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Extraction of Nearshore Steel Tubular Piles: An Application for a Bridge Construction in Abu Dhabi Emirate

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ABSTRACT: *This paper presents innovative methodologies for extracting vertical steel tubular piles from marine environments, specifically developed and implemented for a bridge construction project in Abu Dhabi Emirate, designed by the well-known architect Zaha Hadid. Two distinct techniques are described: the Uplift Water Pressure method for pile cutoff level above water, utilizing the uplifting force from pressurized water combined with the effects of the vibrating hammer; and the Water Jet method for underwater cutoff pile extraction, combining high-pressure water jetting with vibration to drive a casing pile around existing piles. The study demonstrates the effectiveness of these methods in cohesive soils and very weak rock formations, providing practical solutions for contractors managing temporary foundation systems, demolition of existing deep foundations, buried pipelines, cables, or other items in the seabed de-burial and salvage, and any other relevant application. Production rates achieved in the specific conditions were three piles per shift with the Uplift Pressure method and five piles during double-shift operations with the Water Jet method. These techniques offer significant advantages, reducing the extraction time, minimizing environmental impact, and enhancing operational flexibility for marine construction.*

KEYWORDS: pile extraction, water jetting, marine construction, temporary foundations, steel tubular piles, vibrating hammer, bridge construction, de-burial and salvage, Abu Dhabi, cohesive soils

SITE LOCATION: Geographic Database

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INTRODUCTION

The extraction of temporary steel tubular piles from marine environments presents significant technical and logistical challenges, particularly in projects with geometric constraints and varying soil conditions. Traditional pile extraction methods often prove inadequate in cohesive soils and soft rock formations commonly encountered in nearshore construction projects. The traditional pile extraction methods utilize the vibrating hammer's pullout along with the crane's applied pulling force. For the Vibro Hammer type ICE 815, the manufacturer's recommendation of 40 tons pulling capacity, combined with the crane's applied pulling force of 20 tons, limits the pulling capacity value to a figure of 60 tons only. The vibrating hammer's pullout effect is also restricted by the vibration duration and the soil characteristics.

This paper presents two building-on-experience methodologies developed specifically for the extraction of temporary vertical steel tubular piles driven into the seabed ground for a major bridge construction project in Abu Dhabi Emirate.

The techniques described herein address the practical challenges faced when conventional extraction methods fail to provide efficient solutions. The first method, termed the "Uplift Water Pressure method," utilizes the combination of pressurized water uplift force and vibrating hammer effects for piles cut above water level. The second approach, the "Water Jet method," employs high-pressure water jetting combined with vibration effect to facilitate the extraction of piles cut below water level.

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These methodologies were conceived, developed, and successfully implemented to address the specific requirements of extracting 128 underwater cut-off piles and numerous above-water piles within the constraints of an active marine construction environment. The paper aims to provide essential guidelines for contractors facing similar challenges and to contribute to the advancement of pile extraction techniques in marine geotechnical engineering.

PROJECT BACKGROUND AND SITE CHARACTERISTICS

Falsework Foundation System

The temporary pile foundation system supported module falsework for bridge construction spanning from the mainland to an island in Abu Dhabi Emirate as shown in Figure 1. The network consisted of temporary piles driven into both land and sea areas to support the construction of multiple bridge spans, as shown in Figure 2. Following the completion of deck concrete works and post-tensioning operations, the dismantling of falsework structures commenced.

Figure 1. *Temporary works – Falsework Erection on Piles.*

Figure 2. *Driving of Temporary Piles and Welding of Bracing.*

Due to time constraints and the challenges associated with dismantling falsework in a marine environment, the construction methodology was modified. All supporting piles for main spans were cut at seabed level rather than above water level,

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allowing for undisturbed access to floating barges and direct lowering of module falsework onto them as demonstrated in Figure3. Peripheral piles cut above water level were subsequently removed using the Uplift Water Pressure method during concurrent concrete repair work.

Figure 3. *Falsework Lowered onto a Barge.*

After achieving this milestone, and due to the environmental requirements to remove unnecessary material remains from the substrate, the water jet solution was developed and implemented for 128 underwater cut-off piles located 1.0 m above the seabed level, achieving the complete extraction of all the remaining piles.

A parallel trial using a Crawler Drill Rig "Casagrande C8-2" with 100 mm drill capacity, drilling isolated holes inside the pile and next to its internal perimeter, proved unsuccessful after three days of operation on a single pile. During these three days, eight ~110 mm holes were created throughout the length of the pile, next to its internal perimeter. The difficulty of drilling these holes from a floating unit, along with the ineffectiveness of pulling out the pile with the vibro hammer, after the formation of the holes, the extraction effort was diverted to the water jet technique. This result was somehow expected, due to the scale of the holes with reference to the pile perimeter and the effect that those could have only in the internal friction, leaving the external perimeter in contact with the surrounding soil.

