

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Kęstutis KELEVIŠIUS

STUDY OF VIBRATORY PILE BEARING CAPACITY BASED ON PARAMETERS MEASURED DURING INSTALLATION

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES,
CIVIL ENGINEERING (02T)



Vilnius LEIDYKLA TECHNICA 2013

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

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VIBROPOLIO LAIKOMOSIOS GALIOS NUSTATYMAS PAGAL ĮRENGIMO METU IŠMATUOTUS PARAMETRUS

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VGTU leidyklos „Technika“ 2178-M mokslo literatūros knyga.

Introduction

Topicality of the problem

In civil engineering practice, methods used for determination of pile bearing capacity (static and dynamic tests) are relatively expensive, time consuming and need special equipment for test performance.

Costs of vibratory pile bearing capacity determination could be significantly reduced by creating a method that does not require extra equipment for bearing capacity test. For realisation of the method, characteristics of pile base dynamic response functionally related to pile bearing capacity shall be used.

Research investigations on this field have been done worldwide, but there is no approved methodology for determination of vibratory pile bearing capacity presented.

Object of the work is bearing capacity of vibratory pile.

Aim of the work is to determine vibratory pile bearing capacity using records of pile base dynamic response parameters that are functionally related to pile's bearing capacity.

Tasks of the work

In order to achieve the aim of the work, the following tasks were formulated:

1. To analyse mathematical models used for dynamic and axial compression force pulse tests of pile bearing capacity and to determine their appropriateness for analysis of vibratory pile bearing capacity.
2. To build a method for vibratory pile bearing capacity determination: to create a principle scheme representing behaviour of an installed pile by the vibratory hammer, to create algorithm and software for its realisation.
3. To perform experimental investigations of vibratory pile. During installation, displacements and forces have to be measured in such time intervals that it would be sufficient for the analysis of parameter change and determination of pile bearing capacity; to perform a quick static pile load test for calibration of the determined bearing capacity.

4. To perform analysis of differences of calculated and recorded characteristics obtained during the experiment and determined by the quick static load test.

Methodology of research

1. Analysis method was employed for developing methods for determination of vibratory pile base bearing capacity.
2. Experimental method was employed for determination and recording of pile installation characteristics during installation.
3. Numerical method was employed for realisation of the algorithm used to estimate the bearing capacity of vibratory pile.
4. Collation of the experimental and numerical methods was used.

Scientific novelty

When preparing the doctoral dissertation, the following results, new to engineering, were obtained:

1. Original methodology for determination of vibratory pile bearing capacity was created.
2. Innovative methods for determination of displacements (measurement of magnetic field polarity) and strains (measurement of light flow) during vibratory pile installation were used.

Practical value

1. The method presented in the thesis is applicable in control of bearing capacity of vibratory pile base during installation.
2. The thesis suggests a reliable innovative method of direct displacement measurement (in practice, accelerations are measured directly).
3. The thesis suggests reliable innovative methods for measurements of cyclic repeatable strains.
4. The proposed method of vibratory pile bearing capacity determination is reliable in engineering sense and could be used in preparation of standard documents.

Defended statements

1. Chosen rheological models are the most appropriated for theoretical investigations of vibratory pile bearing capacity determination.
2. When studying bearing capacity of vibratory pile base in an experimental way, dynamic excitation and simultaneous response records are required.

The scope of the scientific work

Thesis consists of introduction, three sections, general conclusions and proposals, the list of references, the list of author's publications and appendices. Appendices are presented in digital format. The scope of thesis is as follows: 102 pages, excluding appendices, 40 numbered formulae, 45 figures and 2 tables, 67 references were used in preparing the thesis.

1. Analysis of Methods of Dynamic and Axial Compression Force Pulse Tests of Pile Bearing Capacity

Vibroinstallation technologies for pile and sheet pile installation are known and spread all over the world. No sufficient studies have been made on the relation of pile or sheet pile response with the bearing capacity. It was determined that using the same vibratory hammer and installation machine, bearing capacity of vibratory pile can differ by 30%, when all tested piles are the same in their length and diameter.

