

Design and Fabrication Analysis of Single Pile Foundation for Offshore Jacket Structures

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Abstrak

Meningkatnya kebutuhan akan struktur lepas pantai yang efisien secara biaya telah mendorong pengembangan sistem fondasi alternatif, salah satunya adalah fondasi tiang tunggal (*single pile foundation*). Penelitian ini menyajikan analisis komprehensif terhadap aspek perancangan dan fabrikasi fondasi tiang tunggal yang diterapkan pada struktur *offshore jacket*. Kajian ini berfokus pada mekanisme transfer beban, interaksi tanah–tiang, integritas struktur, serta tantangan dalam proses fabrikasi. Metode yang digunakan meliputi pendekatan analitis dan studi literatur untuk mengevaluasi kelayakan serta kinerja sistem tersebut. Hasil penelitian menunjukkan bahwa kapasitas dan stabilitas fondasi sangat dipengaruhi oleh diameter tiang, kedalaman penetrasi, serta karakteristik tanah di lokasi pemasangan. Analisis juga menunjukkan bahwa beban lateral akibat gelombang dan arus merupakan faktor dominan yang memengaruhi respons struktur dan memerlukan evaluasi interaksi tanah–tiang yang akurat. Dari aspek fabrikasi, kualitas pengelasan, ketepatan perakitan, dan prosedur inspeksi memiliki peran penting dalam menjaga integritas struktural dan keandalan jangka panjang. Secara keseluruhan, fondasi tiang tunggal dapat menjadi solusi yang efisien dan andal untuk struktur *offshore jacket* pada kondisi tanah yang relatif seragam dan beban operasi yang moderat, dengan syarat dilakukan analisis geoteknik yang memadai serta pengendalian mutu fabrikasi yang ketat.

Kata Kunci: *Fondasi Tiang Tunggal, Offshore Jacket, Fabrikasi, Interaksi Tanah–Struktur, Teknik Lepas Pantai.*

Abstract

The increasing demand for cost-efficient offshore structures has led to the development of alternative foundation systems, one of which is the single pile foundation. This study presents a comprehensive analysis of the design and fabrication aspects of single pile foundations applied to offshore jacket structures. The research focuses on load transfer mechanisms, soil–pile interaction, structural integrity, and fabrication challenges. A combination of analytical methods and literature review is employed to evaluate the feasibility and performance of the system. The results indicate that foundation capacity and stability are strongly influenced by pile diameter, embedment depth, and site-specific soil characteristics. The analysis also shows that lateral loads induced by waves and currents are dominant factors affecting structural response and require accurate evaluation of soil–pile interaction. From a fabrication perspective, welding quality, assembly accuracy, and inspection procedures play a critical role in maintaining structural integrity and long-term reliability. Overall, single pile foundations can provide an efficient and reliable solution for offshore jacket structures under relatively uniform soil conditions and moderate loading scenarios, provided that adequate geotechnical assessment and strict fabrication quality control are implemented.

Keywords: *Single Pile Foundation, Offshore Jacket, Fabrication, Soil–Structure Interaction, Offshore Engineering.*

INTRODUCTION

Offshore jacket structures are widely used in the oil and gas industry to support production facilities in shallow to intermediate water depths [1], [2]. Traditionally, these structures rely on multi-pile foundation systems to distribute loads safely into the seabed [1]. These foundation systems have been extensively applied because they provide adequate resistance against vertical, lateral, and overturning loads generated by environmental actions such as waves, currents, and wind [9], [12]. The structural integrity of offshore platforms depends significantly on the interaction between the jacket structure, foundation system, and surrounding soil conditions, making foundation design a critical aspect of offshore engineering practice [3], [4]. In addition, industry standards and classification societies have established comprehensive design requirements to ensure the safety and reliability of offshore foundations throughout their operational life [12], [15]. However, increasing project cost pressures and the need for simplified installation procedures have encouraged the exploration of alternative foundation concepts [13].

