Department of Civil and Structural Engineering

Underpinning project; owners´ views on technology, economy and project management

Jouko Lehtonen

Aalto University

DOCTORAL DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 80/2011

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Jouko Lehtonen

Doctoral dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the School of Engineering for public examination and debate in Auditorium R1 at the Aalto University School of Engineering (Espoo, Finland) on the 14th of October 2011 at 12 o'clock.

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Aalto University publication series
DOCTORAL DISSERTATIONS 80/2011

ISBN 978-952-60-4276-3 (pdf)
ISBN 978-952-60-4275-6 (printed)
ISSN-L 1799-4934
ISSN 1799-4942 (pdf)
ISSN 1799-4934 (printed)

Aalto Print
Helsinki 2011

Finland

The dissertation can be read at http://lib.tkk.fi/Diss/

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Abstract

Author
Jouko Lehtonen

Name of the doctoral dissertation
Underpinning project; owners´ views on technology, economy and project management

Publisher School of Engineering

Unit Department of Civil and Structural Engineering

Series Aalto University publication series DOCTORAL DISSERTATIONS 80/2011

Field of research Construction Management and Economics

Manuscript submitted 9 December 2010 **Manuscript revised** 9 June 2011

Date of the defence 14 October 2011 **Language** English

☐ **Monograph** ☒ **Article dissertation (summary + original articles)**

Abstract

The dissertation emphasises the know-how needed by the owner or the developer to facilitate timely and cost-controlled implementation of underpinning projects. The property owner - in Finland, commonly a residents' association - typically commissions a single underpinning project, which means that the owner generally does not have any empirical knowledge of such projects. Property owners typically have a choice of several, sometimes dozens, different technical design solutions. The solutions differ in terms of costs, duration and environmental impacts. Some design solutions are only available for properties in those stages of the life cycle where the foundations are still reasonably sound.

In Finland, underpinning is needed in many cities. The centre of Helsinki has seen many large foundation projects since the 1980s. The downtown area has some 120 buildings with wood piling foundations. Respectively, Turku is estimated to have some 400 buildings with wood piling foundations. The projects are relatively large: annually, some 3-5 properties are underpinned, using 400-900 new piles with a typical length of 10m-40m. A database has been compiled from underpinning projects carried out in Turku, with some 200 different parameters stored from approximately 100 projects. The Database on Turku Underpinning Projects (DATU) is one of the largest of its kind in the world.

The dissertation develops and compiles a new classification for load transfer structures in underpinning. The classification can be used in the estimates of project duration and costs. The research proposes a new model and classification of damage in wood foundations which can be used in the evaluation of the usability of alternative underpinning methods and in the planning of the timing and the costs of underpinning works. The dissertation introduces models which provide reasonable accuracy in forecasting the costs and duration of underpinning projects. The research provides a new finding about the effect of underpinning on the property value. An accelerated decrease in the property value prior to the time of repair was modelled using reasonably extensive data.

Keywords underpinning, micropile, cost modelling, real estate management

ISBN (printed) 978-952-60-4275-6 **ISBN (pdf)** 978-952-60-4276-3

ISSN-L 1799-4934 **ISSN (printed)** 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Espoo **Location of printing** Helsinki **Year** 2011

Pages 153 **The dissertation can be read at** http://lib.tkk.fi/Diss/

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Aalto-yliopisto, PL 11000, 00076 Aalto www.aalto.fi

Tiivistelmä

Tekijä
Jouko Lehtonen

Väitöskirjan nimi
Perustustenvahvistushanke; rakennuttajan näkökulmia tekniikkaan, talouteen ja projektinhallintaan

Julkaisija Insinööritieteiden korkeakoulu

Yksikkö Rakennustekniikan laitos

Sarja Aalto University publication series DOCTORAL DISSERTATIONS 80/2011

Tutkimusala Rakentamistalous

Käsikirjoituksen pvm 09.12.2010 **Korjatun käsikirjoituksen pvm** 09.06.2011

Väitöspäivä 14.10.2011 **Kieli** Englanti

☐ **Monografia** ☒ **Yhdistelmäväitöskirja (yhteenveto-osa + erillisartikkelit)**

Tiivistelmä

Väitöstutkimus keskittyy perustustenvahvistuksen rakennuttamisessa tarvittavaan osaamiseen korjaushankkeen onnistuneen toteutuksen varmistamiseksi hankkeen keston ja kustannusten suhteen. Rakennuttaja on Suomessa yleensä asunto-osakeyhtiö, jolla ei kertarakennuttajana ole kokemusta perustustenvahvistuksen hankkeista. Rakennuttajalle on tarjolla lukuisia erilaisia perustustenvahvistusmenetelmiä, joilla on erilaisia vaikutuksia hankkeen kustannuksiin, kestoon ja ympäristöön. Osa menetelmistä on mahdollista käyttää vain perustusten elinkaaren niissä vaiheissa, jolloin perustukset ovat vielä kohtuullisen hyvässä kunnossa.

Perustustenvahvistustarpeita on monissa Suomen kaupungeissa. Helsingin keskustassa on noin 120 puupaalujen varassa olevaa perustusta ja perustustenvahvistuksia on tehty 1980-luvulta alkaen. Turussa arvioidaan olevan noin 400 puuperustusta. Turun hanketoiminta on laajaa, vuosittain vahvistetaan 3-5 kohdetta, joihin asennetaan tyypillisesti 400-900 uutta paalua pituudeltaan 10-40 m. Turun kohteista on kerätty tietokanta, johon on kerätty noin 200 erilaista parametria noin 100 kohteesta. DATU-tietokanta (Database on Turku Underpinning Projects) on laajimpia perustustenvahvistuksen tietokantoja maailmassa.

Väitöstutkimuksessa kehitetään ja laajennetaan perustustenvahvistuksessa käytettävien kuormansiirtorakenteiden luokittelua. Luokittelua voidaan käyttää arvioitaessa korjauksen kestoa ja kustannuksia. Tutkimuksessa ehdotetaan uutta mallinnusta ja luokittelua kuvaamaan puurakenteisten perustusten vaurioitumista. Vaurioluokittelua voidaan käyttää vaihtoehtoisten korjausmenetelmien käyttökelpoisuuden arviointiin sekä perustustenvahvistuksen aikataulu- ja kustannussuunnitteluun. Väitöstutkimuksessa esitellään laskentamalleja, joiden avulla voidaan ennustaa perustustenvahvistushankkeen kustannuksia ja kestoa kohtuullisen tarkasti. Tutkimuksen löydös kiinteistön arvon kehityksestä suuren korjaushankkeen yhteydessä osoittaa, että arvo alenee kiihtyvällä vauhdilla ennen korjaushankkeen käynnistämistä.

Avainsanat perustustenvahvistus, pienpaalu, kustannusmalli, kiinteistöjohtaminen

ISBN (painettu) 978-952-60-4275-6 **ISBN (pdf)** 978-952-60-4276-3

ISSN-L 1799-4934 **ISSN (painettu)** 1799-4934 **ISSN (pdf)** 1799-4942

Julkaisupaikka Espoo **Painopaikka** Helsinki **Vuosi** 2011

Sivumäärä 153 **Luettavissa verkossa osoitteessa** http://lib.tkk.fi/Diss/

Preface

Underpinning is a sort of exceptional refurbishment, which is done particularly when the existing foundation is based on wood piles. Underpinning is typical in many old cities, because the settlement has originally been situated by the waterfront, on soft soil. Turku is one of the largest underpinning target areas in the world. Approximately 100 buildings have been underpinned during the last 20 years, and the activity is still going on. All information on the underpinning targets in Turku has been saved in the DATU database (Database on Turku Underpinning Projects) since the year 2004. The DATU database is the basic source material of this doctoral thesis.

I wish to thank everybody who has been involved in the development of the DATU database. The database has been co-funded especially by Tekes, Turku University of Applied Sciences, Rautaruukki Oyj, Lemminkäinen Oyj, Senate Properties and the Real Estate Foundation.

For my thesis, I have received invaluable support from my instructor, Professor emeritus Juhani Kiiras. In addition, I am grateful to Professor Juha-Matti Junnonen and Professor Arto Saari who have guided me the last miles of the dissertation. Also the support of my research team has been in many ways essential, thanks especially to Ville Hyyppä, Jussi Hattara, Heli Kanerva-Lehto and Antti Perälä. Additionally, I wish to thank my colleagues Jussi Riihiranta, Sari Loppela-Rauha, Marko Kortetmäki and Sirpa Lehti-Koivunen for their support in the several phases of the work. My family has empathized with me during the whole research period, thanks for everything. And final thanks to Soila – following her growth has ensured the birth of my thesis in an atmosphere full of confidence for the future.

Turku, December 2010
Jouko Lehtonen

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I. Jouko Lehtonen and Ville Hyyppä (2010). Classification of Micropile Underpinning Methods Exemplified by Projects in Turku. Electronic Journal of Geotechnical Engineering, 15 (Bundle C), 295-310.

