methods, which require rapid installation and high load-bearing capacity while minimizing soil disruption, might be more appropriate. The study highlights that Deep Soil Mixing (DSM) offers advantages comparable to CMCs and has proven effective in different soil conditions. This research aims to provide valuable insights into selecting optimal ground improvement techniques for bridge foundations in challenging soil conditions, ensuring stability and performance while addressing project-specific requirements.

Keywords: Optimal Design, Bridge Foundation, Ground Improvement Techniques, Challenging Soil Conditions

Abstrak: Penelitian ini mengkaji desain optimal fondasi jembatan yang mengintegrasikan teknik perbaikan tanah dalam kondisi tanah yang menantang, menggunakan pendekatan studi kasus. Fondasi jembatan berfungsi untuk mentransfer beban dari jembatan ke tanah di bawahnya, sementara teknik perbaikan tanah bertujuan meningkatkan sifat tanah, terutama di lingkungan yang kompleks. Kondisi tanah yang sulit memberikan tantangan besar dalam perancangan dan konstruksi fondasi jembatan, sehingga insinyur perlu menggunakan metode khusus untuk memastikan stabilitas dan ketahanan jangka panjang. Solusi-solusi ini sangat penting di area dengan tanah yang lemah atau tidak stabil yang tidak mampu menopang struktur besar seperti jembatan. Penelitian ini bertujuan untuk melakukan analisis komparatif untuk mengevaluasi kelayakan penggunaan Controlled Modulus Columns (CMC) dalam proyek jalan raya di kawasan Jawa Tengah bagian utara, di mana kondisi tanah menjadi tantangan signifikan. Dengan mengumpulkan dan menganalisis data sekunder dari berbagai sumber, termasuk literatur, studi kasus, dan penelitian empiris, penelitian ini menilai efektivitas, efisiensi, dan kinerja teknik perbaikan tanah dalam kondisi geoteknik serupa. Tujuannya adalah untuk menentukan apakah CMC merupakan pendekatan yang paling menguntungkan untuk meningkatkan stabilitas dan kinerja jalan raya atau apakah metode alternatif yang memungkinkan instalasi cepat, kemampuan menahan beban tinggi, serta meminimalkan gangguan pada tanah lebih sesuai. Penelitian ini juga menyoroti bahwa Deep Soil Mixing (DSM) menawarkan keunggulan yang sebanding dengan CMC dan terbukti efektif pada berbagai kondisi tanah. Penelitian ini bertujuan memberikan wawasan berharga dalam memilih teknik perbaikan tanah yang optimal untuk fondasi jembatan pada kondisi tanah yang sulit, memastikan stabilitas dan kinerja sekaligus memenuhi kebutuhan spesifik proyek.

Kata kunci: Desain Optimal, Fondasi Jembatan, Teknik Perbaikan Tanah, Kondisi Tanah Terdegradasi

1. INTRODUCTION

The design of bridge foundations is a crucial component of civil engineering, as it guarantees the stability and durability of bridge constructions (Li et al., 2020). The primary objective of a bridge foundation is to transmit the stresses exerted by the bridge to the underlying soil (Kudryavtsev et al., 2021). This requires a comprehensive assessment of the soil and surrounding factors. Bridge foundation techniques typically include shallow, deep, pile, and drilled shafts (Khalilovich et al., 2020). Every approach has distinct applications and is selected depending on load capacity, soil properties, and environmental repercussions. Establishing a solid and long-lasting base is crucial to guarantee the safety and longevity of the bridge.

Ground development techniques are crucial for improving soil characteristics, particularly in challenging settings (de Almeida et al., 2023). These solutions are crucial in regions with frail or unsteady soils that cannot sustain substantial structures such as bridges. Techniques such as soil stabilization, compaction, grouting, and geosynthetics are frequently utilized to enhance soil strength and decrease settlement. Ground restoration enhances the soil's load-bearing capacity and reduces the likelihood of liquefaction and erosion. These technologies are vital for effectively carrying out infrastructure projects in challenging soil conditions.