Literature review was performed on the following topics:

1. Review of vibratory hammer systems. Modern vibro driveability technologies, principles of operation and main parameters of technologies were reviewed.
2. Review of vibro driveability experiments.
3. Review of main parameters that influence vibro driveability. These parameters are related with characteristics of vibrations, piles and soil.
4. Review of vibro driveability principal models. Rheological models and terms of its use were also reviewed.

During literature analysis, the methodology of determination of vibratory pile bearing capacity, when installation characteristics records are applied, were not found. It was determined that the pile's acceleration records are not suitable for displacement calculations, because the pile is installed with sufficiently small speed comparing with vibrations. Cyclic strains can corrupt strain gauge measurements during installation of vibratory pile. The principal scheme of determination of vibratory pile bearing capacity has to be designed using the most similar one to vibratory pile installation, i.e. the principal scheme of the test of axial compression force pulse. Measurement systems of vibratory pile installation characteristics have to be sufficient for correct and precise measurements.

2. Proposed Model of Vibratory Pile Bearing Capacity Determination

The current section proposes principal and mathematical models of vibro driveability process. Additionally, selection of principal and mathematical models is based there, as well as verification of mathematical model and calculations are presented.

Based on characteristics of force pulse test determination, the author suggests that the performed test has to be analysed employing the methodology of force pulse test, as during half of vibratory hammer oscillation pulse acoustic wave travels to the pile's bottom and returns more than 10 times.

Single degree of freedom system is used for bearing capacity analysis. The principal scheme of analysis is given in Figure 1. It consists of one vibrating part of vibratory hammer and pile mass finite element that is connected in parallel with soil shaft friction and base rheological models.

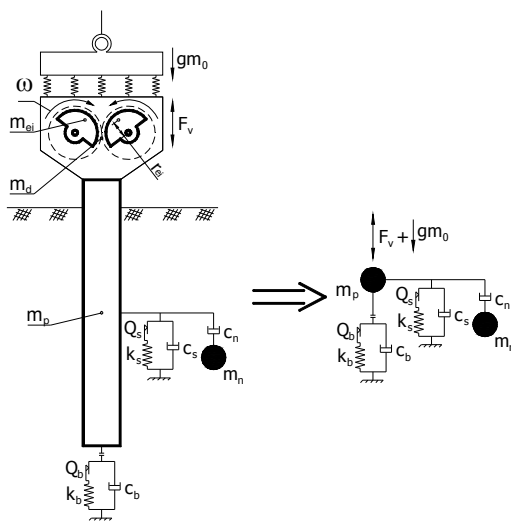


Fig. 1. Principal scheme of vibratory pile bearing capacity

For realisation of the principal scheme, software VibPolis was created by the author. Excitation force and pile ultimate bearing capacity is determined using the entered characteristics of vibratory hammer. The analysis is

performed by changing characteristics of rheological models. The purpose of analysis is to determine properties of rheological models finite elements when analysis results have the best match with the recorded ones. The amplitude deviation from start vibratory hammer position before test is proposed as match criteria.

3. Experimental Investigation of Vibratory Pile Bearing Capacity

Vibro driveability experiment was held in administrative buildings with an underground parking lot, Constitution Ave. 21, Vilnius building site. One 3 m length pile was installed using vibro driveability technology. Before the experiment, one CPT and boring for determination of soil stratigraphy was done.