II. Jouko Lehtonen, Antti Perälä and Jussi Hattara (2010). New tool for choosing micropile type – decay of modeling of wood pile foundations in Turku, Finland. Proceedings of the IWM 2010, Washington DC

III. Lehtonen, Jouko Lennart & Kiiras, Juhani Matti (2010). Cost Modelling in Underpinning Projects. Construction Management and Economics, 28:9, 985-995.

IV. Jouko Lehtonen and Jussi Hattara (2009). Duration of the Micropile Underpinning Projects in Turku. Proceedings of the IWM2009, London.

V. Jouko Lehtonen and Matti Grönroos (2008). The impact of major refurbishment projects on property value, exemplified by underpinning (original publication in Finnish: Suuren korjaushankkeen vaikutus kiinteistön arvoon, esimerkkinä perustustenvahvistus). Maanmittaus 83:2, 18-37.

Author's contribution

In all papers, the authors´s role was to produce the content.

For Appendix I, the author contributed Fig. 4 and the tables. In addition, the author outlined the contents of Fig. 5 and Fig. 6 whereas the co-author provided the graphic representation of the contents.

For Appendix II, the author contributed Fig. 4, Fig. 5 and the tables. In addition, the author outlined the contents of Fig. 2 and Fig. 3 whereas the first co-author provided the graphic representation of the contents. The second co-author assisted in processing data derived from the DATU database.

For Appendix III, the author contributed the figures and the tables. The co-author provided counselling during the writing process of the paper.

For Appendix IV, the author contributed Fig. 1, Fig. 2 and Fig. 3 and the tables. In addition, the author outlined the contents of Fig. 4 to Fig. 9 whereas the co-author assisted in processing data derived from the DATU database and provided the graphic representation of the contents.

For Appendix V, the author contributed Fig. 2 to Fig. 5 and the tables. The co-author provided advice on the use of the statistical research method applied.

Appendix V has been published originally in Finnish as a peer-reviewed article. The author has made sure that the English version reviewed by the native translator follows the original article in the technical contents. In addition, the supervisor of the dissertation has reviewed the translation.

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Figure 16. The costs of underpinning have been traditionally estimated based on empirical data, which results in a wide range of variation. Model 1 provides a level of costs but with high deviation. Model 2 provides a reasonably accurate level of costs with reasonably low deviation.

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1. Introduction

1.1 Background

Throughout time, cities and villages have been founded at waterside locations: by seas, lakes and, very often, on river deltas. Geologically, the ground soil at these locations is often soft and compressible, such as silt, clay, mud or peat. What is more, early inhabitation of these sites may have produced several meters of culture layers, which are also highly compressible.

Errors in foundation design and construction, rotting wood piles, the uneven settlement of cohesive piles and subsidence of the load-bearing soil are common reasons for underpinning (Juhola 1991). For a long time, foundations have been improved by widening their footing or by deepening them (Juhola 1991). The top ends of rotted wood piles have been replaced with new concrete structures, or piles have been shortened enough to facilitate the construction of a new basement under the building. Reducing the level of wood pile heads has not entirely eliminated the risk of decay. Wood piles can rot both above and below the groundwater level. Below the groundwater level, rot can extend to the tips of the piles (Klaassen 2008).

Extensive reconstruction is generally carried out when structural components reach the end of their service life (Wong 2000) or in conjunction with large conversion projects. Aikivuori (1994) lists five reasons for reconstruction: (i) structural damage, (ii) change of use, (iii) optimising financial return, (iv) subjective factors in the owner's decision-making, and (v) environmental changes in the building's surroundings. Therefore not all reconstruction works are based on technical requirements: in some cases, the reason is the effect that refurbishment will have on the building's value or profitability, and there are other objectives, such as the conservation of cultural-historical constructions.

Reconstruction work is characterised by a wide scope of design tasks which are difficult to estimate; the need for local on-site guidance during the design and construction process, unprecedented issues during demolition, and the continued use (residential or commercial) of the property during reconstruction. In many reconstruction projects, the old plans are either inaccurate or not available. (Kiiras et al. 2007)

The results of reconstruction can be visible or invisible (Chau et al. 2003). If a property is in the late stages of its service life, reconstruction is essential to keep the property in use for another life cycle or longer. Whereas most refurbishment works (HVAC repairs, facade works, etc.) apply to all properties, underpinning is only required in buildings where the existing foundation is supported with wood piles or rafts or there is a need to increase the load-bearing capacity of the foundation. Foundations are often not underpinned until uneven settlement or cracks become excessive. Underpinning is also used in earthquake zones to improve the safety of buildings (Herbst 1997, Lizzi 1982, Mason 1997, Okahara et al. 1997, Schlosser and Frank 1997).

Underpinning is a rapidly growing sector in the construction industry all around the world. Underpinning techniques have advanced considerably, especially since the 1950s when methods were developed to rescue notable buildings damaged during World War II (Lizzi 1982).

A number of different underpinning techniques have been used over time (Mason and Kulhawy 1999, Thorburn 1993). Until the 1980s, the preferred methods included deepening the foundations and different types of piling, soil nailing, freezing and chemical grouting (Jokinen 1991, Bradbury 1993, Bruce 1993, Cole 1993, Harris 1993, Hutchison 1993, Littlejohn 1993, Lizzi 1982, Pryke 1993, Thorburn 1993). Micropiles and jet grouting have been the most common underpinning techniques since the 1980s (Jokinen 1991, Klosinski 2000, Schlosser and Frank 1997, Eronen 1997). New micropiles or jet grouting columns are installed symmetrically around the structure. Old structures are typically unable to withstand significant torsional forces (Figure 1). Depending on conditions and the availability of equipment, steel micropiles are installed by drilling, driving, jacking or screwing (Lizzi 1982, Jokinen 1991, Lizzi 1993, Bredenberg 2000, Bredenberg 2003, CEN 2005, ADSC 2008). High-strength steels are normally used in micropiles, with a yield strength of 440-550 MN/m^2 (Lehtonen 1997, Eronen et al. 1997). The geotechnical and structural capacity of piles, as well as their corrosion resistance, can be improved by grout injection (e.g. Bruce and Juran 1997, Eronen et al. 1997, Lehtonen 2001, Lehtonen and Aronsson 2003).

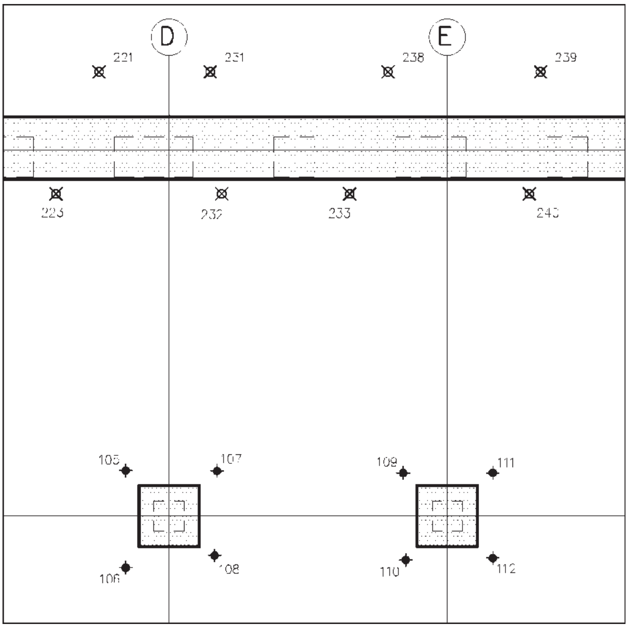

Figure 1. Underpinning piling map: new micropiles are placed symmetrically throughout the foundations (City of Turku 2009).

Micropiles are commonly used in underpinning projects, and their development has been a subject of extensive international cooperation since the 1990s. The International Workshop on Micropiles (IWM) has been held ten times from 1997 until 2010. Since 2006, the IWM has been organised by the International Society for Micropiles (ISM 2009).

In Finland, underpinning is needed in many cities. The centre of Helsinki has seen many large foundation projects since the 1980s. The downtown area has some 120 buildings with wood piling foundations. Foundation work is still required in properties such as the central railway station and the adjoining post office headquarters (Pitkänen et al. 1999).

Underpinning projects are very common in the city of Turku (Heikinheimo et al. 2000, Korkeakoski et al. 2000). The number of subject properties in Turku (Figure 2) is exceptionally high, even in international comparison. Turku is estimated to have some 400 buildings with wood piling foundations (Pitkänen et al 1999). The projects are relatively large: annually, some 3-5 properties are underpinned, using 400-900 new piles (Figure 3) with a typical length of 10m-40m (Figure 4).

