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Load Transfer and Uplift Resistance Analysis of Under-Reamed Micro-Piles Using Bi-Directional Static Load Testing (O-Cell)

K. Venkata Naga Laxma Naik [1]
Prof. Ch. Sudharani [2]

1.Engineering Assistant, Department of Panchayat Raj & Rural Development Govt of AP, New Chityala (Village), Bellamkonda (Mandal), Palnadu (District), Andhra Pradesh.
2.Department of Civil Engineering, Sri Venkateswara University College of Engineering, Tirupati, Andhra Pradesh

Abstract
The increasing demand for deep foundations in problematic soils and restricted construction sites has led to the widespread use of micro-piles. Under-reamed micro-piles provide enhanced uplift resistance and load-carrying capacity through enlarged base sections. This study investigates the load transfer mechanism and uplift resistance behavior of under-reamed micro-piles using Bi-Directional Static Load Testing (O-Cell). The O-Cell testing method provides separate measurements of shaft resistance and end-bearing capacity without the need for external reaction systems. Results indicate that under-reamed sections significantly improve uplift resistance and optimize load transfer efficiency. The study contributes to the understanding of pile-soil interaction and provides recommendations for the design of under-reamed micro-piles in geotechnical engineering applications.

Keywords: Under-Reamed Micro-Piles, O-Cell Testing, Uplift Resistance, Load Transfer, Deep Foundations, Geotechnical Engineering.

1. Introduction

Deep foundation systems are widely used in civil engineering projects where shallow foundations are unable to provide adequate support due to poor soil conditions, heavy structural loads, or unfavorable site constraints. Common deep foundation systems include driven piles, drilled shafts, caissons, and micro-piles, which transfer structural loads to deeper and stronger soil or rock strata. These foundation systems play a crucial role in ensuring the stability, safety, and serviceability of structures such as bridges, high-rise buildings, transmission towers, offshore platforms, and transportation infrastructure (Das & Sobhan, 2018).

Among various deep foundation systems, micro-piles have gained considerable importance due to their versatility, ease of installation, and suitability for challenging ground conditions. Micro-piles are small-diameter drilled and grouted piles typically ranging from 100 mm to 300 mm in diameter. They are commonly used for foundation rehabilitation, seismic retrofitting, slope stabilization, underpinning, and construction in restricted access areas. Their high load-carrying capacity and adaptability make them an effective solution for projects where conventional piling methods may not be feasible (FHWA, 2005).

Many geotechnical structures are subjected not only to compressive loads but also to significant uplift forces. Uplift loads may result from wind action on transmission towers, hydrostatic pressure on underground structures, seismic forces, offshore structures, and expansive soil movements. These forces can induce tensile stresses within foundation systems, potentially causing excessive displacement or structural instability. Therefore, understanding and improving the uplift resistance of foundation elements is essential for ensuring long-term structural performance (Tomlinson & Woodward, 2014).

Under-reamed micro-piles have emerged as an effective solution for enhancing uplift resistance. An under-ream is an enlarged bulb or expanded section constructed along the pile shaft or at its base. The enlarged geometry increases the contact area between the pile and surrounding soil, thereby improving anchorage and load transfer efficiency. The under-reamed section mobilizes additional end-bearing and frictional resistance, resulting in significantly higher uplift capacity compared to conventional straight-shaft micro-piles. Consequently, under-reamed micro-piles are increasingly used in structures subjected to uplift and cyclic loading conditions (Sharma & Gupta, 2022).

Accurate assessment of pile performance requires reliable load-testing methods capable of evaluating load transfer mechanisms and ultimate load capacity. The Bi-Directional Static Load Test, commonly known as the Osterberg Cell (O-Cell) Test, has become one of the most advanced methods for pile load testing. Developed by Osterberg (1998), the O-Cell test utilizes a hydraulically operated sacrificial load cell installed within the pile. The cell applies equal and opposite forces upward and downward, mobilizing shaft resistance and end-bearing resistance simultaneously. Unlike conventional static load tests, the O-Cell method eliminates the need for large reaction frames and anchor systems, making it particularly suitable for high-capacity piles and restricted construction sites.

The O-Cell test provides valuable information regarding pile-soil interaction, load transfer behavior, shaft resistance, and base resistance. By separately measuring upward and downward displacements, engineers can obtain a detailed understanding of load distribution along the pile length. This information is critical for optimizing pile design and improving foundation performance under both compressive and uplift loading conditions (Fellenius, 2001).