The experiment was performed in the following way:

1. Mounting of strain gauges to the pile.
2. Mounting of displacement indicators to the vibratory hammer and to soil surface.
3. Mounting of the pile top to the vibratory hammer.
4. Lifting the pile and mounting bottom plate.
5. Putting the pile at the design place and fixation on vertical position.
6. Starting record of dynamic soil response characteristics.
7. Starting experiment – switching on the vibratory hammer.
8. Observation of recorded results.
9. Finishing experiment when the pile is installed 3 m into soil.
10. Finishing record of dynamic soil response characteristics.
11. Detaching of the vibratory hammer from the pile.
12. Disconnecting and dismounting of sensors from the pile and vibratory hammer.
13. Driving of the vibroaggregate under the pile.
14. Covering of the pile with a metal plate and putting a hydraulic jack on it. The upper part of the hydraulic jack is pushing the vibroaggregate.
15. Mounting of displacement indicators for the quick static test.
16. Application of the quick static test according to ASTM D1143M–07. During the test, displacements were recorded in a computer.
17. Dismounting of test equipment and removing it from the building site.

The vibratory hammer is capable to generate 700 kN eccentric force. During working time of the vibratory hammer, eccentric revolutions per minute are constant.

The results of recorded soil dynamic response provide much useful information about occurring processes. One of the most informative results is measurements of the displacement indicator that measures displacements between static and dynamic parts of the vibratory hammer. A part of record of displacement of the static part in respect to the dynamic part is presented in Fig. 2.

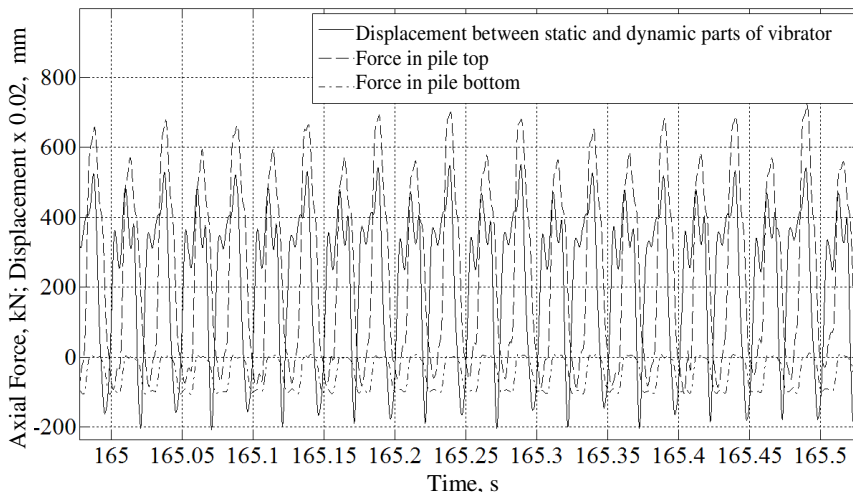


Fig. 2. Characteristics of pile installation at the depth of 3.00 m

Analysis of experiment results is mandatory for determination of characteristic repeatability of displacement curves. Observing change of curves during the experiment, one can notice changes. When modelling pile installation behaviour, these changes could be introduced by increasing or decreasing properties of damper, spring or friction finite elements.

Calibration of mathematical model and bearing capacity should be performed for validation of the results.

Flow of light for strain measurement and magnetic field for displacement measurement were measured and digitally recorded.

Analysis of bearing capacity, when using the software VibPolis, is performed by entering constants needed for calculations first. Then, parameters of rheological models change while match coefficient is closest to 1. The parameters are: stiffness of the spring finite element, the attenuation of the damper and quake of friction finite element. The parameters have to be

changed until analysis results have the closest match with the recorded displacement data. Values of parameters have to be changed in reasonable intervals. The intervals should be approximately determined using investigated soil properties.