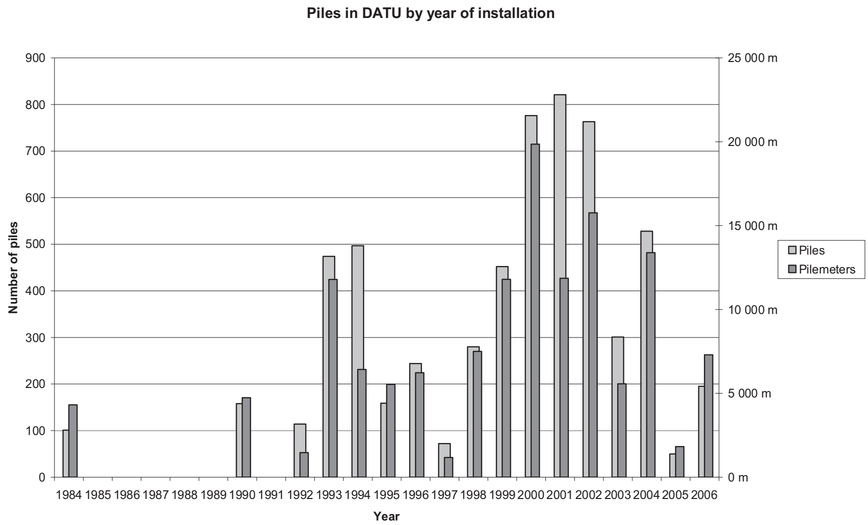

Figure 2. Piles in DATU by year of installation. The statistics since 2005 are incomplete (Lehtonen, Virta & Hattara 2009).

A database (Figure 5) has been compiled from underpinning projects carried out in Turku, with some 200 different parameters stored from approximately 100 projects. The Database on Turku Underpinning Projects (DATU) is one of the largest of its kind in the world. The majority of the underpinning projects are located close to the River Aura (Figure 6). The data has been gathered from property owners, planners and designers, and the Turku building supervision office. The data were collected and compiled from 2004-2006 as part of the DATU project funded by the Finnish Funding Agency for Technology and Innovation (TEKES). Users can register to access the information and to add and modify data according to their user profile. (DATU 2008)

Common construction project practices are followed in underpinning projects. Main tasks include setting and monitoring objectives for quality, scope, schedule and costs, and the appointment of engineers; drawing up design contracts; obtaining all necessary permits for the construction work; producing project specifications; organising the tendering process and supervising the construction work (Kankainen and Junnonen 2001, Levy 2002, Söderberg 2005, Nordstrand 2008).

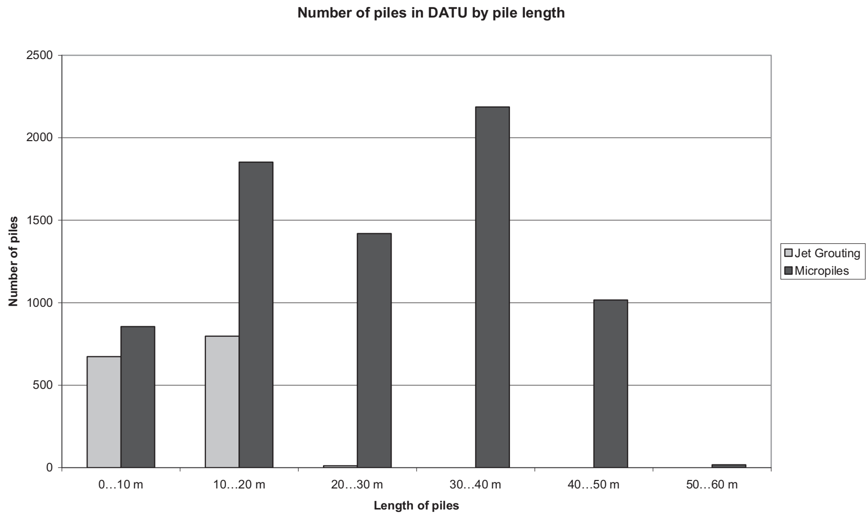

Figure 3. Number of piles in DATU by pile length (Lehtonen, Virta & Hattara 2009).

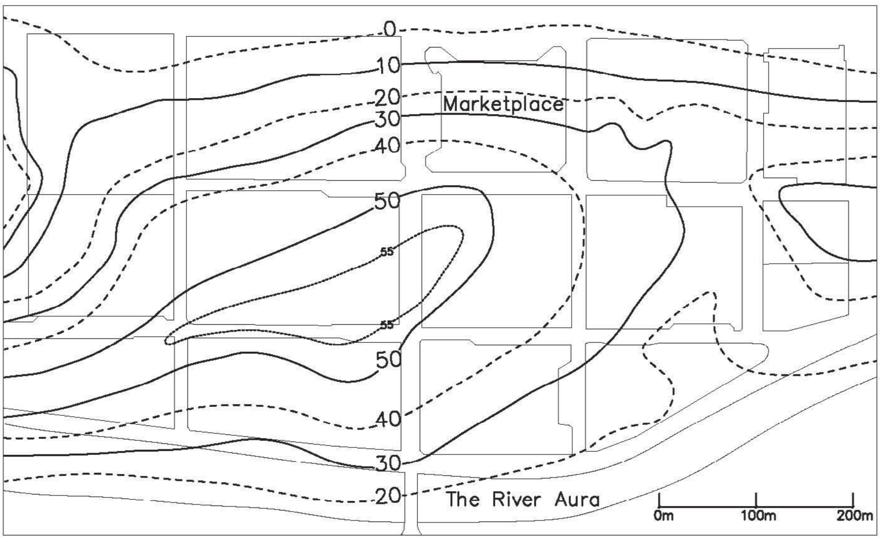

Figure 4. Typical pile length in the Turku city centre (DATU 2008).

Underpinning work is commissioned by the property owner; in Turku, typically a residents' association or a property owning company, sometimes a local authority or parish (DATU 2008). Normally, the owner is not directly in charge of the project execution; instead, project management services are commissioned from an underpinning construction specialist or a professional construction manager. In many cases, the consultant is appointed after long-term monitoring of the foundations when underpinning becomes a necessity. Expertise in underpinning is a key factor in the appointment of engineers and contractors (Lindroos 1991).

According to the Finnish practice standard RAP 95 Scope of the Client's Work in Building Construction, (RT 10 - 10575 en), the owner's task include:

- requirement study
- project planning
- preparation of planning
- planning control
- preparation of construction
- construction control
- acceptance and commisioning
- warranty period.

During the requirement study stage, an initial description of required repairs is produced, along with the project-specific requirements and design options (Kankainen and Junnonen 2001, Nordstrand 2008). During project planning, detailed requirements are formulated for the scope of the project, the extent of repairs, the costs and the schedule. The construction preparation stage includes construction planning, but the main focus is on geotechnical and structural engineering and on HVAC designs. In underpinning projects, like other partial refurbishment projects, determination of the best and the last moment when the refurbishment measures should be done is essential demanding high competences.