The single pile foundation system has emerged as a promising solution, particularly for small to medium offshore platforms [17]. Unlike conventional systems, this approach utilizes a single large-diameter pile to support the entire jacket structure. While this reduces fabrication complexity and installation time, it also introduces significant engineering challenges related to load concentration and soil behavior [2], [5]. The foundation must be capable of resisting combined axial, lateral,



and moment loads while maintaining acceptable displacement and rotation limits under both operational and extreme environmental conditions [7], [11]. Since all structural loads are transferred through a single load path, accurate assessment of pile capacity and soil–structure interaction becomes increasingly important [14], [18]. Furthermore, nonlinear soil behavior, cyclic loading effects, and dynamic responses induced by waves and operational activities can significantly influence the long-term performance of single pile foundations [19], [20]. Advances in offshore geotechnical engineering, numerical modeling techniques, and fabrication technologies have contributed to improving the feasibility and reliability of this foundation concept for offshore applications [4], [17].

From a construction perspective, the adoption of a single pile foundation can reduce offshore installation activities, thereby minimizing vessel utilization time and associated marine operation costs [6], [13]. The simplified structural configuration may also facilitate fabrication processes and quality control procedures during manufacturing [10], [16]. Nevertheless, successful implementation requires careful consideration of pile geometry, material strength, welding quality, installation tolerances, and site-specific geotechnical conditions to ensure satisfactory structural performance and serviceability throughout the design life of the platform [5], [10], [15].

This paper aims to analyze the design considerations, fabrication processes, and performance characteristics of single pile foundations in offshore jacket applications. Particular attention is given to the influence of geotechnical parameters, structural design requirements, fabrication quality, and operational performance in determining the overall effectiveness of the single pile foundation system for offshore structures [3], [11], [17].

LITERATURE REVIEW

Offshore Jacket Structures

Jacket structures are steel-framed tubular systems designed to withstand environmental loads such as waves, currents, and wind [9], [12]. They are typically fixed to the seabed using driven piles [1]. The structural configuration consists of vertical legs and horizontal and diagonal bracings, forming a stable three-dimensional framework [10]. These structures have been widely adopted in offshore oil and gas developments due to their high strength, durability, and ability to operate effectively in shallow to intermediate water depths [1], [2]. The design of jacket structures must consider static and dynamic loading conditions, including operational loads, environmental loads, and extreme storm events to ensure long-term structural integrity and safety [12], [15]. Proper integration between the jacket and foundation system is essential to achieve adequate load transfer and overall platform stability [2], [13].

Single Pile Foundation Concept

The single pile foundation, often comparable to monopile systems used in offshore wind turbines, employs a single large-diameter steel pile [17]. This pile transfers loads through a combination of end bearing and shaft resistance [3], [5]. The concept is particularly advantageous in homogeneous soil conditions and moderate loading scenarios [3]. Compared with conventional multi-pile systems, the use of a single pile can reduce fabrication requirements, installation time, and offshore construction activities [6], [13]. However, because all structural loads are concentrated on a single foundation element, the pile must be designed to resist significant axial, lateral, and overturning loads while maintaining acceptable serviceability limits [7], [11]. The feasibility of this foundation concept depends largely on pile geometry, soil characteristics, and the magnitude of environmental loading acting on the structure [17], [18].

Soil–Pile Interaction

The behavior of a single pile foundation is governed by soil–structure interaction [14]. Key parameters influencing the performance of the foundation include axial bearing capacity, lateral resistance, pile deflection and rotation, as well as soil stiffness and stratification. The interaction mechanism determines how loads are transferred from the pile to the surrounding soil and significantly affects the overall response of the offshore structure [4], [5]. Accurate evaluation of soil properties is therefore essential for predicting foundation performance and ensuring structural reliability [11], [19]. In offshore environments, cyclic loading from waves and currents may cause changes in soil behavior and pile response over time, making nonlinear analysis an important consideration in foundation design [14], [20]. Furthermore, both ultimate capacity and serviceability requirements must be satisfied to ensure safe and efficient operation throughout the platform's design life [7], [18].