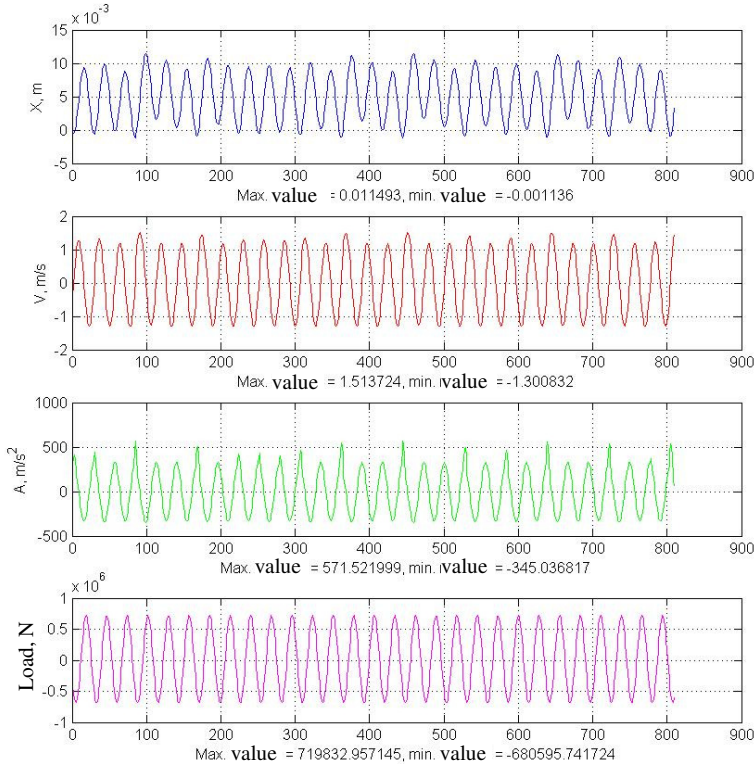


Fig. 3. Analysis results of vibratory pile bearing capacity

Analysis for the thesis was performed using the software VibPolis. Data for comparison of the analysis results is taken from 165.0–165.5 second interval (see Fig. 3). The interval represents the greatest soil bearing capacity when 5mm/sec pile installation speed is observed. The interval represents soil bearing capacity that was determined using the quick pile test.

Software VibPolis analysis window is presented in Fig. 3. Analysis time steps are shown on the X axis in the horizontal direction. The analysis was

performed using 404 time steps per second. Frequency of analysis of time steps was sufficient for getting reliable results.

During the analysis, the shape of the recorded displacement curve could not be repeated because of soil inhomogeneity, vibro driveability system resonant vibrations and looseness and proposed simplified engineering mathematical model. Match criterion is a match factor that is determined according to displacement deviations from the start position.

After the analysis, it was determined that the pile at the investigated interval was end bearing one. The pile rebounded from the soil, because the greatest part of the displacement curve is above 0 displacement line. Stiffness of soil spring for the test pile diameter is 19610 kN/m. Comparing the analysis and quick static pile test results, it was determined that spring stiffness determined in the performed analysis is 1.6 times smaller than it was determined from the quick pile test. The ratio of calculated and determined subgrade reaction modulus during the analysis is 1.7.

In engineering practice, it is assumed that pile bearing capacity determined immediately after vibratory pile installation in cohesive soil becomes ~1,5–2 times greater after 28 days.

It was determined that the match factor is 2.26. That error is sufficient for usage in engineering practice.

General Conclusions

1. Having analysed the methodology of calculation of bearing capacity of dynamic and axial compression force pulse in pile base, it was established that chosen rheological models are the most appropriate for calculation of bearing capacity of a vibratory pile. Moreover, rheological models of force pulse test are the most efficient for preparing principal schemes of shaft and base resistance.
2. The analysis of the mathematic model of principal scheme of estimation of bearing capacity in the proposed vibratory pile and its base allowed suggesting the calculation method. Principal scheme consists of the vibrating part and the finite element of gross mass of pile material, when the finite element is paralleled with rheological models of shaft and base resistance.
3. Experimental studies of the vibratory pile enabled setting dynamic characteristics of displacements and forces of the vibratory pile. The innovative equipment of reading magnetic and light flow sensor measurements digitally recorded the following parameters of the pile installation: displacements of vibrating and static parts of the vibratory

