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Design of Vibro-Installed Offshore Monopiles in Dense Sand

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ABSTRACT: Vibro-installation of offshore monopiles foundations is now being used as an alternative to traditional, impact-driven methods in sand-dominated profiles due to the advantages of a single lifting operation, reduced installation times, reduced environmental noise, and mitigated pile run risks. In dense sands, key vibro-installation field- and model-tests have been observed to alter the state of the in situ soil, dependent on installation parameters, typically loosening (dense) sands leading to a softer monopile load-displacement response. Industry requires development of a robust approach for the geotechnical, and subsequent structural, design of vibro-installed monopiles that suitably captures the softening of the load-displacement response and that can be readily embedded into established state-of-the-art design methods.

This paper presents an FEA-based design approach for vibro-installed monopiles that can be embedded within a PISA-type workflow. The proposed design approach uses validated advanced constitutive models with reduced stiffness and strength parameters. The reduction is inferred from vibro-installation field and laboratory-scale model tests, implemented in an effective stress reduction framework for an intrinsic physically based reduction in the strength and stiffness response which is consistent for both monotonic and cyclic conditions. Stiffness degradation resulting from vibro-installation is captured directly in a 3D FEA model through inclusion of a vibro-degraded soil-volume around the monopile. Results of published pile-load tests on paired impact-driven and vibro-installed monopiles are used to validate the method. The full methodology, results of validation and impact on geotechnical monopile design are presented in this paper, alongside a gap analysis on the current state of knowledge regarding geotechnical design of vibro-installed monopiles.

Keywords: Monopile, Vibro-installation, Lateral Design, FEA, Sand

1 INTRODUCTION

For the installation of large diameter monopiles in sand-dominated profiles, vibratory driving represents an economic and fast alternative to traditional impact-driven methods. Vibratory installation also presents the added benefits of significantly reduced noise emissions during operation and mitigation against pile run risk.

Vibratory driving, however, has been observed to impact the load-bearing performance of the installed monopile. Dense sands can loosen, dependent on installation parameters (e.g. frequency and penetration velocity), resulting in a softening of the monopile load-displacement response compared to an impact-driven monopile.

This study presents an FEA-based design approach for vibro-installed monopiles that can be readily embedded within industry standard, PISA-type workflows (Byrne et al., 2017) . Softening is achieved by inclusion of a vibro-degraded soil volume around the monopile, of dimensions and properties informed by published field and model-scale tests. An intrinsic, physically based strength and stiffness reduction is achieved by adoption of an effective stress reduction framework, which can be applied to undrained, cyclic degraded design approaches in a consistent manner. The approach is validated against published pile-load tests on paired impact-driven and vibrated piles.

2 MOTIVATION

2.1 General

There is limited research regarding the impact of vibratory installation on the lateral load-bearing performance of monopile foundations, and industry lacks the required fidelity to inform detailed characterisation for inclusion within state-of-the-art lateral monopile design approaches (e.g. PISA).

Table 1. Key field- and model-scale test programmes that support softening due to vibro-hammering

Project Name	Soils	Diameter [m]	Penetration [m]	Reference
TANDEM Project	Dense Sands	0.91 to 1.22	6.15 to 7.5	Spill et al. (2022)
VIBRO Project	Dense Sands	4.30	18.2 to 18.7	Achmus et al. (2020)
TU Berlin	Dense Sands	0.20	0.87	Hoffmann et al. (2022)
SIMOX	Medium- to Dense Sands	0.32	1.5	Peccin da Silva et al. (2023)

Several completed programmes of both field- and model-scale tests observe softening of load-displacement response following vibratory installation, although discrepancies exist regarding the overall impact (positive or negative), magnitude, soil conditions and vibratory installation parameters that influence.

2.2 Load-Bearing Behaviour

Table 1 presents key published field- and model-scale test results that observe softening of the load displacement response of vibro-installed piles compared to impact-driven piles.