Diverse ground augmentation techniques have been effectively employed globally to support substantial infrastructure projects (Durgadevi et al., 2022). Deep mixing techniques have been extensively utilized in Japan to enhance the quality of soft clay soils (Neha Madhava Sundhram & J. P. Pramod, 2024). The Tokyo Bay Aqua-Line, a project that involved both a bridge and tunnel, employed the technique of cement deep mixing to strengthen the bottom and provide structural stability for the entire system. The procedure entails combining cement with the existing soil to form soil-cement columns, which significantly improves the longevity and stability of the foundation. These advancements showcase the efficacy of ground improvement techniques in conquering difficult soil conditions.

Ground enhancement techniques have proven to help address challenging soil conditions encountered during bridge construction in Indonesia (Ongkowijoyo et al., 2021; Purnomo, 2011; Yang et al., 2019). The Suramadu Bridge encountered difficulties due to soft and compressible clayey soils, which posed issues throughout its construction process. To tackle this issue, preloading and vertical draining techniques were employed to accelerate the soil consolidation process and enhance its load-bearing capability. In addition, the technique of deep cement mixing was used to enhance the stability of the soil. Implementing these procedures ensured the efficient construction of the bridge, demonstrating the versatility of ground improvement technologies in adapting to specific local circumstances.

Despite extensive research on various ground improvement techniques, a gap remains in understanding the comparative efficiency of different methods in highly compressible and weak soil conditions. A comprehensive examination of a particular case study will achieve this. The study will assess the pragmatic execution of these tactics by concentrating on a specific bridge project situated in a region with demanding soil conditions. This study aims to fill this research gap by conducting a comparative analysis of Controlled Modulus Columns (CMC) and alternative ground improvement techniques, such as Deep Soil Mixing (DSM) and Jet Grouting, in the context of a roadway project in North-Central Java. The urgency of this research lies in ensuring the effectiveness, cost-efficiency, and long-term performance of bridge foundations built on weak soils.

2. METHODOLOGY

The study article will employ a comprehensive comparative analysis to evaluate the suitability of Controlled Modulus Columns (CMC) for the roadway between Pemalang and Batang in north-central Java (Yee & Rizal, 2018). The study systematically gathers secondary data from literature, case studies, and empirical research to assess various ground improvement methods. This will enable a thorough assessment of different ground improvement methods. This review will thoroughly examine each technique's performance, efficacy, and efficiency, considering their application in comparable soil and geotechnical conditions. The analysis will specifically examine the implementation timetable, geographical locations, rationale for selecting specific projects, issues addressed, and execution methodologies of each ground improvement strategy. This thorough investigation aims to ascertain whether Controlled Modulus Columns

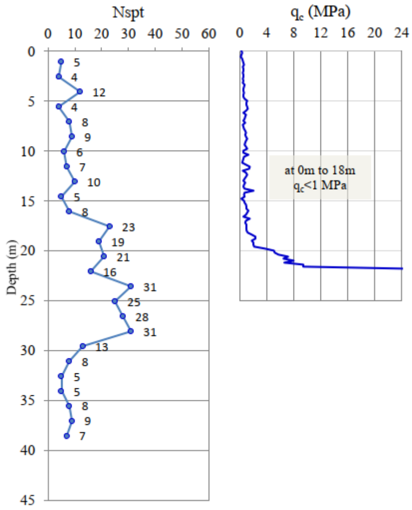
(CMC) are the optimal solution for enhancing the stability and performance of the highway, explicitly considering the problematic soil conditions found along its route in north-central Java.