pile (displacement changed at intervals from -4 to 12 mm in respect of the initial position), common displacements of the vibratory pile in respect of the ground surface and forces on the top of the pile (forces on the top of the pile changed at intervals from -600 kN to 750 kN) and at the bottom (forces at the bottom of the pile changed from -600 kN to 0 kN). Bearing capacity shall be calibrated based on the results of the quick static test performed immediately after the vibratory pile installation. The analysis and comparison of theoretical and experimental results of determination of bearing capacity of the pile led to the match coefficient, which is 2.26. The established bearing capacity of the pile according to the Davisson's criterion is 139 kN, and the bearing capacity of the pile calculated using the estimated subgrade reaction modulus is 131 kN, and the one established during the analysis of bearing capacity of the pile is 222 kN. These errors are sufficient to determine the long-term bearing capacity of the vibratory pile.

List of Published Works on the Topic of the Dissertation In the reviewed scientific periodical publications

Amšiejus, J.; Norkus, A.; Kelevišius, K.; Macijauskas, D. 2009. The Engineering Method for Determining the Settlement of Point Due Adjacent Constantly Distributed Circular Load, *Engineering Structures And Technologies* 1(4): 195–201. ISSN 2029-2317.

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Kelevišius, K.; Gabrielaitis, L.; Amšiejus, J.; Norkus, A.; Sikora, Z. 2014. Study of bearing capacity of vibratory pile applying acceleration record, *Journal of Civil Engineering and Management*. ISSN 1392-3730 (accepted).

Žaržojus, G.; Kelevišius, K.; Amšiejus, J. 2013. Energy Transfer Measuring in Dynamic Probing Test in Layered Geological Strata, *Procedia Engineering. 11th International Conference on Modern Building Materials, Structures and Techniques (MBMST)*: vol. 57. May 16–17, 2013, Vilnius, Lithuania. Amsterdam: Elsevier Science Ltd, 1302–1308. ISSN 1877-7058.

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First degree in Civil Engineering, Faculty of Civil Engineering, Vilnius Gediminas Technical University, 2003. Master of Science in Civil Engineering, Faculty of Civil Engineering, Vilnius Gediminas Technical University, 2005. In 2003–2012 was working at UAB Vilniaus rentinys as a foundation designer. In 2009–2013 – PhD student of Vilnius Gediminas Technical University. in 2011–2012, Kęstutis Kelevišius was on internship at Gdansk University of Technology, Poland, in Department of Geotechnics, Geology & Maritime Engineering. At present – working as a geotechnical engineer at Lietuvos Energija, UAB, in Visaginas Nuclear Power Plant department and a geotechnical engineer at AB Klapėdos Nafta in Liquefied Natural Gas Terminal department.

VIBROPOLIO LAIKOMOSIOS GALIOS NUSTATYMAS PAGAL ĮRENGIMO METU IŠMATUOTUS PARAMETRUS

Mokslo problemos aktualumas

Šiuo metu inžinerinėje praktikoje naudojami vibropolio tikrosios laikomosios galios nustatymo metodai (statiniai ir dinaminiai) yra brangūs, užima daug laiko, jų realizacijai reikia panaudoti papildomą specializuotą bandymo įrangą.

Nagrinėjamo polio laikomosios galios nustatymo sąnaudas galima būtų reikšmingai sumažinti sukuriant metodą, kuris nereikalauja papildomų specializuotų polio bandymų. Realizuojant šį metodą būtų panaudojami polio įrengimo metu išmatuoti jo pagrindo dinaminio atsako parametrai, kurie yra funkciškai susiję su jo laikomąja galia. Šia kryptimi pasaulyje yra atlikti paieškieji tyrimai, tačiau išbaigtos ir aprobuotos metodikos nėra.

Tyrimo objektas yra vibropolio pagrindo laikomoji galia.

Darbo tikslas yra sukurti vibropolio pagrindo laikomosios galios nustatymo metodiką pagal įrengimo metu išmatuotus parametrus.