Geological Conditions

The Geotechnical Investigation survey included nearshore drilling operations, as well as sampling, lab testing, and the provision of a factual report.

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Boreholes were drilled up to depths of 25 m from the existing and smooth morphological seabed level, i.e., at around -33 m CD, including collecting undisturbed and disturbed samples, and conducting the Standard Penetration Test (SPT) at selected depths. A split spoon sampler was used at 1.00 m intervals up to refusal, and thereafter, a continuous coring through rock. In the process of drilling, the borehole wall was protected with casing to prevent collapse.

Continuous sampling was performed at a rock bed. The drilling commenced with a rock drill bit with a diameter of no less than 50.8 mm, with three sets of coring sampling tubes. The procedure of coring complied with ASTM D2113, with the length of each sample no longer than 2 m. Sample length adjusted as per the respective nature of the rock bed. A record of drilling length and sample length was kept each time. Once the rock core was retrieved for the tests, it was wrapped in plastic and sealed in wax immediately with a permanent and clear detailed tag.

Elastometer Field Tests were executed with pressuremeter equipment to measure the elastic response of soil or rock around a borehole. The pressuremeter expands radially against the borehole walls while measuring pressure and volume changes to determine elastic and shear modulus.

The project site geology consists of medium dense to dense silty sand in the upper layers, underlain by weak calcarenite interbedded with weak mudstone and crystalline gypsum inclusions. Lower layers contain light grey weak siltstone with crystalline gypsum traces. The most critical geological substrate, crystalline gypsum, appears in lower layers with thicknesses ranging from 0.5 to 3 m. Table 1 presents the geotechnical parameters for the primary soil types encountered at the relevant to the manuscript depths, and Figure 4 illustrates the typical soil profile:

Table 1. *Geotechnical parameters envelope (min-max) for site soil conditions.*

Soil Type	**UCS (kg/cm^2)**	**Cu (kg/cm^2)**	**DD ($tons/m^3$)**	**Typical Depth (m, at CD)**
Light Creamy Calcarenite	10-25	6.3	1.61	Usually until -12.5 m
Creamy to light gray Mudstone	20-43	33.6	1.68	Until -15.0 & after -22.0 m
Light gray to dark gray Siltstone	30-40	15.0	1.75	From -12.5 to -22.0 m
Light gray Crystalline Gypsum	80-165	40-100	2.25	From -12.5 to -22.0 m

UCS: Unconfined Compressive Strength; Cu: Undrained Shear Strength; DD: Dry Density; CD: Chart Datum Level

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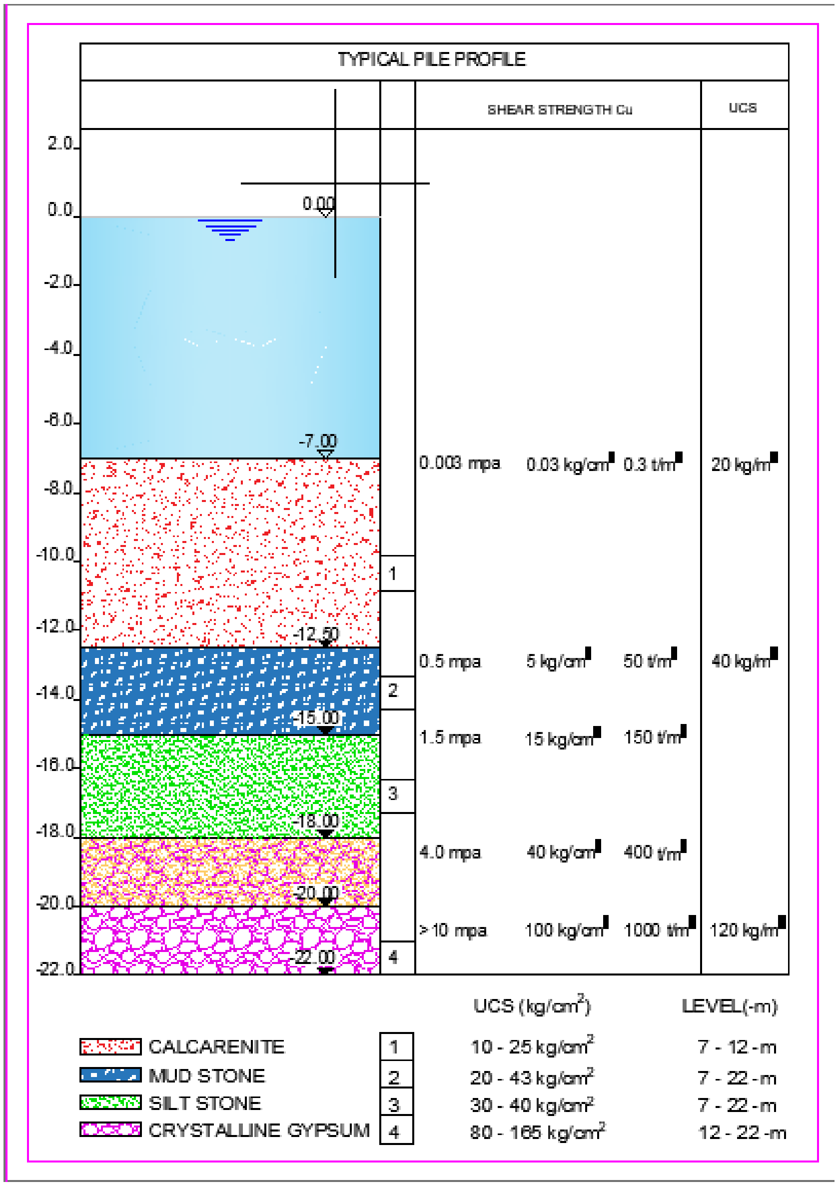