METHODOLOGY

This study adopts a qualitative and analytical approach, combining theoretical design principles with fabrication practices. The methodology includes:

1. Data Collection

Relevant data are obtained from geotechnical soil reports, environmental loading conditions, and material specifications required for offshore jacket structure analysis and foundation design. The collected geotechnical data include soil



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stratification, shear strength, bearing capacity, and stiffness parameters that influence pile performance and soil–structure interaction [3], [11], [19]. Environmental data consist of wave, current, and wind loading conditions that govern the design loads acting on offshore structures [2], [9], [12]. Material specifications, including steel grade, mechanical properties, and fabrication requirements, are gathered to ensure compliance with applicable offshore design standards and construction practices [1], [10], [15].

2. Structural Analysis

The structural analysis includes axial load capacity calculation, lateral load and bending moment analysis, as well as stability and safety factor evaluation to ensure the structural reliability of the single pile foundation system [5], [11]. Axial capacity assessment considers the contribution of shaft resistance and end bearing in supporting vertical loads [3], [18]. Lateral load analysis evaluates pile response under environmental loading conditions and examines pile deflection, rotation, and bending behavior [7], [20]. In addition, the effects of soil–pile interaction are considered to determine the overall structural performance and foundation stability under operational and extreme loading scenarios [4], [14], [17]. The analysis is conducted in accordance with offshore structural design principles and industry standards [1], [12].

3. Fabrication Assessment

Fabrication processes are evaluated based on material preparation techniques, welding procedures, assembly accuracy, and inspection and quality control methods to ensure compliance with offshore structural standards [15], [16]. The assessment includes verification of dimensional tolerances, weld quality, structural alignment, and fabrication sequence to minimize defects that may affect structural integrity [10], [15]. Particular attention is given to welding performance and quality assurance procedures because welded connections play a critical role in the strength and durability of offshore steel structures [16]. Inspection activities such as visual examination and non-destructive testing are also considered to verify compliance with applicable classification and offshore construction requirements [6], [15].

RESULT AND DISCUSSION

Axial Capacity of Single Pile

The axial capacity of the pile is determined by the sum of end bearing resistance and skin friction along the shaft [5], [18]. The results show that increasing pile diameter significantly enhances load-bearing capacity. However, this also increases fabrication complexity and material cost [17]. Larger pile diameters provide greater contact area between the pile and surrounding soil, resulting in higher shaft resistance and improved load transfer efficiency [3], [18]. In addition, the ultimate axial capacity is influenced by soil properties, pile geometry, and installation conditions [4], [11]. Therefore, an optimal balance between structural performance and economic feasibility must be considered during the design process [1], [17].

Lateral Load Behavior

Lateral loads induced by waves and currents play a dominant role in offshore structures [9]. The analysis indicates that pile stiffness and embedment depth are critical factors in controlling deflection [7]. Excessive lateral displacement may compromise structural integrity and operational safety [6], [20]. The results further indicate that increasing pile diameter and penetration depth improves lateral resistance by enhancing soil confinement around the pile [5], [7]. Soil stiffness also has a significant effect on lateral performance, as softer soils generally produce larger displacements and bending moments under the same loading conditions [11], [14]. Consequently, accurate assessment of environmental loading and soil characteristics is essential for reliable foundation design [2], [12].

Optimal Embedment Depth

The embedment depth must be sufficient to mobilize both axial and lateral resistance [3], [5]. In soft soil conditions, deeper penetration is required to reach more competent soil layers [19]. The study suggests that improper depth selection can lead to instability or excessive settlement. Furthermore, insufficient embedment depth may reduce the pile's ability to resist overturning moments generated by environmental loads, thereby increasing structural vulnerability [7], [9]. The findings emphasize that embedment depth should be determined based on detailed geotechnical investigations and site-specific design requirements [4], [11]. Proper penetration depth not only improves foundation stability but also enhances the long-term performance of the offshore structure [17].