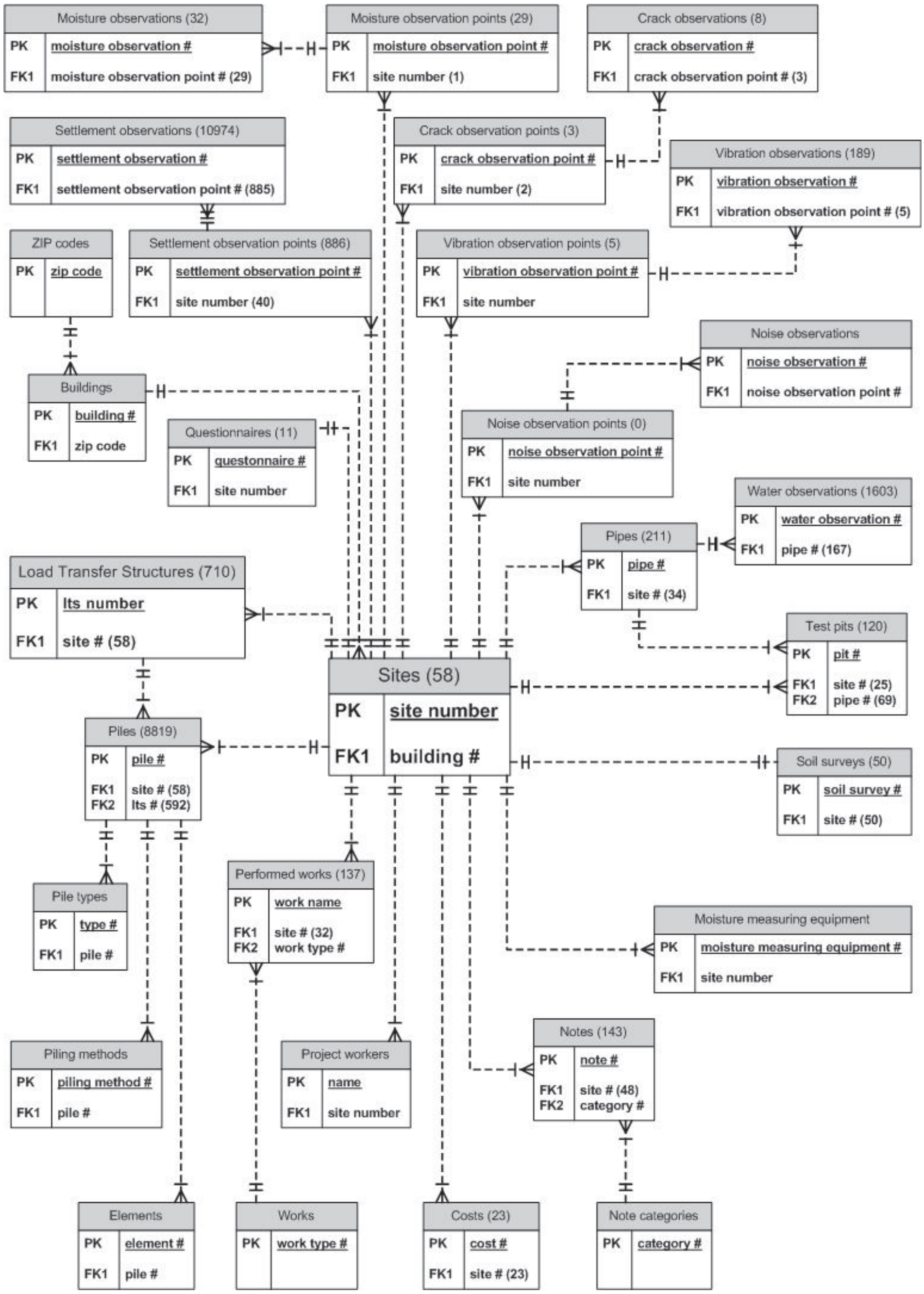

Figure 5. Structure of database for underpinning projects in Turku. Data number of the parameters is given in the boxes. (DATU 2008)

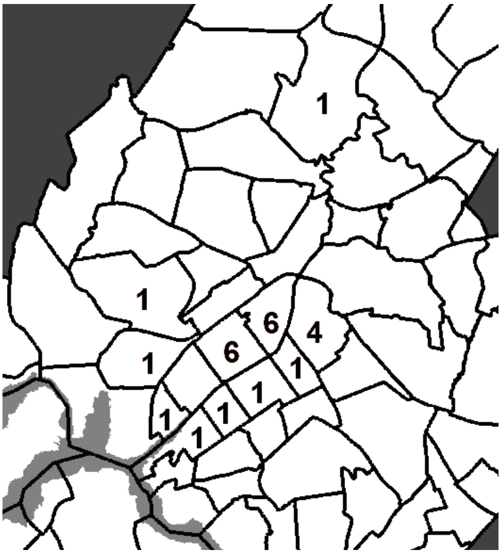

Figure 6. The distribution of the underpinning projects (N=24) in the DATU database by the city districts in Turku.

Underpinning contracts in Finland are generally fixed price contracts. Pile quantities are normally linked to estimates derived from the geotechnical plans, and possible changes in quantities are paid by unit price (Heikkilä 1991, Lindroos 1991).

The owner's project manager is usually assisted by a structural/foundation engineer. Underpinning projects require a continuous ability to modify the plans in response to unprecedented findings during demolition or piling. Continuous and productive collaboration between the project manager, the contractor's representative and design enigeers is essential to guarantee flexible execution. (Heikkilä 1991)

1.2 Research problem

A lot of research results have been published on different piling techniques and jet grouting. Thus far, the main focus has been on the load-bearing capacities and usability of piles in different geotechnical conditions (e.g. Bruce et al. 1997). Research has focussed more on planning or implementation and less on the owner's point of view.

This research emphasises the know-how needed by the owner or the developer to facilitate timely and cost-controlled implementation of underpinning projects. The property owner - in Turku, typically a residents' association - typically commissions a single underpinning project, which means that the owner generally does not have any empirical knowledge of such projects. While property management professionals (property managers/engineers) may have experience in previous underpinning projects, this rarely covers all types of design solutions. Property owners typically have a choice of several, sometimes dozens, different technical design solutions. The solutions differ in terms of costs, duration and environmental impacts. Some design solutions are only available for properties in those stages of the life cycle where the foundations are still reasonably sound.

1.3 Aim of the research

In the dissertation, underpinning is approached as a technical-financial process. The research focuses both on technical design solutions and their impacts on project costs and duration. The research questions are:
RQ1. What alternative design solutions are available on the basis of the life cycle stage of the foundation?
RQ2. How can the costs of underpinning be assessed; what are the costs of different design solutions?
RQ3. How can the duration of the repair work be estimated based on the chosen design solution?
RQ4. What effect does the repair work have on the property value?

1.4 Research Methods

This research consists of five separate papers. The research methods are detailed in each paper (Appendices I, II, III, IV, V). A summary of the research methods is provided in Table 1.

Some of the research is descriptive. One of the aims is to examine the main reason for underpinning, namely the decay of wood piles. Research into load transfer structures and their classification is also descriptive research. Both the decay of wood piles and the load transfer structures are presented in models (Appendices I, II), with classification provided for quantitative research purposes.

Load transfer structures are modelled (Appendix I) for classification purposes using the principles of Unified Modeling Language™ (UML). Tawast (1993) classifies load transfer cases using seven different force diagrams (example: Figure 7). Some of the force diagrams show the situation after the completion of the load transfer structure, while others include the structure's construction stages, in most cases the use of a jack. Tawast's diagrams can be presented in a form which identifies the load transfer structures as stages (Figure 8); the stages are also presented in the form of a flow diagram (Figure 9). In this case, the description of one classified case requires three different figures: two phase diagrams and a flow diagram that shows their interaction. In this research, applied UML modelling is used to facilitate the visualisation (upon which the classification is based) with one diagram for each case. In UML modelling, time-based process descriptions (horizontal timeline) can be presented together with the flow diagrams which identify the load transfer cases (vertical force arrows: downward arrow for compression and upward arrow for tension). UML (Unified Modeling Language™) modelling is primarily used in information technology to describe processes and relevant factors (Bell 2010).

Table 1. Summary of research methods.

Research question	Paper	Research methods
What alternative design solutions are available on the basis of the life cycle stage of the foundation?	I, II	- Applied UML modelling - Modelling of wood decay
How can the costs of underpinning be assessed; what are the costs of different design solutions?	III	- Statistical-mathematical modelling
How can the duration of the repair work based on the chosen design solution be estimated?	IV, Summary	- Statistical-mathematical analysis - Statistical-mathematical modelling
What effect does the repair work have on the property value?	V	- Statistical-mathematical modelling

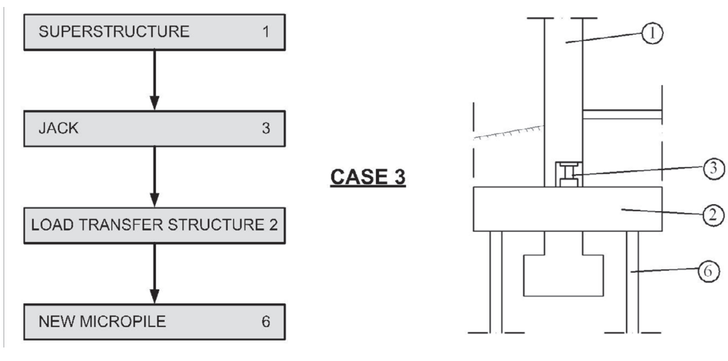

Figure 7. Example: force diagram for the classification of the load transfer structure (Tawast 1993).

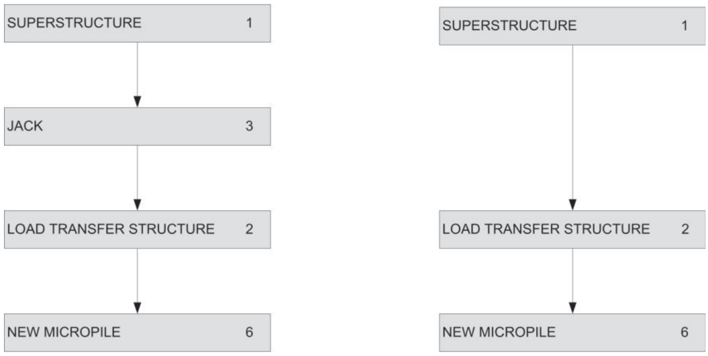

Figure 8. Load transfer structure case 3: load transfer during the jacking stage (left) and during the final stage (right) (original diagram: Tawast 1993).

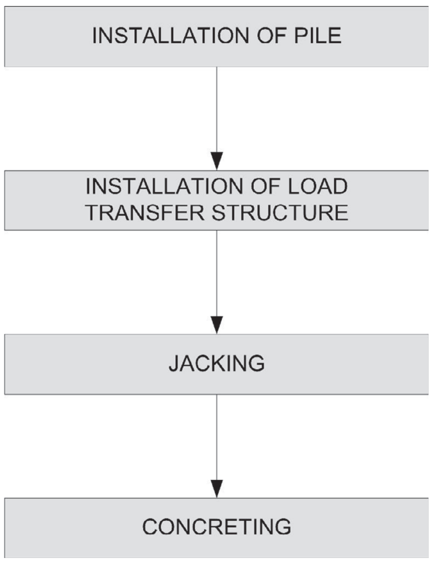

Figure 9. Flow diagram for the production process of a load transfer structure in underpinning, case 3.