Figure 4. *Typical Soil Profile.*

Pile Driving Analysis and Driving Criteria

The falsework foundation system utilized two types of vertical, open-end steel tubular piles: 762 mm and 914 mm diameter, both with 16 mm wall thickness. Initial driving employed the vibrating hammers, ICE 1412C and ICE 815C, until being plugged into the hard layer strata starting at approximately -15.00 m CD depth.

The FEM (Finite Element Analysis) using the PLAXIS software, concluded for a D914 mm Pile the results below:

- Pile Toe -19.0, Ultimate Bearing Capacity in Compression = 1,200 tons
- Pile Toe -18.0, Ultimate Bearing Capacity in Compression = 1,000 tons
- Pile Toe -18.0, Ultimate Bearing Capacity in Extraction = 750 tons
- Pile Toe -16.0, Ultimate Bearing Capacity in Extraction = 300 tons

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Interpolating the above Ultimate Bearing Capacity in Extraction value of 300 tons for the D762 mm, results in 249 tons at -16.0 m.

- Inner Extreme Shear Stress = 165 KN/m2 (KPa) = 16.5 tons/m2
- Outer Extreme Shear Stress = 220 KN/m2 (KPa) = 22 tons/m2

(The values above were confirmed by the Pile Load Test on the D762 mm)

Pile Driving Analysis (PDA) revealed ultimate resistance values of 1,200 tons for 914 mm piles (775 tons shaft friction, 425 tons toe resistance) and 950 tons for 762 mm piles, approximately 65% from shaft friction and 35% from toe resistance.

Drop hammer driving criteria varied by pile diameter. For 914 mm piles using IHC S150 hammer at 60–70 energy level, the requirements include either five consecutive 250 mm increments with over 150 blows or one 250 mm increment with over 350 blows. For the 762 mm piles driven with IHC S90 hammer, the criteria required five consecutive 250 mm increments exceeding 150 blows or one increment exceeding 300 blows. Refusal of 914 mm piles was usually achieved between -20.0 m and -22.0 m CD.

Site Constraints

The bridge location at a narrow water channel near the Abu Dhabi islands complex presented specific operational challenges. While significant wave action was minimal, strong tidal currents dominated the area, changing direction throughout the day. Water levels varied from -1.0 m (LWL) to +1.0 m (HWL), with seabed levels ranging from -6.0 m to -8.0 m CD.

Bridge soffit elevation between +15.0 m and +17.0 m CD restricted the use of long boom cranes and extended machinery attachments. Permanent bridge piers founded on bored concrete piles from -6.0 m to -27.5 m CD prohibited bulk excavation below pilecap toe level (-6.0m CD) for temporary pile removal.

UPLIFT WATER PRESSURE METHOD

Principles and Design Considerations

This method combines vibrating hammer effects with uplift forces generated by a 25-bar pressure water pump and a crane tension force. In the circumference of the cutoff pile, a pile cap plug is welded and seals the internal area of the pile. The cap is provided with a 2-inch pipe inlet, through which pressure is exerted by the water pump. The pressure from the pump is exerted on the interior of the pile, and through the water, it is transferred to the soil surface on the seabed level, pushing the pile internally upwards. This pressure corresponds to an uplift force of 114 tons for a 762 mm pile diameter and 163 tons for a 914 mm diameter, supplemented by 20 tons of periodic crane tension during extraction operations.

The vibrating hammer's pullout effect depends on vibration duration and soil characteristics. The applied vibrations liquefy the surrounding soils, loosening soil cohesion and reducing friction resistance between the steel surfaces and the surrounding soil. However, vibrating hammers demonstrate reduced effectiveness in cohesive soils such as clays and weak rocks.