Darbo uždaviniai

1. Išanalizuoti polių pagrindo dinaminių ir jėgos pulso laikomosios galios bandymų nustatymo metodų matematinius modelius ir jų tinkamumą vibropolio laikomosios galios analizei.
2. Sutartyti vibropolio ir jo pagrindo laikomosios galios skaičiavimo metodą: jo elgsenos matematinio modelio struktūrinę schemą, jos realizavimui sukurti algoritmą ir kompiuterinę programą.
3. Atlikti vibropolio eksperimentinius tyrimus. Įrengimo metu inovatyviai matuoti poslinkius bei veikiančias jėgas tokiais laiko intervalais, kad analizuojant parametrų kitimą laike būtų galima atlikti laikomosios galios analizę. Atlikti įrengto polio pagrindo laikomosios galios statinį bandymą nustatytos polio laikomosios galios kalibravimui.
4. Atlikti sumodeliuotų ir polio įrengimo metu išmatuotų parametrų ir laikomosios galios skirtumų analizę.

Tyrimų metodika

1. Analizės metodas taikytas polio pagrindo laikomosios galios nustatymo metodams.
2. Eksperimentinis metodas buvo taikytas polio įrengimo metu nustatant ir fiksuojant polio įrengimo parametrus.
3. Skaitinis metodas taikytas polio, įrengiamo vibrogramzdinimo būdu, pagrindo laikomosios galios skaičiavimo algoritmo realizavimui.
4. Eksperimentinių ir skaitinių metodų gretinimas.

Mokslinis naujumas

Rengiant disertaciją buvo gauti šie statybos inžinerijos mokslui nauji rezultatai:

1. Sukurta originali metodika vibropolio pagrindo laikomajai galiai skaičiuoti.
2. Pritaikyti inovatyvūs būdai poslinkių (magnetinio lauko poliariškumo matavimas) bei santykinų deformacijų (šviesos srauto matavimas) matavimui polio vibrogramzdinimo metu.

Darbo rezultatų praktinė reikšmė

1. Siūlomas metodas taikytinas vibrogramzdinimo metu įrengiamų vibropolių pagrindo laikomosios galios kontrolei.
2. Disertacijoje siūlomas patikimas inovatyvus tiesioginių poslinkių matavimo būdas (praktikoje tiesiogiai matuojami pagreičiai).
3. Disertacijoje siūlomas patikimas inovatyvus ciklinių santykinų deformacijų matavimo būdas.

4. Sukurtas polio pagrindo laikomosios galios nustatymo metodas yra inžineriškai patikimas ir gali būti panaudotas ruošiant norminius dokumentus.

Ginamieji teiginiai

1. Vibropolio pagrindo laikomosios galios nustatymo teoriniams tyrimams tinkamiausi yra parinkti reologiniai modeliai.

2. Tiriant vibropolio pagrindo laikomąją galią eksperimentiniu būdu turi būti atlikti dinaminio žadinimo ir atsako viena laikiai matavimai.

Darbo apimtis

Disertaciją sudaro įvadas, keturi skyriai ir rezultatų apibendrinimas. Taip pat yra trys priedai kurie yra pateikti skaitmeninėje laikmenoje.

Darbo apimtis yra 102 puslapiai, neskaitant priedų, tekste panaudotos 40 numeruotos formulės, 45 paveikslai ir 2 lentelės. Rašant disertaciją buvo panaudota 67 literatūros šaltiniai.

Įvadiniame skyriuje aptariama tiriamoji problema, darbo aktualumas, aprašomas tyrimų objektas, formuluojamas darbo tikslas bei uždaviniai, aprašoma tyrimų metodika, darbo mokslinis naujumas, darbo rezultatų praktinė reikšmė, ginamieji teiginiai. Įvado pabaigoje pristatomos disertacijos tema autoriaus paskelbtos publikacijos ir pranešimai konferencijose bei disertacijos struktūra.