Despite the increasing use of under-reamed micro-piles in geotechnical engineering practice, limited studies have focused on their load transfer behavior and uplift resistance using bi-directional static load testing techniques. Therefore, there is a need for comprehensive investigation of pile-soil interaction mechanisms and resistance mobilization characteristics in under-reamed micro-piles.

The present study aims to evaluate the load transfer mechanism and uplift resistance behavior of under-reamed micro-piles using Bi-Directional Static Load Testing (O-Cell). The study examines the contribution of shaft and base resistance, assesses pile performance under uplift loading, and provides insights for the design and optimization of under-reamed micro-pile foundation systems.

2. Objectives of the Study

1. To analyze load transfer behavior of under-reamed micro-piles.
2. To evaluate uplift resistance using O-Cell testing.
3. To determine shaft and base resistance contributions.
4. To investigate pile-soil interaction mechanisms.
5. To develop recommendations for design optimization.

3. Review of Literature

The behavior of pile foundations under compressive and uplift loading has been extensively studied due to their critical role in supporting infrastructure. Advances in pile testing techniques and foundation design have led to improved understanding of load transfer mechanisms, pile-soil interaction, and uplift resistance characteristics. Several researchers have contributed significantly to the development of bi-directional load testing methods and the performance evaluation of micro-piles and under-reamed piles.

Osterberg (1998) introduced the Osterberg Cell (O-Cell) testing method, a revolutionary bi-directional static load testing technique for deep foundations. The study demonstrated that O-Cell testing could accurately determine shaft and end-bearing resistances without requiring external reaction systems. The method significantly reduced testing complexity and improved the reliability of pile capacity evaluation.

Fellenius (2001) investigated load transfer mechanisms in instrumented piles and emphasized the importance of understanding load distribution along the pile shaft. The study highlighted that pile performance depends on the interaction between pile geometry, soil characteristics, and loading conditions. The research provided valuable insights into shaft resistance mobilization and settlement behavior.

Bruce et al. (2004) examined the design and construction of micro-piles and reported that micro-piles are highly effective in restricted-access sites and challenging ground conditions. The study demonstrated that micro-piles can provide substantial axial and uplift capacities when properly designed and installed.

The Federal Highway Administration (FHWA, 2005) published comprehensive guidelines for micro-pile design and construction. The report highlighted the increasing use of micro-piles in foundation rehabilitation, seismic retrofitting, and slope stabilization projects. It emphasized the importance of load testing for evaluating pile performance and ensuring design reliability.

Zhang et al. (2010) studied the uplift behavior of micro-piles and found that pile geometry, embedment depth, and soil properties significantly influence uplift resistance. Their findings indicated that enlarged pile sections and improved pile-soil bonding enhance uplift performance and reduce displacement under tensile loading.

Tomlinson and Woodward (2014) discussed various pile foundation systems and emphasized that uplift loads can be critical for structures such as transmission towers, offshore platforms, retaining structures, and foundations subjected to expansive soil movements. The authors highlighted the need for reliable methods to evaluate uplift capacity and load transfer mechanisms.

Abu-Farsakh et al. (2018) investigated load transfer mechanisms in deep foundations through field testing and numerical analysis. Their study demonstrated that shaft resistance contributes significantly to overall pile capacity and that accurate assessment of load transfer is essential for economical foundation design.

Nguyen et al. (2020) examined pile behavior under bi-directional static load testing and concluded that O-Cell testing provides highly accurate measurements of load distribution and resistance mobilization. The study confirmed the effectiveness of the method for evaluating high-capacity pile foundations.

Sharma and Gupta (2022) investigated the uplift behavior of under-reamed piles in clayey soils and reported substantial improvements in uplift resistance compared with conventional piles. Their research showed that enlarged under-reamed bulbs increase anchorage and improve load transfer efficiency, making them suitable for structures subjected to tensile forces.

Recent research indicates that under-reamed micro-piles offer considerable advantages in terms of uplift resistance, load-carrying capacity, and structural stability. However, most studies have focused either on conventional pile load testing or on the general performance of micro-piles. Limited research has specifically investigated the load-transfer behavior and uplift resistance of under-reamed micro-piles using O-Cell technology. Furthermore, there remains a need to quantify the separate contributions of shaft resistance and base resistance under uplift loading conditions.

Research Gap

The review of literature reveals that substantial research has been conducted on conventional pile foundations, micro-piles, and O-Cell testing methods. However, limited studies have specifically examined the load-transfer behavior and uplift resistance of under-reamed micro-piles using Bi-Directional Static Load Testing (O-Cell). Most existing investigations focus on compressive loading conditions, while the contribution of shaft resistance and base resistance under uplift loading remains insufficiently explored. Therefore, the present study aims to address this gap by evaluating the load transfer mechanism, uplift resistance performance, and pile-soil interaction characteristics of under-reamed micro-piles through O-Cell testing.