An approach to calculate the vibro hammer pullout effect utilizing the *Cole and Stroud formula,* Equation (1), for pile ultimate bearing capacity, was performed using the Cs value from the PDA for the Outer Extreme Shear Stress = 220 KN/m2 (KPa) = 22 tons/m2.

$$Q_{safe} = 1/F\,[C_u N_c A + a\, C_s\, \pi\, d\, L] = [Bearing + Skin\ Friction] \qquad (1)$$

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The general form Q = Q_bearing + Q_friction is fundamental to pile design and appears in virtually all geotechnical engineering textbooks.

Equation (1) Primary References:

1. Das, B.M. (2007). Principles of Foundation Engineering (7th Edition). Cengage Learning.

2. Tomlinson, M.J. and Woodward, J. (2015). Pile Design and Construction Practice (6th Edition). CRC Press.

3. Coduto, D.P., Yeung, M.C.R., and Kitch, W.A. (2016). Foundation Design: Principles and Practices (3rd Edition). Pearson.

Where:

Qsafe: Safe capacity in axial compression; Cu: Shear strength below pile base; Nc: Bearing capacity factor = 9; a: Multiplying factor (0.9 compression, 0.4 extraction); Cs: Drained average shear strength adjacent to shaft; A: Pile tip bearing area; L: Socket length; d: Pile diameter; F: Factor of safety = 1 (for the pullout resistance)

Remarks on the Equation (1):

The coefficient "a" is applied only to the skin friction component, yet the tip resistance may also be reduced by water jetting or vibration. Equation (1) assumes full tip resistance.

The value of 0.4 for "a" is empirical and may not be valid for different soil or rock types, depths, or extraction methods.

The coefficient "a" partially accounts for soil vibration, pore pressure changes, and loosening during extraction, but the real behavior can be significantly more complex.

For a 762 mm-diameter pile with a multiplying factor a=0.4 for extraction, the pullout resistance values were calculated from Equation (1) as 190 tons at -16.0 m CD and 274 tons at -20.0 m CD. The Bearing capacity element has not been taken into consideration on the pullout calculations. The derived value of 190 tons is less but of the same magnitude as the PDA Ultimate Bearing Capacity in Extraction for a 762 mm pile at -16.0 m CD, of 249 tons.

The 762 mm piles that were extracted with this method were mainly driven at a tip level of -16.0 m CD.

The extractions of the 762 mm piles corresponded to a vibro hammer pullout effect of 56 tons, when the Q pullout resistance *is* calculated from Equation (1) as demonstrated in Equation (2), up to a value of 115 tons when the Q pullout is calculated based on the PDA Ultimate Bearing Capacity in Extraction of a 762 mm pile, of 249 tons:

Q Pullout resistance = Vibro Pullout Effect + Uplift of water pressure + crane tension force ➔ Vibro Pullout Effect = 190 tons -114 tons – 20 tons = 56 tons (2)

The weight and the buoyancy of the pile cylinder have not been taken into consideration due to their minor effect compared to other values.

The value of 56 tons derived from the *Cole and Stroud formula* is higher, but close to the hammer manufacturer's recommendation of 40 tons pulling capacity for Vibro Hammer ICE 815. It is worth mentioning that the vibro pullout effect

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proved to be relevant with the vibrations applied time, until a threshold point, along with the stratigraphy for the sound vibration transmission.

Overall, this method proved to be effective only for the smaller diameter piles (762 mm diameter) founded up to a maximum of -16.0 m CD elevations.

For piles driven at levels more than the -16.0 m CD, corresponding to extraction values above 190 tons and up to 274 tons at -20.0 m CD, or even more, the Uplift Water Pressure extraction method couldn't be applied. This is attributed to the Q pullout resistance threshold value, which eventually is increased at depths more than the -16.0 m CD level. The increase in the pullout resistance is related to the accumulated effect of the skin friction at longer segments and skin friction variations at deeper elevations.

It is important to highlight that this procedure can only be carried out for piles with a cut-off level above the water table, due to the requirements of a pile cap plug welding.

Equipment and Methodology

Required equipment included:

- Crane Barge "Manitowoc 4400" with 24 m boom
- Vibrating Hammers "ICE 815" and "ICE 1412C"
- Water pump 160 l/min at 25 bars onboard crane barge
- Deck barge for extracted pile accommodation
- Fabricated pile cap plugs with 2-inch pipe nipples, Figure5

Figure 5. *Uplift Water Pressure Method setup, showing pile cap plugs with a 90° elbow and nipple.*

The methodology involved constructing access platforms around piles, fitting and welding pile cap plugs using floating cranes, connecting water hoses to inlet pipe nipples, and attaching vibrating hammers as shown in Figure 6. Following 45–60 minutes of continuous vibration, piles loosened from the surrounding cohesion and moved upward with a periodically applied 20-ton crane uplift force. Height restrictions under the bridge necessitated cutting piles at designated levels for complete extraction in two segments.