In the VIBRO Project (Achmus et al., 2020), under primary horizontal loading, lateral mudline deflections were between 24% and 58% greater, dependent on load magnitude, for vibro-installed piles compared to impact-driven. For unloading and reloading the effects were lessened, between 17% to 34%, but still present. Figure 1 presents an example comparison of the load-displacement curves for vibro- and impact-installed monopiles (Achmus et al., 2020)

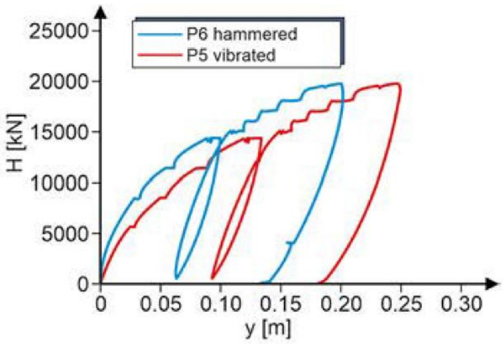

Figure 1. Measured load-displacement curves from field-scale pile load tests (Achmus et al., 2020)

TU Berlin Model Tests (Hoffmann et al., 2022) showed a reduction in stiffness for vibro-installed piles under lateral loading compared to impact-driven. The conducted model tests also investigated the impact of installation parameters (frequency, displacement amplitude and penetration velocity).

The TANDEM Project (Spill et al., 2020) observed softer lateral load-bearing behaviour for vibro-installed piles compared to impact-driven. It was observed that the degradation was greatest across small mobilisations, becoming lesser and constant towards greater displacements.

2.3 In Situ Effects

The VIBRO Project performed CPTs pre- and post-installation for both vibro-installed and impact-driven monopiles, at an offset of 1.2 m from the pile wall (Figure 2). The cone tip resistance (q_c) reduced between 18% to 32% post impact-driven installation, and reduced between 40% to 46% post vibro-installation. The average observed ratio between vibro-installed and impact-driven was therefore ~70%.

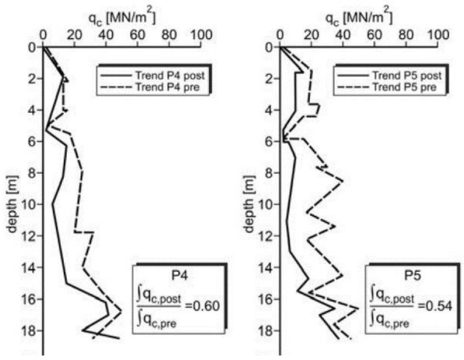

Figure 2. Comparison of pre- and post-installed (1.2 m pile offset) CPT trends for vibro-installed piles (Achmus et al., 2020)

Informed by the TU Berlin Model Tests, Kirsch et al. (2022) undertook numerical simulations and interpreted radial stresses at different radial offsets around the piles to assess installation effects. The ratio of vibro-installed and impact-driven radial stresses ($\sigma_{vibro}/\sigma_{impact}$) was found to increase from ~0.60 at an offset of ~0.5D to ~1.00 at ~2.00D.

2.4 Installation Parameters

It is understood that vibratory installation parameters, including frequency, displacement amplitude, penetration velocity and crane loading, can be linked to the level of, and indeed presence of, degradation of the load-bearing response.

In the TU Berlin Model Tests (Hoffmann et al., 2022) the effect of vibratory installation parameters was investigated, namely two cases: cavitational (slower penetration, elastic-plastic behaviour) and non-cavitational (faster penetration, plastic behaviour). It was observed that the degradation of the lateral pile response was much less severe for the cavitational mode, compared to non-cavitational. For both cases, the response was softer than the reference impact-driven test.

Le Blanc Thilsted (2014) reported on the eigenfrequency of full-scale offshore wind turbines with vibrated and driven piles at the Anholt offshore windfarm, from which it was concluded that the lateral soil-structure stiffness of vibro-driven piles is equal to that of impact-driven piles.

Peccin da Silva et al. (2023) investigated installation parameters (frequency, lowering speed, crane (hook) load) on the lateral performance using 1g scaled model tests. For dense sands, it was observed that the lateral stiffness for vibro-driven piles was dependent on the hook load during installation, presenting softer when the installation was free hanging and stiffer when the installation was crane-controlled. Further, when the installation was crane-controlled, the vibro-driven lateral load-displacement response was only slightly softer than the corresponding impact-driven case.

For medium-dense sands, where all vibro-driven scale tests were crane-controlled, the lowering speed during installation affected lateral stiffness. High-speed installations were distinctly softer than low-speed. Further, low-speed were only marginally softer than the impact-driven case.