3. RESULT AND DISCUSSION

3.1 Project Background & Ground Conditions

When constructing a roadway, it is necessary to consider several factors, such as the structural, geotechnical, construction, and maintenance aspects (Yee & Rizal, 2018). Maintaining a seamless and unbroken connection between a flexible pavement and a rigid bridge structure is crucial to avoid car inconvenience and potential hazards. Excessive settlement after construction can pose a significant problem when dealing with heavy, compressible, and cohesive soil deposits. Moreover, there is a possibility of instability occurring during the process of filling the embankment if the load-bearing capacity is surpassed. Substantial differential settling in the transition area may lead to sudden bumps, necessitating ongoing maintenance that disrupts highway operations and generates substantial expenses.

Ground rehabilitation techniques were considered the most feasible approach, considering the expensive nature of structural solutions and the insufficient condition of the soft, cohesive soil (Yee & Rizal, 2018). Initial site surveys were carried out (**Error! Reference source not found.**), and the Standard Penetration Test (SPT) results indicated that the soil remained solid up to 18 meters. Afterwards, the soil transitioned to a densely packed state until it reached a depth of 28 meters. Beyond that level, it returned to a solid state until it reached its maximum depth of 40 meters. The ramifications of these findings are disconcerting. When selecting ground improvement techniques, we considered environmental constraints such as a strict construction timeline, the need to prevent damage to existing structures, and the goal of minimizing vibration and lateral soil movement throughout the project. Given these limitations, Controlled Modulus Columns (CMC) were selected due to their ability to generate negligible vibrations and exceptional load-bearing capability while mitigating the possibility of column bulging.



Gambar 1. Typical SPT N-Values and Cone Resistance (qc) Values.
Source: (Yee & Rizal, 2018)

3.1 Comparative Analysis

Deep Soil Mixing (DSM) and Jet Grouting are ground improvement techniques that are specifically compatible and comparable to Controlled Modulus Columns (CMC). Deep Soil Mixing (DSM) is a technique that involves blending the existing soil with cementitious materials to form soil-cement columns, hence enhancing the strength and rigidity of the ground (Solihu, 2020). This technique is highly advantageous for construction projects that require improved soil stability and offers other benefits, such as reduced vibration during the mixing process, making it suitable for sensitive environments (Yung et al., 2022). DSM, also known as Deep Soil Mixing, efficiently controls horizontal soil displacement by improving load-bearing capacity, significantly reducing soil settlement(Jung et al., 2020). DSM, similar to CMC, builds composite ground systems that enhance load-bearing capacity and control settlement with minimal disruption to the surrounding environment.

Jet grouting is a method employed to improve the soil's quality by injecting pressurized streams of grout into the ground, causing the creation of a solidified mass of soil (Manne et al., 2020). This technique enhances the mechanical properties of the soil by forming solidified grout columns (Guler & Gumus Secilen, 2021). These columns stabilize the adjacent soil and reduce lateral displacements. It exhibits less vibration than conventional pile driving, rendering it highly suitable for projects in vibration-sensitive areas. The increased stiffness and ability to support the weight these columns provide lead to a substantial reduction in settlement (Manne et al., 2020). Jet grouting is a versatile method that may be applied to several soil types, including soft clays, silts, sands, and gravels. It is frequently used for supporting structures, managing leakage, and securing slopes. The method offers exceptional adaptability in its application, exact control over the shape and placement of the filled columns, and achieves remarkable durability and resistance to water infiltration. However, it is costly and complex, requiring careful oversight and perhaps leading to difficulties with waste management.

Deep Soil Mixing (DSM) is a method that involves blending soil and cementitious materials underground utilizing rotating augers or mixing equipment, resulting in the formation of soil-cement columns (Kang & Cheung, 2023; Yung et al., 2022). These columns significantly improve the soil's durability and stiffness. DSM, or Deep Soil Mixing, is a highly efficient technique for improving the characteristics of soft clays, silts, and organic soils. It is widely used for strengthening the foundations of structures, retaining walls, and embankments. DSM has numerous advantages, including reduced vibration and noise during installation, effectiveness in diverse soil conditions, enhanced shear strength, and lower compressibility. Nevertheless, the utilization of DSM requires careful control over the quantity of cement employed and the precision of the mixing procedure, and its installation can be time-intensive and require a substantial amount of manual work (Kitazume, 2021).