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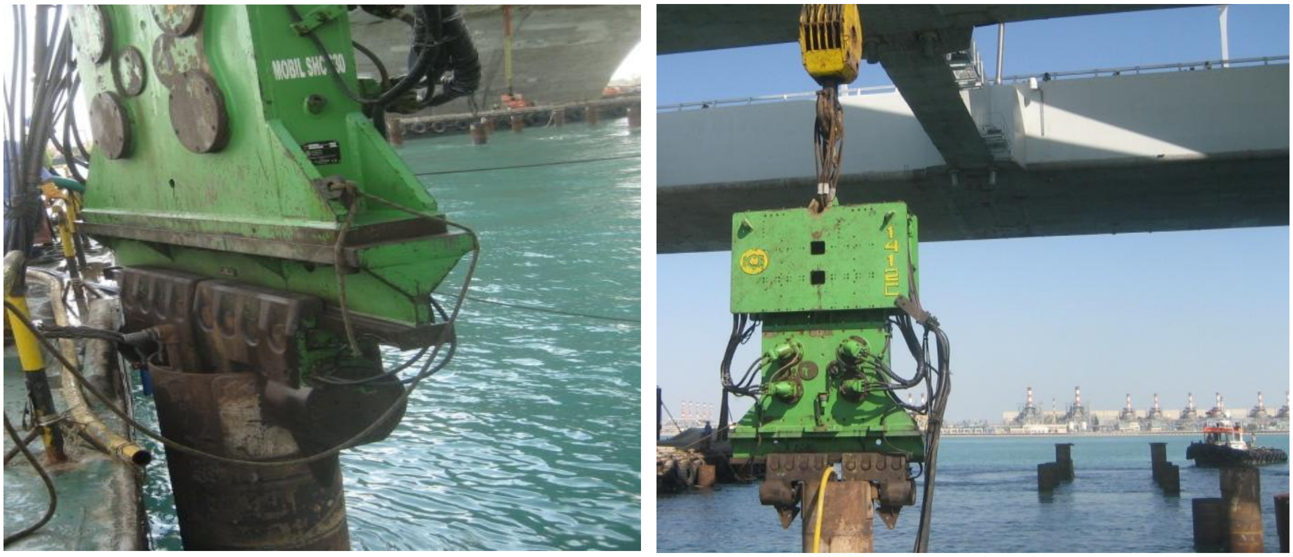

Figure 6. *Pile Extraction by Uplift Water Pressure Method.*

Production Results

The Uplift Water Pressure method achieved the removal of three piles during 12-hour shifts, with simultaneous pile cap plug welding at one plug per five hours for two welders. Failure rates approximated one failure per three to four piles, typically involving welded connection cracking between plugs and piles. A groove welding type was used in this process to fill the pile and pile cap groove with conventional electrodes for metal arc welding. In this temporary welding process, while qualified welders were introduced to perform the activity, testing of these joints was not to be included, due to the temporary nature of the works and the deployment of additional resources required for the NDT (nondestructive testing). Thus, the failure frequency of these welds could potentially be decreased in any other given project with the involvement of Quality Control testing.

Six pile cap plugs remained available throughout the operations to accommodate production and breakdown sequences.

WATER JET METHOD

Literature Reference

The Water Jet method, in general, combines high-pressure water jetting at the tip of the pile, sometimes used alongside air, with vibration force from a vibrating hammer to advance sheet piles or piles.

The general jetting mechanism is used for sheet pile-driving and enhances significantly the pile-driving performance in various soil conditions. It works by softening cohesive soils, liquefying silt, sand, and gravel, and breaking up rock beds or improved soils, thereby reducing the resistance at the toe of the pile during penetration. Additionally, in certain ground conditions, the returning water lubricates the pile's surface, minimizing the likelihood of pile plugging.

The required water flow rate varies with soil type: in permeable ground, a higher flow rate of 120 to 250 liters per minute per jet is needed at a lower pressure of around 10 bar. In contrast, in clayey or marly soils, a much lower flow rate combined with higher pressure (exceeding the soil's limit pressure) is more effective for cutting through the ground. The German Committee for Waterfront Structures, Harbours, and Waterways (EAU) recommends using water consumption rates of 30 to 60 liters per minute per pipe in silty, clayey, and extremely dense soils, supplied by high-pressure pumps operating at 250 to 500 bar (piston pumps).