2.5 Cyclic Behaviour

Very limited information on the long-term, cyclic degraded lateral performance of vibrated monopiles exists. Cyclic load tests, performed as part of TU Berlin Model Tests (Hoffmann et al., 2022), show that the influence of the installation method becomes less pronounced and almost negligible. Regardless of installation method (cavitational, non-cavitational, impact-driven), accumulated displacements converge with application of an increasingly large number of cycles. This conclusion is congruent with the SIMOX scale model tests, which also showed decreasing impact of installation method and installation parameters under cyclic loading.

2.6 Existing Approaches

Based on the pile load tests performed as part of the VIBRO Project, Gavin et al. (2022) showed that direct correlation between CPT strength reductions (i.e. q_c reductions) and sand properties, applied in sequential zones of disturbance around the monopile within an FEA model, could reproduce the observed level of mudline stiffness degradation.

Kirsch et al. (2022) suggest an alternative, empirically based approach, whereby reductions factors were applied to the vertical stress with depth to derive design corrected vibro-modified *p-y* curves.

2.7 Summary

Predominantly, dense, clean sands are investigated; consistent with application of vibro-installation. Further, conducted field tests (e.g. the VIBRO Project) targeted rapid installations. Coupled, these lead to vibro-induced loosening of the in situ soils and associated softening of the lateral load-bearing performance.

Dependent on soil type, in situ state and installation parameters, it is feasible that vibro-installation could be specified such that negative effects on monopile response are mitigated or non-existent. However, the current evidence basis is not mature enough to neglect potential negative effects; particularly during feasibility and concept design phases.

3 DESIGN APPROACH

3.1 Introduction

An FEA-based location-specific approach, as depicted in Figure 3, is desirable for a number of reasons:

- Installation effects can be captured within the FEA model directly.
- In the advent of composite vibro- then impact-installed piles, turbine-specific vibro-installation depths can be considered.
- Adopting a PISA-type design approach, vibro-degradation is intrinsically captured in 3D FEA optimised 1D soil reaction curves.

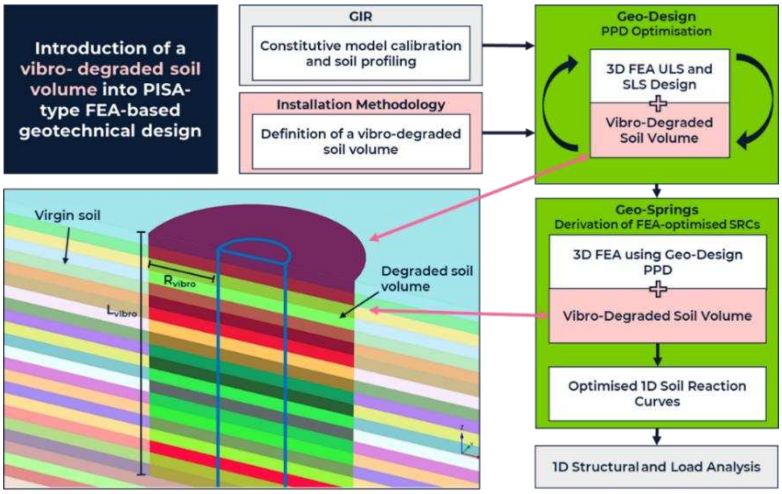

Figure 3 – Inclusion of a vibro-degraded soil volume inside a PISA-type, FEA-based lateral monopile design approach

3.2 Vibro-Degraded Sand Parameters

For sand soils surrounding the monopile, there are several ways to model the reduction in strength and stiffness: relative density reduction, CPT integral resistance reduction and/or effective stress reduction. In reality these parameters are inter-related.

It was deemed that an effective stress reduction framework, whilst a simplification of the invoked vibratory loosening mechanism, presents a convenient method for an intrinsic physically based reduction in strength and stiffness, that is consistent for both monotonic and cyclic degraded analyses.

For monotonic conditions, in combination with the drained, stress-dependent isotropic double hardening plasticity model HSsmall, commonly adopted in industry, a stress reduction factor (v_{sd}) can be assumed allowing for strength and dilation to intrinsically reduce due to stress relaxation:

$$E_{50} = E_{50}^{ref}\left(\frac{c\cos\varphi - v_{sd}\sigma'_3\sin\varphi}{c\cos\varphi + p_{ref}\sin\varphi}\right)^m \quad (1)$$

$$E_{oed} = E_{oed}^{ref}\left(\frac{c\cos\varphi - v_{sd}\sigma'_1\sin\varphi}{c\cos\varphi + p_{ref}\sin\varphi}\right)^m \quad (2)$$

$$E_{ur} = E_{ur}^{ref}\left(\frac{c\cos\varphi - v_{sd}\sigma'_3\sin\varphi}{c\cos\varphi + p_{ref}\sin\varphi}\right)^m \quad (3)$$

$$G_0 = G_0^{ref}\left(\frac{c\cos\varphi - v_{sd}\sigma'_3\sin\varphi}{c\cos\varphi + p_{ref}\sin\varphi}\right)^m \quad (4)$$