In papers where the quantitative research method is used, statistical-mathematical models are developed to examine changes in property values (Appendix V) and the costs of repair work (Appendix III) in underpinning projects. The duration of underpinning projects (Appendix IV) is analysed by statistical-mathematical methods.

Descriptive research and the different classifications used (Appendices I, II) are restricted by the limited availability of research material. On the other hand, considering that underpinning is generally quite rare (only in certain ground conditions and in wood pile constructions) both in Finland and internationally, the data on underpinning construction available in this research has been relatively extensive. Statistical-mathematical modelling (Appendix III) and analysis

(Appendix IV) are also somewhat limited by the availability of research material, whereas research material on property values is reasonably extensive (Appendix V).

1.5 Scope of the research

This research examines the effects of design solutions and chosen methods on the costs and duration of work and on the timing of underpinning, primarily from the owner's point of view. The piling methods examined are different steel piles and jet grouting used in Turku. Load transfer structures include only those design solutions which have been used in Turku.

The research excludes pile types and load transfer structures which are not commonly used in Finland and Turku. Therefore, friction piles - the most common method internationally - are not included in this research. In Turku, end-bearing piles are most common; jet grouting works both as an end-bearing pile and a friction pile.

1.6 Research structure

The research comprises five original papers (Appendices I, II, III, IV, V) and the summary. Research material primarily consists of data retrieved from the DATU database (Database on Turku Underpinning Projects) of Turku University of Applied Sciences which contains data on some 100 underpinning projects carried out in Turku.

The first paper (Appendix I) describes a new classification for the different load transfer methods used in underpinning; the classification provides a basis for the assessment of project costs and duration in subsequent papers. The second paper (Appendix II) examines a typical reason for underpinning, namely the decay of wood piles, and presents a new classification for describing the life cycle of wood piles in terms of available repair methods. Two computing models are developed for estimating the costs of underpinning projects; the models are updateable and they can be calibrated by inputs (Appendix III). The duration of underpinning projects is examined by comparing different pile types and load transfer structures (Appendix IV). In addition, a proposal to model duration of underpinning is introduced in the Summary of the dissertation. The effect of underpinning on property values is examined in Appendix V.

In all papers, the researcher's role was to produce the paper content. Other authors have assisted in the illustrations and processing of material (Appendices I, II, IV) and in the application of the research method (Appendices III, V).

2. Results

2.1 Classification of load transfer structures in underpinning

Underpinning involves connecting an existing superstructure to new piles (Bruce 1989) or other structures such as jet grouting columns. Tawast (1993) has proposed a specific classification for load transfer structures based on a force diagram which identifies compression and tension. Lizzi (1982) describes underpinning without the preloading of piles, i.e. based on Tawast’s Cases 1 and 2. According to research literature, the transfer of superstructure loads has generally been implemented based on Cases 1 and 2 (Bradbury 1993, Cole 1993, Harris 1993, Littlejohn 1993, Samchek 2003, Dietz and Schurman 2006, Fross 2006, Siel 2006); however, the preloading of piles using hydraulic jacks has also been a common method, based on Cases 3 and 4 (Bradbury 1993, Cole 1993, Gupte 1989, Hutchison 1993, O´Neill and Pierry 1989, Vehmas 2000). Preloading has also been used in projects where foundations are deepened (Pryke 1993) or when piles are jacked, since pretension is achieved at installation (Bradbury 1993). In addition to pile installation and preloading, jacks have been used for levelling or lifting the superstructure (Vehmas 2000, Smith 2003).

In Paper I, a new method in the form of a sequence diagram of UML (Unified Modeling Language™) modelling is used to describe the transfer of forces (as a force diagram) combined with the timing of different construction methods. The UML sequence diagram describes the interaction of a group of objects in a particular case. The applied UML sequence diagram facilitates the task of combining a process flow diagram and a force diagram. The time axis is presented horizontally and forces are presented vertically; compression is a downward arrow, and tension is an upward arrow. The different stages are presented in the order of occurrence. An underpinning procedure, e.g. the installation of a new pile, is presented as a model object, symbolised by a rectangle over the time of action. The object can cease to exist, and the end of action is indicated with an “X” (Figure 10). (Bell 2010)

Tawast’s classification was primarily based on force diagrams. Different load transfer structures are believed to have an effect on the duration and costs of underpinning projects (Tawast 1993).

Cases 1-7 (Figures 10, 11, 12, 13, Annex 1) were originally introduced by Tawast, and cases 8-12 have been identified in underpinning projects in Turku (Lehtonen 2004a). In addition, the research literature identifies Case 10 (Richards and Kartofilis 2006) and Case 13 (Bruce 1990, Hayward Baker 2005). The classification identifies the following factors which are considered to have an effect on the costs or construction time of underpinning projects:

- Transfer of forces as compression or tension
- The use of separate structures to transfer the forces from the superstructure to new piles
- Possible pre-compression of piles, i.e. the use of a hydraulic jack.

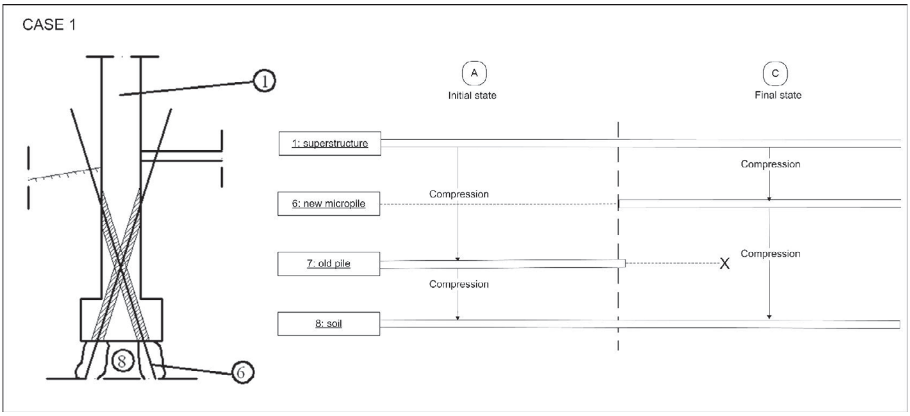

Figure 10. In LTC (load transfer structure) category A (no beam – no jack), the superstructure loads are transferred to the new piles without a separate beam or respective structure.

Load transfer cases can be divided into two main groups: methods which result in small settlement of the foundations as a result of the elastic compression of the new piles, and methods which do not cause settlement post construction (Lehtonen 2004).

Main categories of load transfer structures are presented in Table 2. All the cases are presented in Annex 1.

Table 2. Main categories of load transfer structures.

	Beam or respective load transfer structure	Jacking
A	no	no
B	yes	no
C	no	yes
D	yes	yes

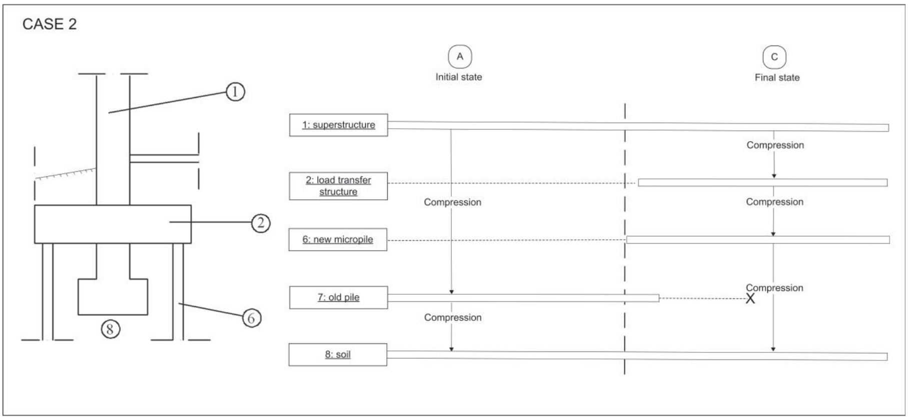

Figure 11. In load transfer structure (LTC) category B (beam – no jack), a separate beam is used to transfer the superstructure loads to new piles. Category B does not involve jacking, and the structure settles after the reconstruction by an amount determined by the elastic compression of the piles.