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Other advantages of water jet-assisted pile-driving include:

- Reduction of the driving time by 60-75%
- Significant decrease in the required drive power and increase in the driven length
- Reduction of ground vibration velocities on nearby foundations and buildings
- Decrease in the noise exposure by up to 35%

Principles and Equipment

The concept involves driving tubular pile casing outside the existing pile perimeter, extending to their tips to create external soil detachment around the existing pile's outer surfaces. This method combines a powerful water jetting force at casing pile tips with variable tension from vibrating hammers to advance casing piles, enabling subsequent existing pile extraction, Figure 7.

Two casing piles were fabricated: 1020 mm diameter steel tubular pipe with 20 mm wall thickness for both pile types, and 914 mm diameter with 16 mm thickness for 762 mm piles (comprising 90% of the remaining underwater piles).

Figure 7. *Water Jet Method - Casing Pile.*

Steel plates ranging from 20 to 50 mm in thickness were welded inside the end and middle sections as guides for gap management and centering. The difference in the annulus gap between the casing piles and the existing pile proved to be insignificant for the work. These plates were used as guides to manage the gap difference and center the driven casing piles.

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The distribution of 12 nozzles was every 24 cm along the circumference of the tip of the 914 mm casing pile and every 27 cm for the 1020 mm, Figure 8.

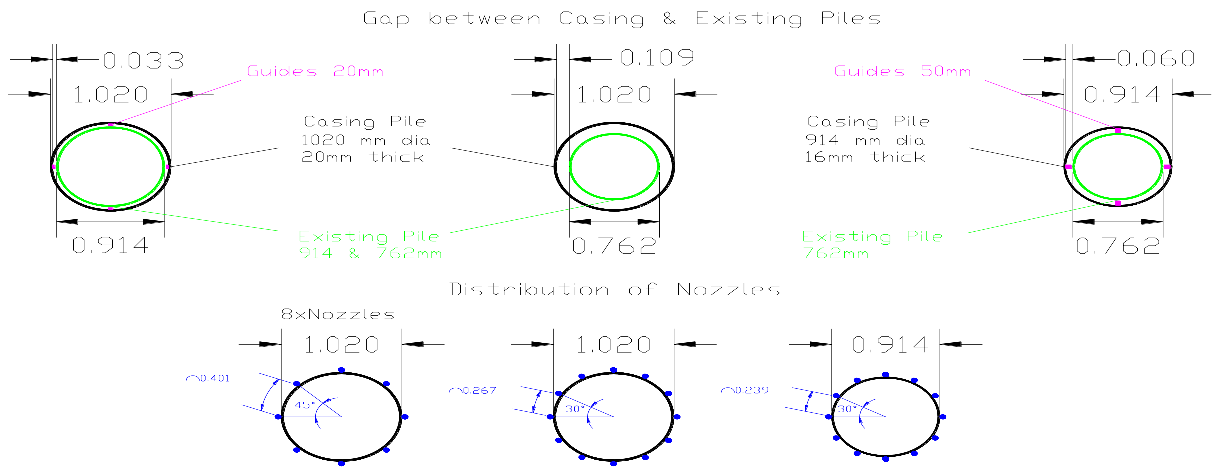

Figure 8. *Annulus Gap between Casing and Existing Pile and Distribution of Nozzles.*

Initially, eight nozzles were distributed around the 1,020 mm casing pile. The nozzles, which were distributed every 45o/401 mm around the casing pile circumference, proved from a field trial to be inefficient with relation to the 25o of nozzle spreading angle. Thus, the decision to increase the nozzles to 12 with 30o distribution angle around the casing pile was implemented.

The length of the casing piles was calculated to be 16.5 m to meet the site's geometrical requirements and restrictions.

High-pressure water pipes (22 mm outer diameter, 14 mm inner diameter) were distributed around external pile perimeters. The pipes were welded every 1.5 m and interconnected through distributors 80 cm below pile tops to accommodate hammer grapple connections, as demonstrated in Figure 9. The decision for the longitudinal welding spacing was empirical. The water pipes were not exposed to any lateral perpendicular stresses, and the welding was only to avoid any accidental lateral load. Water entered the system from a high-pressure unit (HPU) pump, mounted on the crane barge via a main umbilical line with a 1-inch (25.4 mm) inner diameter, leading up to the distributor at the top of the pile.

Figure 9. *Distribution Lines on top of Casing Pile.*

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The pipes were connected to nozzles at the pile tip by a fabricated threaded coupler. This coupler was welded to the pipes and threaded to the nozzles, which were protected by a pair of steel plates and a 10 cm long steel angle. The tip of the casing pile has been designed with a saw-tooth shape to enhance its ability to penetrate the ground, as shown in Figure 10.