Where φ is internal friction angle, c is cohesion, m is a stress dependency coefficient, p_{ref} is the reference pressure, σ'_1 is the major principal stress, σ'_3 is the minor principal stress, G_0 is the shear modulus at small strains, E_{50} is the secant stiffness, E_{oed} is the oedemetric stiffness and E_{ur} is the unloading/reloading stiffness.

Therefore, for isotropic stress conditions, the effect of the vertical stress reduction factor is achieved simply by a reduction in unit weight.

For cyclic degraded strength, it is acknowledged that superposition of cyclic- and vibro-degradations represents the absolute most cautious case. Whilst the long-term cyclic behaviour of vibro-installed piles is uncertain, available literature does suggest that after application of a large number of cycles the accumulated displacements for impact- and vibro-installed piles converge (Hoffmann et al., 2022).

However, assuming that the vertical stress reduction framework will be applied to cyclic degraded analysis, the effective stress reduction can be applied to the cyclic envelope stress-strain curve (also termed the N_{eq} stress-strain curve), which represents the equivalent accumulated strain for storm loading at different stress mobilisations; after the methodology presented by Andersen (2015). For which, in sands, the cyclic envelope stress-strain curve is normalised by a reference effective stress (σ'_{ref}) given by:

$$\sigma'_{ref} = p_a\left(\frac{v_{sd}\sigma'_{vc}}{p_a}\right)^n \quad (5)$$

Where n is a stress dependency coefficient, σ'_{vc} is the vertical consolidation stress and p_a is the reference pressure, 100 kPa.

3.3 Vibro-Degraded Soil Volume

Similar to Gavin et al. (2020), and after the FEA-based method proposed by Imperial College for capturing installation effects in design of chalk as part of the ALPACA project (Pedone et al., 2023), it is proposed that installation induced degraded soil strength and stiffness parameters are captured directly in the FEA model by inclusion of a degraded soil volume around the monopile.

An example degraded volume is presented in Figure 3, and can be described by the radius (R_{vibro}) and depth (L_{vibro}). For simplicity, befitting the general state of knowledge, a single degraded zone of constant degradation is proposed inside the continuum model. Vibro-degraded soil parameters are also applied to the internal soil plug.

3.4 Calibration

For determination of the vibro-degraded response, characterised by an effective stress reduction framework and applied within a vibro-degraded soil volume, three parameters are required:

- Stress reduction factor (v_{sd})
- Radius of the vibro-degraded volume (R_{vibro})
- Length of the vibro-degraded volume (L_{vibro})

Following calibration, and based on initial proxies for the three parameters, the following were determined. Dimensions for the vibro-degraded soil volume have been related to the dimensions of the modelled monopile.

- v_{sd} is taken as equal to 0.70, consistent with the average observed ratio between vibro-installed and impact-driven q_c from the VIBRO Project (see Section 2.3), and broadly congruent with the ratio of vibro-installed and impact-driven radial stresses presented after the TU Berlin Model Tests.
- The radius of the vibro-degraded soil volume is taken equal to 1D, again, broadly congruent with the radius of influence of the reduced radial stresses presented after the TU Berlin Model Tests.
- The length of the vibro-degraded soil volume is assumed equal to the depth of vibro-installation, i.e. not considering development of a degraded zone below the monopile toe.

For validation, both conventional impact-driven (i.e. unmodified) and vibro-degraded monotonic pushover FEA analyses have been performed. For comparisons against the VIBRO Project, the analysis considers a pseudo entirely cohesionless, medium-dense to dense sand profile. A monopile, of 10 m diameter and length over diameter ratio (L/D) of 4.0, has been considered; i.e. L/D consistent with the VIBRO Project (Table 1).

The results are compared in Figure 4 to the pile load tests results from the VIBRO Project (Achmus et al., 2020) in double normalised space. The field tests are normalised against the impact-driven equivalent tests at 0.015D horizontal mudline displacement. The FEA benchmark is normalised against the impact-driven (unmodified) FEA case at 0.015D horizontal mudline displacement. The 0.015D horizontal mudline displacement is selected to motivate common mobilisation for the comparison and is deemed to represent a realistic static utilisation from cyclic driven lateral monopile design.