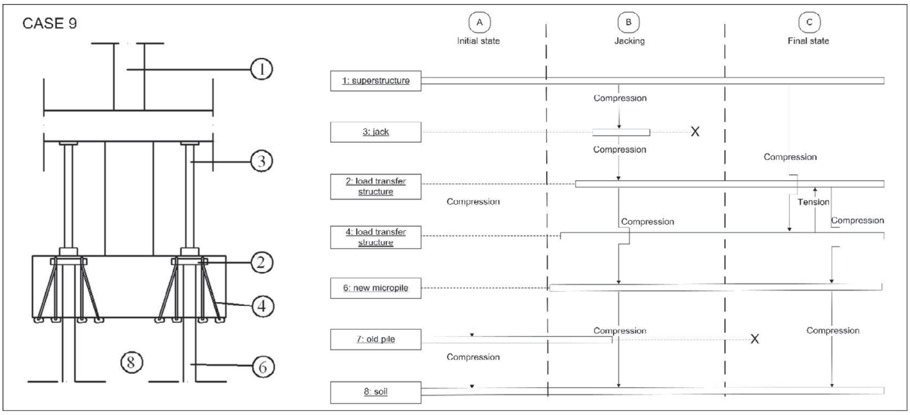

Figure 12. In load transfer structure (LTC) category C (no beam – jack), a jack is used to transfer the superstructure loads to new piles, avoiding post-construction elastic deformation of the piles and subsequent settlement. No separate beam is used, and the load transfer structure does not require significant material input.

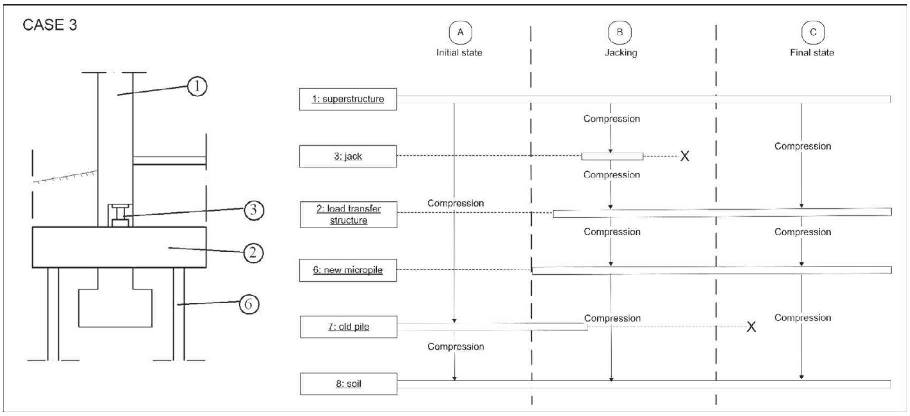

Figure 13. In load transfer structure (LTC) category D (beam – jack), a jack is used to prevent settlement caused by the elastic deformation of piles; the load transfer structure consists of a beam or pilasters.

2.2 Life cycle of foundations

Wood piles have been used for thousands of years (e.g. Ulitskii 1995). It was long assumed that wood piles could remain undamaged below the groundwater level. Recent research, especially from Holland, indicates that even wood piles which are below the groundwater level are susceptible to damage due to bacterial rot (Klaassen 2008, Klaassen 2009).

Damage to wood piles has been mostly assessed on the basis of samples from individual piles (Pitkänen et al. 1999, Stichting Platform Fundering 2007). Piles have been examined on site or samples have been collected for laboratory testing. The condition of piles has been assessed in terms of the volume of decay compared to the amount of undamaged wood; the usefulness of such estimates depends on the number and representativeness of samples.

This research includes a proposal for a new classification for the assessment of the condition of wood piling and the need for repair (Appendix II). The classification is based on a common method of monitoring the settlement of a wood-piled property such as annual high-precision levelling. The proposed classification (Figure 14) is based on interpreting the rate of settlement: classes C1 (undamaged or minimally damaged cohesive piles) and E1 (undamaged or minimally damaged end-bearing piles) have the lowest rate of settlement, and classes C3 and E3 have the highest rate of settlement. Negligible or minimal settlement (Table 3) is interpreted as sound wood foundation without recognised need for repair. A slightly higher rate of settlement is interpreted as significant damage to the wood structure which signifies a need for repair with fairly flexible timing. Accelerating or significant settlement is interpreted to mean a need for immediate repair of the wood foundation.

The life cycle stage of a wood foundation and the corresponding timing of repair work have different effects on the property and the available methods and the consequent costs. Wood foundations which are in good condition (C1, E1) can tolerate the loads during underpinning better than structures which are at the end of their life cycle; settlement which occurs during underpinning ranges from 2mm-10mm, whereas underpinning at a later stage (C3, E3) can result in settlement of 10mm-30mm (Appendix II).

Underpinning a foundation that is in good condition can be implemented by any method both in terms of piling options and load transfer structures (see 2.1 and Appendix I for details). A foundation that is in poor condition cannot be repaired by all methods; for safety reasons, the method that causes the least disruption and vibration should be chosen (Figure 15). Preliminary recommendations for the use of different methods are presented in Table 3. The limitations of each recommendation are based on the observations about significant settlement occurring during underpinning (Appendix II). The data includes some occurrences of very high rate of settlement (30mm-50mm) which may be related to the risks indicated in specific piling or load transfer methods. A limited number of available methods has an effect on costs, and underpinning can be much more expensive for a badly deteriorated foundation than for one in good condition. The service life model of wood foundations can be used to establish the timing of underpinning work and the costs of different available methods.

Table 3. Classification of settlement in wood piling foundations based on the average rate of settlement (Appendix I).

	Settlement *s* in average, mm/year
C1, cohesive wood piles	$s < 4$
C2, cohesive wood piles	$4 \leq s \leq 6$
C3, cohesive wood piles	$s > 6$
E1, end bearing wood piles	$s < 2$
E2, end bearing wood piles	$2 \leq s \leq 4$
E3, end bearing wood piles	$s > 4$

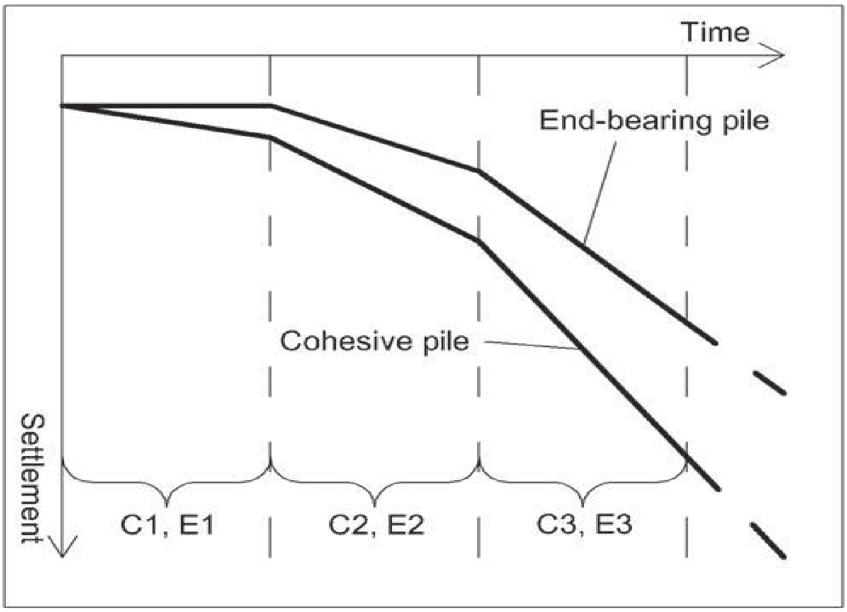

Figure 14. Classification of settlement in a wood-piling foundation at different stages of the life cycle. Stages C1/ E1 have no recognised need for underpinning, stages C2/E2 signify a recognised need for underpinning with fairly flexible timing, and stages C3/E3 signify a need for immediate remedial action.

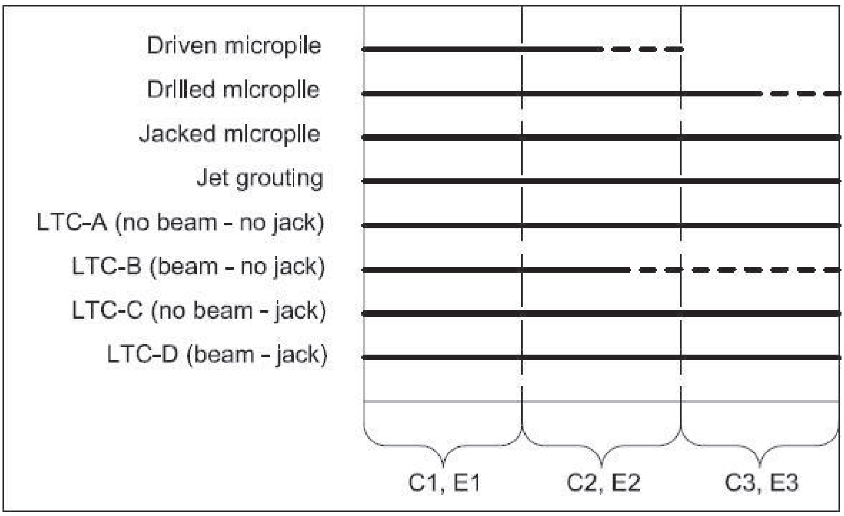

Figure 15. Recommended use of different piling methods and load transfer structures in relation to the service life and settlement of wood piles. LTC Load Transfer Structure.