Figure 10. *Couplers and water pipe's protective steel at the Casing Pile's tip.*

Equipment used:

- Crane Barge "Manitowoc 4400", 24 m Boom attached with:
- Vibrating Hammer "ICE 1412 C" (or smaller capacity hammer)
- High Pressure Unit (HPU) Pump "Casagrande MP7-600" 353 l/min at 345 bars onboard Crane Barge attached with a 4-inch submersible pump for water inlet.
- Diving Station mounted in the front side of the Crane Barge
- Deck Barge alongside Crane Barge to accommodate the casing and the extracted piles
- Fabricated pile casings (2 Nos: 1020 mm & 914 mm diameter)

Nozzle Design and Hydraulic Calculations

High-pressure threaded nozzles (1.7 mm diameter) were positioned 5 cm above pile tips. Individual nozzles delivered 29.5 liters per minute at 345 bars pressure. The high-pressure pump supplied 353 liters per minute at 345 bars, accommodating a maximum of 12 nozzles around the casing pile circumferences, Figure 11.

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Figure 11. *Testing of Nozzles: The two nozzles at the sides are spreading the water at an angle of 25°, and the two in the middle are jetting it linearly.*

Critical soil penetration involved the crystalline gypsum with a maximum UCS of 165 kg/cm² (i.e., 162 bars) and an Undrained Shear Strength of 100 kg/cm² (i.e., 98 bars). Since the applied water pressure of 345 bars exceeded the soil strength, the pump pressure was assumed to be sufficient for penetrating the ground effectively. This assumption was validated throughout the first trial of the casing pile assembly. No prior trials were conducted to validate this assumption, due to time limitations and scarcity of resources.

The impact force, dynamic pressure increases with the square of velocity (v^2), making speed the most critical factor, exerting localized pressure spikes that exceed the material's yield strength.

Water outflow velocities calculated using the *Bernoulli formula*, Equation (3), for closed conduit hydraulics, yielded 164 m/s for 1.7 mm nozzles and 59 m/s for 3.0 mm nozzles. The difference in half the diameter resulted in almost triple the water outflow speed (maintaining the same pressure), which highlights the importance of a nozzle reduced outfall diameter.

$$Z_A + P_A/\gamma + V^2{}_A/2g = Z_B + P_B/\gamma + V^2{}_B/2g + Hm + \sum hf(A\text{-}B) + \sum hL(A\text{-}B) \quad (3)$$

Where:

P: Pressure at points A and B; ρ: Fluid density; γ: Specific weight of fluid (ρg); g: Gravitational acceleration; v: Fluid velocity at points 1 and 2; z: Elevation above reference datum; Hm: Pump Pressure; ∑hf(A-B): Linear Losses; ∑hL(A-B): Local Losses

Operation and Methodology

Casing piles were designed to penetrate entirely until the existing pile tips for optimal production results, though advancement to 1.5 m above the tip yielded similar extraction results at reduced speeds. During operations, casing pile-driving was typically stopped approximately 50 cm above existing pile tips to prevent inadvertent dragging of the pile itself during the casing extraction, as shown in Figure 12. The driving logs of the temporary piles were available during the extraction operations to assess the details of the operations.

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Figure 12 and Figure 13 illustrate in detail the sequence of driving the casing pile, considering the geometric restrictions of the soffit. Following the installation of the casing pile, the initial setting was done by water jet only, followed by the vibro hammer. Once the casing was driven to the predetermined level, the extraction of the casing pile was executed in reverse order. The operation was completed with the extraction of the existing pile (EP) by the vibrating hammer. The entire extraction operation cycle was completed in approximately 120 minutes.

Once the casing pile was released from the ground at a certain level, the vibrating hammer was disconnected, and the divers then attached the casing pile to the crane hook using shackles and slings, allowing the casing pile to be removed from the annulus entrapment and placed back onto the barge. The vibro hammer is attached afterwards to the existing pile, and the removal operations of the pile commence.

