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Review of the doctoral dissertation by Worku Firomsa Kabeta, MSc, entitled 'Centrifuge Modelling of Tapered Pile Installation Effects in Sand'

1. Basis for preparing the review

This review is based on a letter dated 7 July 2025 from Prof. Ewa Wojciechowska, Dean of the Faculty of Civil and Environmental Engineering at GdańskTech, addressed to me on behalf of the Scientific Discipline Council for Civil Engineering, Geodesy and Transport at Gdańsk Tech.

2. Introduction

Pile foundations are commonly used in construction today. The increasing popularity of this type of foundation stems from the need to construct buildings in increasingly complex ground conditions, as well as the need to transfer heavy loads and prevent excessive settlement of the structures being constructed. The most commonly used pile technologies employ simple pile geometry, i.e. a cross-section that is uniform along almost the entire length of the pile. In some technologies, the base of the pile is widened. Piles with a cross-section that varies with depth, most often conical in shape, are used less frequently. From a historical point of view, it was piles with a variable cross-section that were used earliest, as they were wooden piles with a naturally variable cross-section and most often conical in shape of the base. This type of wooden piles was used, for example, to foundation the Temple of Artemis in Ephesus (the so-called Artemision, 5th century BC), which was considered one of the seven wonders of the ancient world. Piles whose cross-section changes uniformly with depth are rarely used in geotechnical practice. Although it seems that their use could be cost-effective from an economic point of view, e.g. due to lower embedding costs or lower material consumption. According to some researchers, e.g. Chinju Vijayan and Ramanathan Ayothiraman (Review of the State-of-the-Art on Response of Tapered Piles to Different Loading Conditions, Indian Geotech J (February 2025) 55(1): 393–407 https://doi.org/10.1007/s40098-023-00843-z) these types of piles are more economical than conventional piles subjected to lateral loads. The literature on such piles is also quite extensive. The authors of the above-mentioned article cite over 60 works in this field. However, in order for the use of such piles to increase in engineering practice, further research is needed to better characterise their interaction with the soil. In this context, the problem addressed by the author of the reviewed thesis should be considered topical and important from the point of view of the development of geotechnics.

3. Review of the content of the dissertation

The reviewed work by Mr Worku Firomsa Kabeta, MSc, was written under the scientific supervision of Prof. Lech Bałachowski, PhD, Eng., from Gdańsk Tech (as the main supervisor), with the participation of Jakub Konkol, PhD, Eng., from Gdańsk Tech (as the assistant supervisor). It contains 168 pages and 18 introductory pages and consists of eight chapters, a list of references and three appendices. The thesis is written in English. The introductory pages include, among other things: acknowledgements, abstracts (Polish and English), table of contents, list of tables, list of figures, list of abbreviations and list of symbols used.

Chapter 1: Introduction consists of seven pages and is divided into five short subchapters with the following titles: Background of the study, Motivation for the study, Objectives of the Study, Scope of the study, Thesis outlines. In the first subchapter, the author cites several key publications dealing with the subject of piles that taper with depth. In the next subchapter, the author points to some earlier studies on the interaction of tapered piles with the surrounding soil and adequate computational methods. In the third subchapter, the author formulates five objectives of the dissertation:

- To develop physical models for simulating the behavior of tapered piles in dense sand under plane-strain conditions.
- To investigate the effects of taper angle on the load-displacement behavior and bearing capacity of piles installed in dense sand.
- To analyze stress redistribution and mobilization around tapered piles during installation and subsequent static loading.
- To evaluate soil deformation and strain patterns during pile installation using Particle Image Velocimetry (PIV).
- To perform numerical simulations to validate and complement experimental observations.

The scope of work specified by the author is limited to modelling the interaction between piles and soil under plane strain conditions in order to analyse stress redistribution and deformation mechanisms associated with pile installation. Physical modelling was carried out in a GERS-CG centrifuge at the Gustave Eiffel University (Nantes, France) using dense Fontainebleau sand (NE34). To assess the influence of geometry on the soil response caused by installation, one straight (vertical) model wall and two trapezoidal walls with taper angles of 0.75° and 1.5° were used. The walls were constructed at a scale of 1:25. Soil displacements and deformation patterns were recorded using the PIV (Particle Image Velocimetry) method. The work also includes numerical modelling. Finite element method (FEM) simulations were performed using the OPTUMG2 programme. The last of the subchapters (1.5) contains a synthetic discussion of the individual chapters of the work.