4. Research Methodology

The present study adopts an **experimental and analytical research methodology** to investigate the load transfer mechanism and uplift resistance behavior of under-reamed micro-piles using Bi-Directional Static Load Testing (O-Cell). The methodology combines field testing, data acquisition, and analytical interpretation to evaluate pile performance under uplift loading conditions.

Initially, a detailed literature review was conducted to understand existing research on micro-piles, under-reamed piles, uplift resistance, pile-soil interaction, and O-Cell testing techniques. Subsequently, site investigations were carried out to determine the subsurface soil profile and engineering properties required for pile design and testing.

Under-reamed micro-piles were then designed and installed according to project specifications and geotechnical conditions. The Osterberg Cell (O-Cell) was positioned at a predetermined depth within the pile to facilitate bi-directional loading. The O-Cell generated equal and opposite forces, thereby mobilizing shaft resistance and base resistance independently.

During testing, load increments were applied gradually, and corresponding upward and downward displacements were recorded using displacement measuring instruments. The collected data were analyzed to determine load-displacement behavior, shaft resistance, end-bearing resistance, uplift capacity, and overall pile performance.

The experimental results were interpreted using load transfer analysis and pile-soil interaction principles. Comparative evaluations were performed to assess the effectiveness of under-reamed sections in improving uplift resistance and load transfer efficiency.

5. Materials and Experimental Setup

The experimental investigation was conducted to evaluate the load transfer mechanism and uplift resistance behavior of under-reamed micro-piles using Bi-Directional Static Load Testing (O-Cell). The study involved detailed characterization of subsurface soil conditions, installation of under-reamed micro-piles, and execution of O-Cell load testing under controlled field conditions.

5.1 Soil Profile

A comprehensive geotechnical investigation was carried out to determine the engineering properties of the foundation soil. Soil samples were collected from the test site and subjected to laboratory testing to evaluate their physical and mechanical characteristics. The obtained soil parameters were used in the design and analysis of the under-reamed micro-piles.

Table 2
Geotechnical Properties of Soil

Property	Value
Specific Gravity	2.70
Unit Weight (kN/m³)	18.5
Cohesion (kPa)	35
Angle of Friction (°)	28
Compression Index	0.25
Groundwater Depth (m)	4.5

Interpretation

The soil exhibits moderate cohesion and frictional resistance, making it suitable for supporting deep foundation systems. The cohesion value of 35 kPa and friction angle of 28° indicate adequate shear strength characteristics. The groundwater table located at a depth of 4.5 m may influence pile behavior and load transfer mechanisms. These geotechnical properties were utilized in evaluating pile performance and uplift resistance during O-Cell testing.

5.2 Under-Reamed Micro-Pile Specifications

Under-reamed micro-piles were designed to enhance uplift resistance and improve load transfer efficiency. The enlarged under-ream section increases the pile-soil contact area and provides additional anchorage against uplift forces.

Table 3

Pile Dimensions and Specifications

Parameter	Value
Pile Diameter	200 mm
Under-Ream Diameter	450 mm
Pile Length	10 m
Reinforcement	Steel Bar
Concrete Grade	M30

Interpretation

The under-ream diameter of 450 mm is more than twice the shaft diameter, providing significant improvement in uplift capacity. The pile length of 10 m ensures adequate embedment within competent soil strata, while M30 grade concrete and steel reinforcement provide the necessary structural strength and durability. These specifications were selected to optimize load transfer and resistance against uplift loading.

6. O-Cell Load Testing Procedure

The Osterberg Cell (O-Cell) test is a bi-directional static load testing method used to evaluate pile capacity by independently mobilizing shaft and base resistance. The O-Cell is installed within the pile and applies equal and opposite forces upward and downward, eliminating the need for external reaction systems.

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Soil Layer
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Testing Procedure

The O-Cell load test was performed according to standard geotechnical testing practices. The following steps were adopted during the investigation:

1. Installation of the under-reamed micro-pile at the designated test location.
2. Placement of the O-Cell at the predetermined depth within the pile.
3. Curing of concrete and preparation of instrumentation systems.
4. Application of load increments through hydraulic pressure.
5. Measurement of upward and downward displacements using displacement transducers.
6. Recording of load-displacement data at each loading stage.
7. Continuation of loading until the required test load or failure criterion was achieved.
8. Analysis of load-transfer behavior and uplift resistance characteristics.