2.3 Estimation of underpinning costs

No previous cost model-based research data has been published on underpinning. Some cost data has been published in the form of empirical observations based on area; the costs of underpinning have varied greatly from €150-€675/m² (Korhonen

1991, Pitkänen et al. 1999, Lehtonen 2008). Published observations are in non-updateable form, and they don't include information about cost structures or inputs.

Cost estimates are produced throughout the different stages of an underpinning project. Typically, cost estimates are drawn up before the bidding stage for budgetary purposes in the project planning stage and for the comparison of different design solutions (Ashworth 1994). In the bidding stage, cost estimates can be used to evaluate received bids.

Underpinning costs can be estimated by modelling the costs. In this research, the following principles proposed for cost modelling have been applied (Kiiras 2006b):

- Cost data should be processed into systematic files; raw data is not used.
- Cost data should be analysed on the basis of its application, not in terms of the availability of the data.
- The data should be itemised using generally accepted categories.
- The cost data is analysed using a top-to-bottom principle. This ensures the cumulative effect of different costing factors in the total cost.
- Costing items must be identified in terms of structure (e.g. input price structure); the value cannot be used alone.
- The level of the cost file is empirically set to correspond to the mean; the differences between data items are computed with the use of structures.
- The costing file should be tested with statistical methods before use.

In this research, cost modelling for underpinning is implemented using two different models, Model 1 and Model 2. Model 1 is a simple statistical-mathematical model based on empirical observations, and it involves estimating the pile volume. This requires pile length data obtained from ground surveys. The model uses the following formula:

$$C = L * 11 \quad (1)$$

where

C is the total project cost (€/m²)

L is the piling depth (numeric value given in meters).

In Model 2, a computing model is developed based on the input structure. The Talo 2000 classifications are used where applicable. The following formula is used in Model 2:

$$C = a + b + c + L * k_1 + n_1 * k_2 + n_2 * k_3 \quad (2)$$

where

C is the total project cost (€/m²)

a is the cost of project management and planning (€/m²)

b	is the HVAC repair costs (€/m²)
c	is the cost of shoring needed in the excavation (€/m²)
L	is the average piling depth (numeric value given in meters)
k_1	is the design cost of the pile length (numeric value given in euros per meter)
n_1	is the design number of piles (numeric value given in pieces)
k_2	is the cost of cutting a design pile plus the pile point (numeric value given in euros per piece)
n_2	is the number of load transfer structures which depends on the number of piles; in the model, the number of structures is half the number of piles
k_3	is the cost of a load transfer structure (numeric value given in euros per piece) based on the input price structure; in jet grouting, this value is 0.

In Model 2, cost estimates are produced based on the Talo 2000 classifications as follows:

- Construction management costs can be estimated using existing data on the costs of specific items. If existing data are not available, the value is €10/m² (corresponds to the average cost per item in the DATU database).
- HVAC repair costs during underpinning are itemised by area at four different grades ranging from €5-€150/m².
- Supports are itemised by two area-based classifications, €5 or €25/m².
- A resource-based cost structure has been drawn up for piling (Table 4). Piles have a unit price per pile, and a second unit price based on pile length.
- The resource-based cost structure for load transfer structures (Table 5) is based on the classification of structures into four categories (Appendix I). The number of load transfer structures is linked to the number of piles so that the number of load transfer structures is assumed to be half of the number of piles.

The coefficient of determination is very different between Models 1 and 2. Model 1 is a very rough cost model ($100R^2$ = 23.2% without index increase, for actual costs), although the deviation is less than in data derived from the empirical cost per square metre. In Model 2, the coefficient of determination ($100R^2$) is reasonably good at 88.7%, calculated from costs without an index increase.

Underpinning costs can be estimated using different estimation methods in different stages of construction as presented in Table 6. Traditionally, underpinning costs have been estimated primarily based on the actual cost data of completed projects. The new models, Model 1 and Model 2, provide additional methods and improved accuracy compared with estimates based on empirical data. Improvement in the accuracy of cost estimates is presented in Figure 16. Due to their ease of use and convenience, Models 1 and 2 could replace estimates based on empirical data in projects where they can be applied. On the other hand, Model 2 is clearly more accurate than Model 1, and it should be applied in the early stages of the project. This requires early implementation of the structural planning of underpinning works, at least at the draft level and if possible, as early as the project planning stage. The models can be updated and calibrated for other construction types, including those not addressed in this research.

Examples of underpinning costs using Model 2 are given in Table 7.

Table 4. Pile unit costs, Model 2 (Appendix III)

		PRICE PER PILE METRE (€/m)	PILE UNIT PRICE (€/pc)
Driven RR pile	RR115	120	300
	RR140	150	300
Jacked RR pile	RR140	120	300
RD pile	RD140	200	400
Jet grouting		300	300
Other pile		200	500

Table 5. Cost structures of load transfer structures, Model 2 (Appendix III)

Task or resource		Load Transfer Category			
		A (no beam – no jack)	B (beam – no jack)	C (no beam – jack)	D (beam – jack)
Demolition	€	300	300	300	300
Load-bearing steel components	kg	50	200	100	200
	€	100	400	200	400
Concrete structures	m^3	0.5	2	1	2
	€	100	400	200	400
Jacking	€			500	500
Total	€	500	1,100	1,200	1,600

Table 6. Cost estimation of underpinning in different stages of the construction project.

Stage	Data required for estimation	Methods of cost estimation	Comments
requirement study	net floor area or building area (m^2)	actual cost data from completed projects	a very rough method; level of costs not determined, only the range
	net floor area, pile length (m)	Model 1 (Appendix III)	roughly determined level of costs, high deviation
project planning	net floor area, pile length (m)	Model 1 (Appendix III)	roughly determined level of costs, high deviation
	draft structural plan (pile type, number, type of load transfer structure, extent of HVAC repairs)	Model 2 (Appendix III)	fairly accurate level of costs; deviation based on the level of competition and the competitiveness of companies (project base, know-how, specialist equipment)
construction planning (comparison of design options), tender stage, bid comparison	draft structural plan (pile type, number, type of load transfer structure, extent of HVAC repairs)	Model 2 (Appendix III)	fairly accurate level of costs; deviation based on the level of competition and the competitiveness of companies (project base, know-how, specialist equipment)
tender stage, bid comparison	bill of quantities	project costing	laborious; fairly accurate level of costs; deviation based on the level of competition and the competitiveness of companies (project base, know-how, specialist equipment)

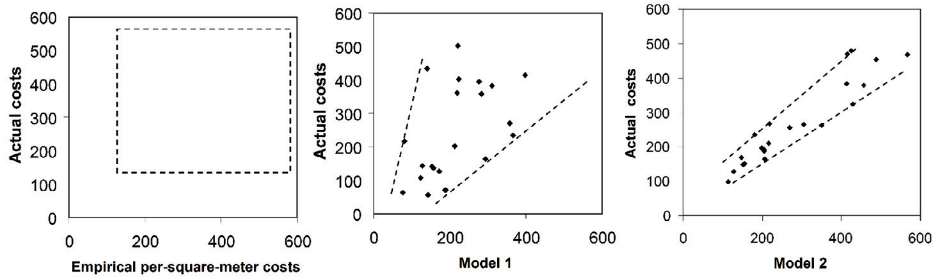

Figure 16. The costs of underpinning have been traditionally estimated based on empirical data, which results in a wide range of variation, left figure. Model 1 (centre) provides a level of costs but with high deviation. Model 2 (right) provides a reasonably accurate level of costs with reasonably low deviation. Range limits drawn by the author.

Table 7. Underpinning costs with different net floor areas and piling depths using Model 2. LTC Load Transfer Structure.

Net floor area (m^2)		2500			4000		
Number of piles		100 piles			200 piles		
Pile length (m)		10	20	30	10	20	30
		Costs (€/m^2)					
Impact driven micropile RR140	LTC-A (no beam – no jack)	102	162	222	122	198	273
	LTC-B (beam - no jack)	114	174	234	138	213	288
	LTC-C (no beam – jack)	116	176	236	140	215	290
	LTC-D (beam – jack)	124	184	244	150	225	353
Drilled micropile RD140	LTC-A (no beam – no jack)	126	206	286	153	253	353
	LTC-B (beam - no jack)	138	218	298	168	268	368
	LTC-C (no beam – jack)	140	220	300	170	270	370
	LTC-D (beam – jack)	148	228	308	180	280	380
Jacked micropile RR140	LTC-A (no beam – no jack)	90	138	186	108	168	228
	LTC-B (beam - no jack)	102	150	198	123	183	243
	LTC-C (no beam – jack)	104	152	200	125	185	245
	LTC-D (beam – jack)	112	160	208	135	195	255
Jet grouting	LTC-A (no beam – no jack)	152	272	not applicable	185	335	not applicable

2.4 Duration of construction in underpinning projects

A typical underpinning project includes the following consecutive stages (Vunneli 2006):

- site establishment
- demolition, punching and excavation works
- reinforcement of old foundations (if applicable)
- installing micropiles or jet grouting columns
- installing load transfer structures
- post-works, e.g. drainage refurbishment.