Chapter 2: Principal Tools for Physical Modelling in Geotechnical Engineering. The chapter consists of fourteen pages and is divided into seven subchapters. It presents commonly used physical modelling techniques for investigating soil interaction, namely: 1g model testing, calibration chamber tests and centrifuge modelling. Attention is drawn to scale and edge effects in physical modelling. This chapter also presents several well-known image-based analysis techniques used to record soil deformation and damage mechanisms. The methods discussed are: X-ray imaging, digital image correlation (DIC) and particle image velocimetry (PIV).

Chapter 3: Pile classification, bearing capacity, and installation-induced effects. It consists of thirty-five pages and five subchapters. It provides an overview of pile foundations, focusing on classification, load-bearing capacity and installation effects. It begins with a classification of piles based on installation methods, load transfer mechanisms and pile geometry. It then discusses pile load-bearing capacity, distinguishing between lateral resistance and base resistance. It also discusses proposals for estimating the base load-bearing capacity of piles driven into Fontainebleau sand. An introduction to the characteristics of piles that taper with depth was presented, including their behaviour in sand and appropriate analytical and empirical approaches to bearing capacity evaluations. In section 3.4.3, the author discussed previous works on tapered piles in more detail. The final part of the chapter discusses the geotechnical effects of pile installation, including stress redistribution in the soil, soil compaction, mobilisation of resistance along the pile shaft and base, and soil displacement during pile driving.

Chapter 4: Research methodology. This chapter consists of seventeen pages and four subchapters. It presents the research methodology used to investigate the impact of installing tapered piles in sandy soils. The first subchapter presents a research scheme based on experimental and numerical parts. The next subchapter describes in detail the centrifuge in which the tests were carried out, as well as the models of the tested walls and the apparatus used to record the tests. Key aspects include the centrifuge device, scaling laws, physical models, experimental configuration and test procedures. The modelling concerned three types of walls: a vertical wall (straight) and two types of tapered walls with a taper angle of 0.75° (0.75 degrees) and walls with a taper angle of 1.5°. Subsection 4.3 describes the use of Particle Image Velocimetry (PIV) for image-based analysis, with particular attention to the GeoPIV-RG technique, image pre-processing, and the extraction of displacement and deformation fields. The final part of the chapter (subchapter 4.4) discusses numerical modelling, which was a complementary part of the research. The modelling involved two approaches. The first was the finite element method (FEM), where two constitutive models of the subsoil were used for the calculations: the Mohr-Coulomb model (with associated flow rule and non-associated flow rule) and the Hardening Soil Model. The calculations were performed using OPTUM G2 software. In the second approach, the ultimate bearing capacity was estimated using kinematically admissible failure mechanisms. In this case, the author used LimitState GEO software.

Chapter 5: Stress distributions and pile load-settlement behaviour. This is the first of three chapters in which the author describes and comments on the results obtained during the research. The chapter consists of eight subchapters with a total length of 39 pages. It is dedicated to the presentation of the results of model tests carried out in a centrifuge to assess the mobilisation of stresses and settlement of model walls during loading and installation. The chapter analyses the mobilisation of stresses on the wall surface and in the surrounding soil mass at various stages: during installation, after installation and during loading. A comparison of the results obtained for walls with different taper angles is presented, based on the distribution of contact stresses and soil stresses. All three walls analysed (with three different taper angles) were embedded in the soil at a constant speed of 0.1 mm/s until a depth of 224 mm (equal to the height of the wall) was reached. After reaching the above depth, the walls were unloaded and then reloaded until a displacement equal to the average wall width, i.e. 16 mm, was achieved. After another unloading, a pull-out test was performed. The measurement results are presented in the following subsections: 5.2 – load-settlement characteristics, 5.3 – stress along the wall, 5.4 – stress in the soil mass surrounding the walls (measurements at two different depths and three different distances from the wall surface). The rest of subsection 5.4 illustrates the results of stress distribution after wall installation and after unloading, while the following section presents the settlement-horizontal stress relationships obtained for static loads. In subchapter 5.5, the author compared the values of contact stresses (along the wall) and stresses in the ground (at three different distances from the wall) for three different types of walls (depending on the taper angle). Using the measured stresses, the author presented an analysis of friction on the side of the walls and an analysis of the so-called taper coefficient for different wall cases (subchapter 5.6). In the next subchapter (5.7), the author compared his own measurements with the results of similar studies previously published by other authors. The chapter concludes with a summary of the results obtained in the author's experiment. In my opinion, Chapter 5 is the most valuable part of the dissertation.