Fabrication Process Analysis

The fabrication process begins with material preparation, where steel plates are cut and rolled into cylindrical sections to form large-diameter piles [16]. Precision at this stage is essential to ensure proper fit-up during welding. Welding is a critical aspect of fabrication because it directly affects structural strength [15]. Both longitudinal and circumferential welds must meet stringent standards [12], as welding defects such as cracks, porosity, and lack of fusion can significantly reduce structural integrity [16]. Furthermore, the integration of the pile with the jacket structure requires accurate assembly and alignment [10]. Misalignment may lead to installation difficulties and uneven load distribution. To ensure fabrication quality, non-destructive



testing (NDT) methods such as ultrasonic testing (UT) and radiographic testing (RT) are used to detect internal defects [15]. In addition, quality assurance procedures must comply with international standards [12].

The analysis shows that fabrication quality plays a crucial role in determining the reliability and service life of offshore foundation systems [10], [15]. Strict control of dimensional tolerances, welding procedures, and inspection activities is required to minimize the risk of structural failure during installation and operation [12], [16]. Moreover, compliance with offshore construction and classification requirements contributes to improved safety, durability, and operational performance throughout the design life of the structure [1], [15]. The adoption of rigorous fabrication and quality control practices therefore remains essential for the successful implementation of single pile foundations in offshore jacket applications [6], [13].

ADVANTAGES AND LIMITATIONS

The single pile foundation system offers several advantages, including a reduced number of structural components, a simplified fabrication process, faster installation time, and potential cost savings [13], [17]. The reduction in structural complexity can minimize offshore construction activities and shorten installation schedules, which may contribute to lower project risks and reduced vessel utilization requirements [6], [13]. In addition, the simplified foundation configuration can facilitate inspection, maintenance, and overall project management compared to conventional multi-pile systems [10], [17]. The use of a single large-diameter pile also enables efficient load transfer when appropriate geotechnical conditions are available [3], [18].

However, the system also has several limitations, such as high load concentration on a single structural element, sensitivity to soil variability, and limited applicability in complex soil conditions. Since all structural loads are transferred through one pile, any deficiency in pile capacity or soil strength may significantly affect overall foundation performance [5], [14]. The system is particularly sensitive to changes in soil stiffness, stratification, and nonlinear soil behavior, which may influence both axial and lateral responses under operational and environmental loading conditions [11], [14], [20]. Furthermore, offshore structures are continuously subjected to cyclic loading from waves and currents, requiring careful evaluation of long-term foundation performance and serviceability [2], [9]. In addition, the system requires high precision in both fabrication and installation processes to ensure structural safety and performance [11], [14]. Compliance with recognized offshore design, fabrication, and quality assurance standards is therefore essential to achieve reliable operation throughout the service life of the structure [1], [12], [15].

CONCLUSION

The single pile foundation system presents a viable alternative for offshore jacket structures under suitable conditions [17]. The study demonstrates that this system can achieve adequate structural performance when supported by proper design and high-quality fabrication practices [1], [12]. The findings indicate that pile diameter and embedment depth are critical design parameters influencing foundation stability and load-bearing capacity [3], [5]. Larger pile diameters generally improve axial and lateral resistance, while adequate embedment depth is necessary to mobilize sufficient soil support and maintain structural stability under environmental loading conditions [7], [18].

In addition, soil-pile interaction significantly affects structural behavior [14]. Geotechnical characteristics such as soil stiffness, stratification, and strength properties directly influence foundation response, load transfer mechanisms, and long-term performance [4], [11], [19]. Therefore, detailed site investigation and geotechnical assessment are essential components of the design process.

Fabrication quality, particularly welding performance, also plays a vital role in ensuring structural integrity and long-term reliability [15], [16]. Accurate assembly, strict dimensional control, and comprehensive inspection procedures contribute significantly to the overall safety and durability of the foundation system [10], [12], [15]. Overall, the system is considered most suitable for offshore structures subjected to moderate loading and relatively uniform soil conditions [17], [19]. When supported by appropriate design methodologies, geotechnical evaluation, and quality-controlled fabrication practices, the single pile foundation system can provide an efficient and technically feasible foundation solution for offshore jacket applications [1], [6], [17].

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