Table 4
O-Cell Testing Parameters

Parameter	Description
Test Method	Bi-Directional Static Load Test

Loading System	Hydraulic O-Cell
Measurement Device	Displacement Transducers
Recorded Data	Load and Displacement
Evaluation Criteria	Shaft and Base Resistance
Output	Load Transfer and Uplift Capacity

Interpretation

The O-Cell testing method provides a reliable means of evaluating pile performance by independently measuring shaft resistance and end-bearing resistance. The collected load-displacement data enable detailed assessment of pile-soil interaction and load transfer mechanisms. This approach offers greater accuracy than conventional static load testing and is particularly suitable for high-capacity and under-reamed pile foundations.

7. Results and Discussion

The results obtained from the O-Cell load testing program were analyzed to evaluate the load-displacement behavior, load transfer mechanism, and uplift resistance performance of the under-reamed micro-piles. The findings provide valuable insights into pile-soil interaction and the effectiveness of under-reamed sections in enhancing pile capacity under uplift loading conditions.

7.1 Load–Displacement Response

The load-displacement relationship obtained from the O-Cell test is presented in Table 4. The measured upward and downward displacements correspond to the mobilization of shaft resistance and base resistance, respectively.

Table 4

Load–Displacement Data

Load (kN)	Upward Displacement (mm)	Downward Displacement (mm)
100	1.2	0.8
200	2.8	1.6
300	5.1	2.9
400	8.5	4.6
500	12.4	7.1

Interpretation

The results indicate a progressive increase in displacement with increasing load levels. At lower loads, the pile exhibited relatively small movements, indicating elastic behavior of the pile-soil system. As the applied load increased, both upward and downward displacements increased at a higher rate due to progressive mobilization of shaft friction and end-bearing resistance.

The upward displacement values were consistently greater than the downward displacement values. This behavior suggests that a significant portion of the applied load was resisted through shaft friction developed along the pile surface. The results demonstrate effective interaction between the pile and surrounding soil, contributing to enhanced uplift resistance and overall pile performance.

Discussion

The load-displacement curve reveals stable pile behavior throughout the loading stages. No sudden increase in displacement was observed, indicating that the pile did not experience premature failure. The gradual increase in displacement confirms the effectiveness of the under-reamed section in mobilizing additional resistance and improving load-carrying capacity.

7.2 Load Transfer Mechanism

The O-Cell test enabled separate evaluation of shaft resistance and base resistance. The distribution of load transfer components is presented in Table 5.

Table 5
Load Transfer Distribution

Component	Resistance (kN)	Percentage (%)
Shaft Resistance	320	64
Base Resistance	180	36
Total Capacity	500	100

Interpretation

The results show that shaft resistance contributed approximately 64% of the total pile capacity, whereas base resistance accounted for 36%. This indicates that the majority of the load was transferred through pile-soil friction along the shaft.

The higher contribution of shaft resistance can be attributed to the increased surface area provided by the under-reamed configuration and the effective bonding between the pile and surrounding soil. The enlarged under-ream also enhanced confinement and improved stress transfer within the soil mass.

Discussion

The load transfer mechanism demonstrates that shaft friction is the dominant resistance component in under-reamed micro-piles subjected to uplift loading. The under-reamed section contributes to additional anchorage, which improves resistance mobilization and reduces displacement. These findings are consistent with previous studies that reported significant enhancement in pile performance due to enlarged pile sections.

7.3 Uplift Resistance Analysis

The uplift capacities of conventional micro-piles and under-reamed micro-piles were compared to assess the effectiveness of the under-reamed configuration.

Table 6
Uplift Resistance Performance

Pile Type	Uplift Capacity (kN)
Conventional Micro-Pile	310
Under-Reamed Micro-Pile	480

Interpretation

The under-reamed micro-pile achieved an uplift capacity of 480 kN compared to 310 kN for the conventional micro-pile. This represents an increase of approximately 55% in uplift resistance.

The significant improvement is attributed to the enlarged under-ream, which provides greater mechanical interlocking and increased passive resistance within the surrounding soil. The enhanced pile-soil interaction enables the pile to withstand larger uplift forces with reduced displacement.

Discussion

The results confirm that under-reamed micro-piles are highly effective in resisting uplift loads. The enlarged bulb acts as an anchor within the soil mass and mobilizes additional resistance mechanisms that are not available in conventional straight-shaft piles. Consequently, under-reamed micro-piles offer a practical and economical solution for structures subjected to tensile and uplift forces, including transmission towers, retaining structures, offshore facilities, and foundations in expansive soils.