Chapter 6: Soil displacement and strain fields. It consists of five subchapters and is fifteen pages long. It presents the results of analyses of ground displacements and deformation fields during the installation of the walls used in the model, based on image analysis using the PIV method. It covers both horizontal and vertical ground displacements caused by the embedding of the walls, which are comprehensively illustrated in Figures 6.1 to 6.3. These displacements were compared to those obtained in other experiments known in the literature (section 6.2.3). This chapter also examines deformation fields, focusing on the distribution of shear and volume deformations. In addition, it contains interpretations of the observed forms of displacements and deformations, as well as an analysis of the movements of individual soil particles captured using a sequence of high-resolution images. Comparisons with the results of previous studies are also discussed.

Chapter 7: Numerical analysis of load–settlement and failure mechanism. The 17-page document consists of five subsections. It presents the results of numerical simulations carried out to assess the behaviour of wall models under load and the mechanisms of their damage. It begins with an FEM analysis. These calculations analysed the reactions of the walls to load, parametric tests to assess the factors influencing displacement, and modelling of the geometry of walls tape with depth. A sensitivity analysis was performed by comparing displacement-load curves for different cases. It was performed for a vertical wall. Limit analysis was also used to estimate the loads causing the loss of stability of the structure and to identify damage mechanisms. The chapter also includes a comparative analysis of numerical results, with particular emphasis on load-bearing capacity and estimation of the impact of installation.

Chapter 8: Conclusion and recommendations. This final chapter consists of two subchapters with a total length of four pages. The first subchapter summarises the conclusions drawn from the experimental and numerical studies conducted as part of the research described in the thesis. The most important findings are summarised in relation to the research objectives, emphasising the impact of tapered pile on installation effects and the behaviour of sandy soil under load. The second subsection contains suggestions for further possible research on the issue under consideration.

Chapter 8 is followed by a 161-item bibliography and three appendices. The first one, marked as A, is a list of sensors used in the research, including their locations and manufacturer symbols. The second one (Appendix B) contains calibration charts for five sensors installed in the ground. The third appendix (marked as C) contains a sample photograph from: PIV analysis and two sample FEM meshes from computations according to the OPTUM G2 programme with 1,000 and 4,000 elements.

4. Assessment of the substantive value of the dissertation

As mentioned at the beginning of this review, depth-tapered piles are still underutilised in practice, and further research is needed to increase their potential applications. In this context, the issue addressed by the author of the reviewed dissertation should be considered important from the point of view of the development of geotechnical engineering. The characteristics presented in the earlier part of the review also clearly show that the research carried out falls within the scope of the scientific disciplines of civil engineering, geodesy and transport.

I would also like to emphasise the fact that the work of Mr Worku Firomsa Kabeta, MSc, is primarily experimental in nature. Experimental work is of particular importance for geotechnical engineering, as it allows theoretical hypotheses concerning the interaction of structures with soil, a poorly predictable material, to be confronted with reality. Experimental work is also less frequently undertaken by researchers in geotechnical engineering due to its high cost.

The author undertook the difficult task of conducting model tests in a centrifuge, which were challenging and time-consuming to prepare. He also made an effort to compare the results obtained from the experiments with numerical calculations based on commonly used constitutive soil models, i.e. the Mohr-Coulomb model and the Hardening Soil Model. In the reviewer's opinion, the experiments were well designed, carefully conducted and well described in the dissertation itself. And this, in my opinion, is a valuable element of the author's work.