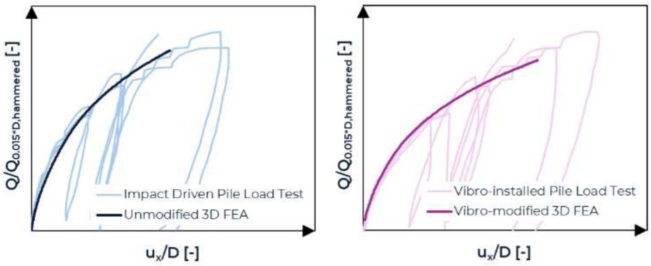

Figure 4. FEA benchmark against the VIBRO Project pile load tests: impact-driven (left) and vibro-installed (right)

The degree of vibro-degradation is observed to be consistent with the measured degradation from pile load tests conducted as part of the VIBRO Project.

3.4.1 Stress Reduction Factor Sensitivity

The stress reduction factor, v_{sd}, controls the vibro-degraded strength and stiffness reduction of the soil inside the vibro-degraded zone. Figure 5 (left) presents the sensitivity to the stress reduction factor.

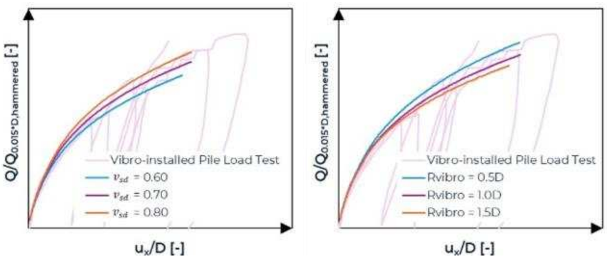

Figure 5. FEA benchmark sensitivity to the stress reduction factor (left) and vibro-degraded soil volume radius (right)

3.4.2 Vibro-Degraded Volume Radius

Figure 5 (right) presents the sensitivity to the radius of the vibro-degraded soil volume, for the same case presented in Figure 4. Consistent with expectation, it is observed that the influence of the radius becomes governing at greater displacements, with minimal impact at low mobilisations.

4 CONCLUSION

This paper presents an FEA-based design approach for vibro-installed monopiles that can be incorporated within a PISA-type workflow. The proposed design approach introduces reduced stiffness and strength soil parameters, inferred from vibro-installation field- and model-scale tests, implemented in an effective stress reduction framework, and applied to a vibro-degraded soil-volume around the monopile. Results of published pile-load tests on paired impact-driven and vibro-installed monopiles are used to validate the method.

The adopted effective stress reduction framework, whilst relatively simple in application, allows for intrinsic, physically based stiffness and strength reductions when used alongside commonplace, drained constitutive models (e.g. HSsmall), whilst also allowing for straightforward and consistent application to cyclic design cases.

The validation basis, the VIBRO Project, represents tangible stiffness and strength reductions for calibration of the effective stress reduction factor and dimensions of the vibro-degraded soil volume. However, the limited L/D range, soil types and installation parameters investigated limit extrapolation of the calibrated method, beyond a somewhat cautious, evidence-based degradation.

In industry, without specification or scheduling of specific vibratory installation parameters, loosening of dense sands and degradation of the lateral monopile load-displacement response should be considered.

Current literature does not provide sufficient fidelity to motivate non-cautious approaches to lateral geotechnical design of vibro-installed monopiles, particularly at feasibility and concept stages, and without specification of site-specific test piles or post-installation in situ testing or monitoring campaigns. Future work should aim to quantify the load-bearing stiffness reduction, if indeed present, in relation to soil type, in situ state and installation parameters in order to accurately characterise the problem and alleviate potential for introduced, uncertainty-driven conservatisms in geotechnical and subsequent structural analysis.

AUTHOR CONTRIBUTION STATEMENT

S. Elliott: Formal Analysis, Investigation, Methodology, Validation, Writing – Original draft. **C. Piatti**: Formal Analysis, Software, Supervision, Writing – Reviewing and Editing. **S. Whyte**: Supervision, Validation, Writing – Reviewing and Editing. **L. Jones**: Supervision, Writing – Reviewing and Editing.

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