Pirmasis skyrius skirtas literatūros apžvalgai. Jame yra pateikta vibropolio įrengimo, reologinių modelių ir polio laikomosios galios nustatymo būdų medžiagos analizė. Skyriaus pabaigoje formuluojamos išvados ir tikslinami disertacijos uždaviniai.

Antrajame disertacijos skyriuje yra pateikiama įrengiamo vibrogramzdinimo būdu polio pagrindo struktūrinė skaičiuojamoji schema. Skaičiuojamoji schema susideda iš atitinkamai sujungtų parinktų reologinių modelių. Taip pat pateikiama polio, įrengiamo vibrogramzdinimo būdu, ir jo pagrindo laikomosios galios struktūrinės schemos skaičiavimo algoritmo sudarymas ir realizavimas. Realizavimui naudojama parašyta kompiuterinė programa.

Trečiajame disertacijos skyriuje yra pateikiamas įrangos, kuri inovatyviais būdais matavo polio įrengimo charakteristikas, aprašymas. Be to yra pateikiama lauko eksperimento eiga bei gauti rezultatai. Dar yra pateikiami eksperimento duomenų analizės atlikimo etapai, laikomosios galios nustatymo rezultatai ir jų priimtino kriterijai.

Bendrosios išvados

1. Atlikus polių pagrindo dinaminių ir jėgos pulso laikomosios galios nustatymo metodų analizę, nustatyta, kad vibropolio pagrindo laikomosios galios nustatymui tinkamiausi yra parinkti reologiniai modeliai. Vibropolio pagrindo laikomosios galios nustatymo struktūrinei schemai sudaryti labiausiai tinka jėgos pulso bandymo reologiniai modeliai.
2. Atlikus sukurto vibropolio ir jo pagrindo laikomosios galios nustatymo struktūrinės schemos matematinio modelio analizę pasiūlytas skaičiavimo metodas. Struktūrinė schema susideda iš vibroplakto ir polio bendros masės baigtinio elemento, su kurio lygiagrečiai sujungti polio pagrindo šoninės trinties bei polio pado reologiniai modeliai.
3. Atlikus vibropolio eksperimentinį tyrimą nustatytos dinaminiai vibropolio poslinkių ir jėgų parametrai. Panaudota inovatyvi magnetinio ir šviesos srautų jutiklių matavimų nuskaitymo aparatūra skaitmeniniu būdu užfiksavo polio įrengimo parametrus: poslinkius tarp vibroplakto vibruojančios ir statinės dalių (poslinkiai kito nuo -4 iki 12 mm pradinės padėties atžvilgiu), bendrus vibroplakto poslinkius žemės paviršiaus atžvilgiu bei jėgas polio viršuje (jėgos polio viršuje kito nuo -600 kN iki 750 kN) ir apačioje (jėgos polio apačioje kito nuo -600 kN iki 0 kN). Laikomosios galios kalibravimas turi būti atliekamas remiantis greito statinio bandymo, atlikto nedelsiant po vibropolio įrengimo, rezultatais. Atlikus analizę ir sugretinus polio laikomosios galios nustatymo teorinius ir eksperimentinius rezultatus nustatytas atitikimo koeficientas yra 2,26. Nustatyta vibropolio laikomoji galia pagal Davisono kriterijų yra 139 kN, apskaičiuota polio laikomoji galia naudojant apskaičiuotą polio pagrindo standumo koeficientą yra 131 kN, o nustatyta polio laikomosios galios analizės metu yra 222 kN. Šios paklaidos yra pakankamos norint nustatyti ilgalaikę vibropolio laikomąją galą.

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STUDY OF VIBRATORY PILE BEARING CAPACITY BASED ON
PARAMETERS MEASURED DURING INSTALLATION

Summary of Doctoral Dissertation
Technological Sciences, Civil Engineering (02T)

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VIBROPOLIO LAIKOMOSIOS GALIOS NUSTATYMAS PAGAL ĮRENGIMO
METU IŠMATUOTUS PARAMETRUS

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