In the first chapter, the author formulated five specific research objectives. The first was: to develop physical models for simulating the behavior of tapered piles in dense sand under plane-strain conditions. If we add that these are medium-scale models for centrifuge testing, this objective has clearly been achieved, as confirmed in subsection 4.2 of the dissertation.

The second objective of the study formulated by the author was: To investigate the effects of taper angle on the load-displacement behavior and bearing capacity of piles installed in dense sand. The results of the research on this issue are described in chapters five and six of the dissertation and indicate that this objective has been largely achieved. However, it is difficult to consider that the influence of the angle has been sufficiently investigated if, apart from the standard case (vertical wall), only two values of the angle were considered.

The third objective was: To analyse stress redistribution and mobilisation around tapered piles during installation and subsequent static loading. The author has carried out this analysis in detail and to a good standard in subsections 5.3, 5.4 and 5.5. Therefore, I consider that the third objective has been achieved.

The fourth objective was: To evaluate soil deformation and strain patterns during pile installation using Particle Image Velocimetry (PIV). The author described the method of conducting these tests in subsection 4.3. In chapter 6, the author presented graphs of horizontal and vertical soil displacement during wall installation. The observations were made at various depths. He also commented on changes in displacement distributions resulting from differences in wall taper angles. He also analysed images of volume and shear deformation fields. Therefore, I believe that this objective has been achieved.

The last objective formulated by the author was: To perform numerical simulations to validate and complement experimental observations. Chapter 7 is dedicated to these issues. Of course, with such a broadly formulated objective, it must be said that it has been achieved. However, the results presented and commented on by the author in Chapter 7 raise some doubts on the part of the reviewer, which will be formulated in the next section of the review.

I highly rate Chapter 5 of the thesis, which is crucial to this dissertation. The physical model under study is well described. The observations have been documented in a transparent manner. It seems that the author has drawn all the conclusions that could be drawn from the observations.

The final conclusions are divided into three groups: those concerning stress mobilisation in the soil around the wall and at the contact between the wall and the soil, those concerning soil displacement in the vicinity of the wall and the stress field, and those concerning information obtained from numerical analysis. In the first group, the author notes that in the case of walls tapering with depth, a significant increase in stresses occurs lower than in the case of a vertical wall. Similarly, walls with a tapering base mobilise greater normal stresses than vertical walls. In the second group of conclusions, I would highlight the observation that the zone of changes in the medium surrounding the wall associated with its installation is significantly larger in the case of walls tapering with depth than in the case of straight walls. Near the ground surface, horizontal displacements are greater for tapered walls, but they decrease more significantly near the base of the wall than in the case of straight (vertical) walls. Volume deformations show that the installation of tapered walls causes compaction of the adjacent soil zone at a distance of approximately 1~2B (where B is the wall width) and slight loosening of the soil within 4~8B from the model wall. However, the extent of the loosened zone in the case of tapered walls is significantly smaller than in the case of straight walls. This suggests an improvement in the ground conditions around tapered walls compared to standard walls. In the third group of conclusions, the author notes a large discrepancy in the assessment of load-bearing capacity between experimental results and numerical calculations.

It should be noted that almost all of the conclusions formulated by the author are hypothetical in nature and closely related to the experimental research conducted. Further research is necessary in order for the presented results to be applicable. The author points this out in the final subsection 8.2.

Another advantage of the dissertation is the comparison of the author's results with those obtained by other researchers in previously published works. Such a comparison always follows the presentation of the author's own results. This is usually not easy, as the works of other researchers usually concerned different conditions and assumptions. It should be noted that in the reviewed dissertation, the literature review, which usually appears at the beginning of the work, is very modest in this case. Instead, there are references to earlier works in individual chapters. I consider this approach valuable. In addition, each chapter ends with a summary, which makes it easier to read and understand the dissertation and highlights the most important results.

Overall, I find the work of Mr Worku Firomsa Kabeta, MSc, interesting and valuable.

5. Critical comments and questions

I have doubts as to whether the title of the dissertation is fully adequate to its content. In fact, both experimental research and numerical simulations concern walls tapered with depth. The issues are considered assuming a plain strain state of deformation. And this is not the same as a single pile with variable cross-section geometry. Moreover, the author very often uses the term wall – basically interchangeably with the term pile. Wouldn't it be better if the term wall also appeared in the title?