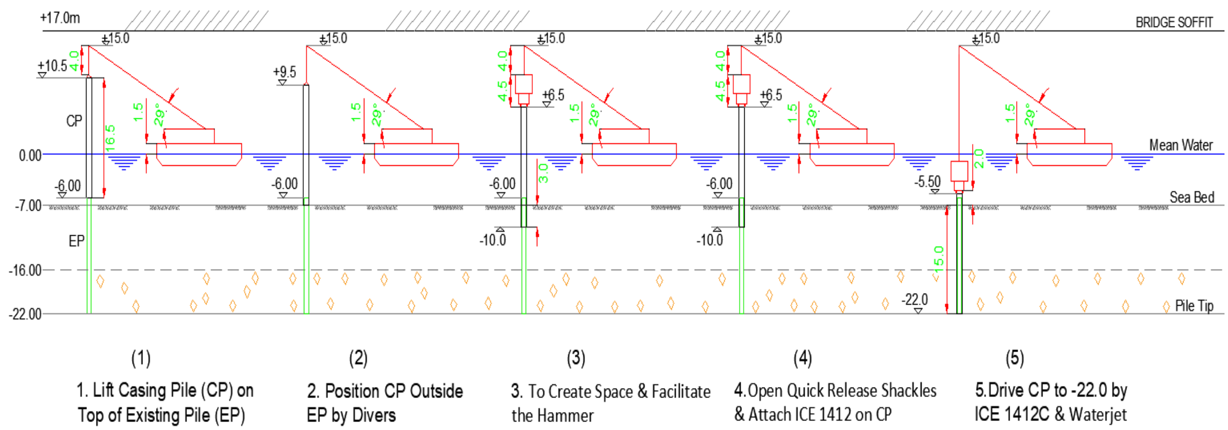

Figure 12. *Casing pile positioning sequence showing geometric restrictions and operational phases at 29º crane boom angle.*

Figure 13. *Casing Pile positioning inside an Existing Pile and view from the Diver's Screen.*

Driving the casing through the soil was conducted with 50% of the ICE 1412C efficiency. Smooth upwards movements (0.5-2.0 m) were also performed during driving through the hard bottom layers to increase the penetration ability.

Underwater operations were supervised by an experienced diving team. Strong underwater currents frequently disrupted the activities.

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It is worth mentioning that, after the extraction described above, the existing pile was empty in the inner circle space of any soil remaining, which indicates the minor effect of the inner friction of the soil material.

Production and Challenges

The Water Jet method successfully extracted up to four piles during 12-hour shifts. Efficiency was enhanced through day operations with night shift-assisted activities, achieving an average of five pile extractions during double-shift periods. Experienced teams drove casing piles during day shifts, while night shift teams focused on extracting disturbed existing piles.

Initial breakdowns with the 1,020 mm casing piles occurred at a frequency of one breakdown every three driven locations, primarily involving water pipe and nozzle damage at tips. Implementation of improved 914 mm casing pile design significantly reduced breakdown frequencies.

Critical operational requirements included maintaining seabed areas free from steel fragments around existing pile circumferences and completing casing pile-driving approximately 50 cm above existing pile tips to prevent inadvertent dragging of the pile itself during the casing extraction, as shown in Figure 14. Strong underwater currents prevented operations for approximately 10 hours daily (5 hours day, 5 hours night), limiting the identical production which could have reached up to ten piles per operational day.

Figure 14. *Extraction of the casing pile along with the existing pile.*

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CONCLUSIONS

The Water Jet method demonstrates effectiveness for extracting steel tubular piles driven onshore and offshore in sand, silty sand non-cohesive layers, and in cohesive soils such as silty soils and stiff clays, as well as to very weak rock formations. Applications could include both above and below water cut-off levels for larger pile diameters and foundation tip elevations. To the contrary, the Uplift Water Pressure method can be used at a smaller pile, with less skin friction.

This application provides contractors with planning and execution flexibility for various project types utilizing temporary heavy bearing foundations made of open-end steel tubular piles, easily extracted upon completion of their intended purpose.

Other applications may include:

- Demolition of existing marine structure foundations
- Burial of subsea cables for wind farms
- Burial of subsea oil and gas pipelines
- De-burial and salvage of unidentified items

The two presented methodologies offer significant advantages over traditional extraction techniques, particularly in challenging geological conditions and constrained marine environments. Production rates achieved demonstrate commercial viability while maintaining operational safety and environmental considerations. Comparison of the two methods is demonstrated in Table 2.

Table 2. *Comparative Table.*

Method	Description	Pile tip Levels	Total Pullout Resistance Force	Soil Conditions	Production
UPLIFT WATER PRESSURE METHOD	vibrating hammer effects with uplift forces generated by a 25- bar pressure water pump and a crane tension force	up to -16.0 mCD	up to 190 tons	no specific soil limitations	3 piles during 12-hour shift
WATER JET METHOD	combines high-pressure water jetting throughout the tip of the pile	up to -23.0 mCD	274 tons or higher, as long as it penetrates the soil through-out the pile length	it was used to penetrate very weak rock formations of UCS up to 165 Kg/m^2 and Cu up to 100 Kg/m^2. However, depending on the water jet flow and pressure, could be utilized for stronger formations	5 pile extractions during double-shift periods, including a 10 hours idle time during strong underwater currents

Future applications may benefit from further optimization of nozzle configurations and casing pile designs based on specific geological conditions.

These techniques represent valuable insights to the geotechnical engineering toolkit for marine construction projects, offering practical solutions where conventional methods proved inadequate. The successful implementation in Abu Dhabi's challenging conditions validates their potential for broader application in similar marine construction environments worldwide.

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