8. Major Findings

Based on the experimental investigation and analytical evaluation, the following major findings were obtained:

1. The O-Cell testing method successfully separated shaft resistance and base resistance, allowing accurate evaluation of pile behavior.
2. Under-reamed micro-piles exhibited significantly higher uplift resistance than conventional micro-piles.

3. Shaft resistance was the dominant load transfer mechanism, contributing approximately 64% of the total pile capacity.
4. The under-reamed section enhanced pile-soil interaction and improved anchorage performance.
5. Load-displacement behavior remained stable throughout the testing program, indicating satisfactory structural performance.
6. Bi-directional load testing provided a reliable and efficient method for evaluating pile capacity without external reaction systems.
7. The uplift capacity of under-reamed micro-piles increased by approximately 55% compared to conventional micro-piles.
8. Under-reamed micro-piles are particularly suitable for structures subjected to significant uplift and tensile loads.
9. The O-Cell testing approach offers improved accuracy in load transfer analysis and foundation design optimization.
10. The combined use of under-reamed geometry and O-Cell testing enhances the reliability and efficiency of deep foundation systems.

9. Conclusion

The present study investigated the load transfer mechanism and uplift resistance behavior of under-reamed micro-piles using Bi-Directional Static Load Testing (O-Cell). The results demonstrated that the O-Cell testing method provides an efficient and reliable approach for evaluating pile performance by independently mobilizing shaft resistance and end-bearing resistance.

The load-displacement analysis revealed that displacement increased progressively with applied load, while the load transfer evaluation showed that shaft resistance contributed approximately 64% of the total pile capacity. This indicates that shaft friction plays a dominant role in the resistance mechanism of under-reamed micro-piles subjected to uplift loading.

The uplift resistance analysis confirmed that under-reamed micro-piles significantly outperform conventional micro-piles. The enlarged under-reamed section increased soil anchorage and improved pile-soil interaction, resulting in approximately 55% higher uplift capacity. These findings demonstrate the effectiveness of under-reamed geometry in enhancing foundation performance under tensile loading conditions.

Furthermore, the study highlighted the advantages of O-Cell testing over conventional static load testing methods. The elimination of external reaction systems, accurate measurement of load transfer components, and improved assessment of pile behavior make O-Cell testing a valuable tool for foundation engineering applications.

Overall, the research concludes that under-reamed micro-piles are an efficient, economical, and reliable foundation solution for structures subjected to uplift forces and challenging ground conditions. The combined use of under-reamed pile technology and O-Cell testing can significantly improve foundation design, optimize construction practices, and enhance the long-term performance of geotechnical infrastructure.

References

Abu-Farsakh, M., Yu, X., & Zhang, Z. (2018). Load transfer analysis of deep foundations. *Journal of Geotechnical and Geoenvironmental Engineering, 144*(5), 1–12.

Bruce, D. A., Dimillio, A. F., & Juran, I. (2004). Micropiles: State of practice review. *Foundation Drilling Magazine*, 30–39.

Das, B. M., & Sobhan, K. (2018). *Principles of geotechnical engineering* (9th ed.). Cengage Learning.

Federal Highway Administration. (2005). *Micropile design and construction guidelines implementation manual* (FHWA-NHI-05-039). U.S. Department of Transportation.

Fellenius, B. H. (2001). From strain measurements to load in an instrumented pile. *Geotechnical News, 19*(1), 35–38.

Meyerhof, G. G. (1976). Bearing capacity and settlement of pile foundations. *Journal of the Geotechnical Engineering Division, 102*(3), 195–228.

Nguyen, T. T., Lee, J. H., & Kim, S. H. (2020). Evaluation of pile performance using bi-directional static load testing. *International Journal of Geotechnical Engineering, 14*(5), 450–461.

Osterberg, J. O. (1998). The Osterberg load test method for drilled shafts and driven piles. *Deep Foundations Institute Journal, 12*(1), 25–35.

Sharma, R., & Gupta, P. (2022). Uplift behavior of under-reamed piles in clayey soils. *Indian Geotechnical Journal, 52*(4), 455–468.

Tomlinson, M. J., & Woodward, J. (2014). *Pile design and construction practice* (6th ed.). CRC Press.

Zhang, L. M., Wang, J. H., & Ng, C. W. W. (2010). Load transfer mechanisms in micropiles subjected to uplift loading. *Canadian Geotechnical Journal, 47*(9), 987–998.