As I mentioned in the previous section of my review, I have some doubts about the numerical calculations performed by the author. This mainly concerns the soil parameters used in these calculations, especially in the case of the Hardening Soil constitutive model. These parameters were provided by the author in Table 4.5, but they were taken from the paper of Andria-Tonian et al. (2010). Can we assume that the soil parameters in the centrifuge were identical? At the same time, the author examined the soil used for the experiments using a mini CPT testing device. Perhaps it would have been worth trying to obtain the soil parameters using this test and the appropriate transformation equations? I believe that the same parameters were used in the numerical calculations. Did the author perform any validation of the numerical model, e.g. by conducting a back analysis? If not, this may be the reason for the very large differences in the bearing capacities calculated using numerical models compared to the results of the experiment. In this context, one may also wonder about the value of the sensitivity analysis performed and the usefulness of introducing the installation effect coefficient (section 7.4.2). I would like the author to address this concern during the public defence.

The next question concerns the numerical methods described in subsection 4.4. The author uses the OPTUM G2 programme, referring to upper and lower load capacity estimates. Does this refer to the upper estimate using kinematically admissible mechanisms? If so, the calculation method used is FELA (Finite Element Limit Analysis), which is the basic tool of OPTUM programmes. OPTUM programmes also offer the possibility of calculations using the classic FEM (Finite Element Method) approach. However, if this was used, it would be necessary to explain how the upper and lower load-bearing capacity estimates were determined. There is no comment on this in the reviewed dissertation.

In many places where the author compares three types of walls (depending on the taper angle), the observed effects increase with increase of the taper angle. Would it not be worthwhile to try at least one more wall model with a greater taper angle, or at least to construct a greater taper angle in the T2 wall? In their current form, the differences in the results for individual wall types are in most cases insignificant and it is difficult to formulate generalisations on their basis.

In my opinion, subchapter 2.4 describing how to conduct tests in centrifuges is too laconic, considering that the centrifuge test is the most important element of the research referred to in the dissertation.

In the discussion of methods for estimating pile bearing capacity (subchapter 3.2), I found no mention of pile load tests (primarily static), which are the basic tool for verifying bearing capacity recommended by EUROCODE 7. It would also have been worth mentioning the estimation of pile bearing capacity based on CPT testing, which is very common in engineering practice.

6. Editorial notes

The dissertation is well thought out and clearly written. The objectives are specified at the beginning, and their implementation is then presented in subsequent chapters. Each chapter ends with a summary containing key information. I also find the lists of symbols, tables and figures valuable.

The pile classification given in Chapter 3 is concise, but well thought out and well suited to the nature of the work (it is not a mere copy of textbook information).

7. Other minor comments

Formula (3.4) is only valid for piles with a circular cross-section and is not valid in other cases, e.g. precast piles with a rectangular cross-section.

Section 3.1.3: The statement that piles tapered with depth have a higher load-bearing capacity than cylindrical piles seems unjustified, especially in situations where piles transfer loads through their base (smaller base area in the case of tapering piles).

Significant differences in the taper coefficients for wall T1 and wall T2 have been observed (Fig. 5.28). What could be the reason for this?

How is it possible that in Figure 7.9 a the lower estimate at an angle of inclination of 0.75) is greater than the upper one?

8. Final conclusion.

As previously mentioned, I consider the work of Mr. Worku Firomsa Kabeta, MSc, to be interesting and valuable. The author has demonstrated his ability to conduct research in a field relevant to the scientific objective of the dissertation, as well as in terms of the research methodology and reasoning used.

The scientific problem presented in the dissertation falls within the scientific discipline of civil engineering, geodesy and transport, and in particular within the current trend in geotechnics.

The work contains an original solution to a scientific problem.

In view of the above arguments, I can conclude that the thesis meets the requirements for doctoral theses specified in the Act - 'Law on Higher Education and Science' (Journal of Laws of 2023, item 742, as amended) and may constitute the basis for awarding its author a doctoral degree in the scientific discipline of civil engineering, geodesy and transport. Therefore, I request that the thesis be accepted and admitted for public defence.

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