Controlled Modulus Columns (CMC) are formed by placing displacement augers into the ground and injecting grout, forming a stable column (Yee & Rizal, 2018). This technology enhances the load-bearing capacity of the ground and reduces subsidence, resulting in a composite ground system composed of various materials. CMC is particularly suitable for soft, cohesive soils, loose sands, and organic soils, making it a favoured choice for supporting structures, embankments, and bridge foundations. CMC offers various advantages, including minimal soil displacement and vibration, efficient load distribution, improved ground rigidity, and rapid installation with immediate load-bearing capability. However, the method requires specialized equipment and skilled operators, and it can only be used on certain types of soil with specific compositions and depths.

When assessing the prices of Deep Soil Mixing (DSM) and Controlled Modulus Columns (CMC), it is crucial to consider factors such as the costs of materials, equipment, and the complexities of the installation process. DSM typically requires less expensive equipment but utilizes more costlier cementitious binders, increasing material expenses. Furthermore, DSM necessitates a substantial amount of human labour and functions at a slower rate, leading to increased overall operational costs. Nevertheless, CMC utilizes expensive grout and advanced drilling equipment, increasing initial costs. However, the accelerated installation process of CMC can reduce labour costs and project time, thereby compensating for the initial higher expenses.

Tabel 1. Comparison Table

Aspect	Controlled Modulus Columns (CMC)	Deep Soil Mixing (DSM)	Jet Grouting
Installation Method	Displacement auger and grout	Mixing soil with cementitious materials	High-pressure grout jets
Vibration	Minimal	Minimal	Low
Lateral Soil Movement Control	Yes	Yes	Yes
Settlement Reduction	Yes	Yes	Yes

Applications	Foundations, embankments	Foundations, retaining walls	Underpinning, seepage control
Advantages	Efficient load transfer, rapit installation	Effective in various soild, enhances shear strength	Flexible, high strength, low permeability
Limitations	Requires specialized equipment	Cement content control, slow installation	High cost, complex equipment

Source: Author

Selecting ground improvement techniques depend on the project's unique requirements, such as soil conditions, project scale, and time constraints. The findings suggest that while CMC provides rapid installation and strong load-bearing capacity, DSM offers a more adaptable and cost-effective solution for large-scale applications. Jet Grouting, though highly effective, is expensive and complex, requiring advanced oversight. The decision between these techniques must be based on project-specific requirements, including soil conditions, cost constraints, and construction timelines.

4. CONCLUSION

In order to maintain stability and safety, it is crucial to thoroughly analyze several factors, such as the structure, soil conditions, construction process, and continuous maintenance when building a highway between Pemalang and Batang in north-central Java. An important issue is a potential for excessive settling, particularly in regions with dense, compressible, and cohesive soils. This might result in instability during the process of filling embankments and give rise to abrupt abnormalities in the road surface, necessitating costly and disruptive maintenance interventions. While Controlled Modulus Columns (CMC) were first favoured, structural solutions' high costs and restrictions have led to recognizing alternate ground augmentation methods, such as Deep Soil Mixing (DSM) and Jet Grouting, as viable possibilities. Deep soil mixing (DSM) is a method that involves blending soil and cementitious ingredients to form soil-cement columns. DSM exhibits comparable benefits to a different technique known as columnar mixed cement (CMC) and has demonstrated efficacy in numerous soil conditions. By addressing the research gap in ground improvement comparisons, this study provides valuable insights for optimizing bridge foundation designs in weak soil conditions. Future research should further investigate hybrid approaches integrating multiple techniques for enhanced efficiency and cost-effectiveness.

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