Underpinning is slow work that takes place in difficult conditions, and a typical project duration is several months. The total duration of projects in the DATU database ranges from 50-350 days. The average rate of pile installation is 0.7-1.6 piles per day. The average installation time by length of pile is 16m-47m/day. Duration observations in the DATU database have been defined following dates of piling in the piling records. (Lehtonen and Hattara 2010)

Based on the data retrieved from the DATU database, the following variations in labour input were observed between different methods:

- Driven piles and jet grouting are somewhat faster to install than jacked piles when productivity is calculated by the number of piles. With drilled piles, productivity according to the number of piles is lower than in other methods, but better than jet grouting if calculated by pile length. One productivity factor in the DATU database is the fact that the average length of drilled piles (35.1m) is considerably greater than that of jet grouting columns, which are generally quite short (average length of 10.5m).
- Differences between load transfer structures were also detected: the highest productivity is in load transfer category A (no beam – no jack) and the lowest is in category B (beam – no jack). This observation can be understood based on the input structures of different load transfer cases (Lehtonen and Kiiras 2010): category A does not involve an additional structure between the new pile and the old foundation, whereas in category B, a steel beam with protective concrete is installed as a load transfer structure on top of new piles.

The research shows that the duration of underpinning works can be only roughly estimated based on actual data such as net floor area or pile length. In any case, the owner receives reliable information about the project duration at the contract agreement stage when the contractor draws up a project schedule.

A forecasting model for estimating the duration of underpinning could be developed adapting principles introduced for cost modelling (Kiiras 2006b), e.g. as follows:

- The data should be itemised using generally accepted categories.
- The duration data is analysed using a top-to-bottom principle. This ensures the cumulative effect of different duration factors in the total duration.
- Duration items must be identified in terms of structure.
- The level of the duration file is empirically set to correspond to the mean; the differences between data items are computed with the use of structures.

The duration of underpinning can be divided into factors using items introduced in the classification of load transfer structures, see Section 2.1. The duration of underpinning can be estimated using a linear model

$$D = a + n * (k_1 + k_2 * L + k_3) \quad (3)$$

where

D	is the duration of an underpinning project (days)
a	is the duration of the starting and finishing phases of the site activities (days)
n	is the number of piles
k_1	is the duration factor of embedding a single pile
k_2	is the duration factor of piling depth
k_3	is the duration factor of a load transfer structure
L	is the pile length (numeric value given in meters).

The variables are introduced in Table 8. The values of the variables have been derived from observations published in Appendix IV. The duration factors concerning piles have been determined directly from the observations whereas the duration factors related to load transfer structures have been determined by the author where contradictory observations between different methods have emerged. The duration model has been tested by linear regression analysis using duration data available in the DATU database. The percentage of explained variance (100 R^2) is 76.9% (all duration information in DATU, site N=58) and on the other hand 81.0% for the sites (Figure 17, site N=22) introduced in Section 2.3. The latter sites are fairly comparable, five- to seven-storey residential buildings located typically in the Turku city centre. Other sites vary more with regard to location and size of the buildings. The developed model simplifies the design solutions of underpinning to some extent. Often, there are several piling methods and load transfer structures in use on a single site. The proposed model covers only the main piling or load transfer method and the total variation of all design solutions can not be taken into account. The duration of underpinning does not depend only on the number and type of micropiles and load transfer structures but also on the accessibility and number of the employed piling rigs. The usability of different types of micropiles depends also on the distance to the decayed wood piles and their response on underpinning work. However, the proposed duration model contributes a reasonable method to set up a schedule after the key design solutions of the project become available. The model could be further developed and adjusted in compliance with variables valid to the underpinned building. A summary of duration examples in different soil conditions and with different load transfer structures is shown in Table 9.

Table 8. Variables in the proposed duration model. LTC Load Transfer Structure.

	a	k_1	k_2	k_3
impact driven micropile	10	0.10	0.02	
drilled micropile	10	0.27	0.03	
jacked micropile	10	0.15	0.02	
jet grouting	10	0.10	0.045	
LTC-A (no beam – no jack)	10			0.10
LTC-B (beam – no jack)	10			0.12
LTC-C (no beam – jack)	10			0.11
LTC-D (beam - jack)	10			0.13

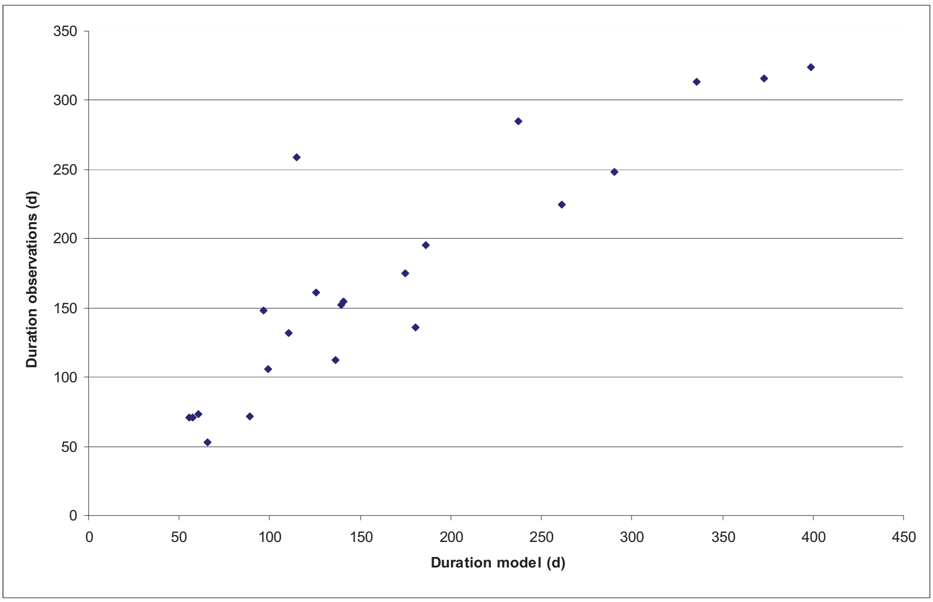

Figure 17. The duration model of underpinning and the respective duration observations from five-to seven-storey residential buildings in the Turku city centre (N=22).

Table 9. Piling duration in underpinning: examples of duration in different sites and at different piling depths. LTC Load Transfer Structure.

Number of piles		100 piles			200 piles		
Pile length (m)		10	20	30	10	20	30
		Duration (days)					
Impact driven micropile	LTC-A (no beam – no jack)	50	70	90	90	130	170
	LTC-B (beam - no jack)	52	72	92	94	134	174
	LTC-C (no beam – jack)	51	71	91	92	132	172
	LTC-D (beam – jack)	53	73	93	96	136	176
Drilled micropile	LTC-A (no beam – no jack)	77	107	137	144	204	264
	LTC-B (beam - no jack)	79	109	139	148	208	268
	LTC-C (no beam – jack)	78	108	138	146	206	266
	LTC-D (beam – jack)	80	110	140	150	210	270
Jacked micropile	LTC-A (no beam – no jack)	55	75	95	100	140	180
	LTC-B (beam - no jack)	57	77	97	104	144	184
	LTC-C (no beam – jack)	56	76	96	102	142	182
	LTC-D (beam – jack)	58	78	98	106	146	186
Jet grouting	LTC-A (no beam – no jack)	75	120	na	140	230	na

(na not applicable)

2.5 Effect of underpinning on the property value

Research results on changes in property values in conjunction with large reconstruction projects have been published mainly in terms of post-construction property value trends (Dildine&Massey 1974, Sweeney 1974, Knight and Sirmans 1996). Refurbished properties are found to have a higher value than non-refurbished properties (Dildine and Massey 1974, Yiu and Leung 2005, McMillen and Thornes 2006, Harding et al. 2007, Kangwa and Olubodun 2007, Wilhelmsson 2008). Refurbished properties have a shorter time on the market than non-refurbished properties (Knight et al. 2000). Buyers generally expect at least a basic level of maintenance (Knight ym. 2000). Refurbished properties have a higher rental yield than non-refurbished properties, and systematic maintenance can lead to an increased rate of local value and, conversely, eliminate a negative trend i.e. a general depreciation of property values in the area (Dubin 1998). A significant increase has been observed in properties with a relatively high value (Chau et al. 2003, Portnov et al. 2005).

However, the trend in the property value before refurbishment has not been researched extensively. A direct correlation has been detected between neglected maintenance and a decrease in property value (Iwata and Yamaga 2007).

In Appendix V, the effect of underpinning on the property value is examined. The research method was statistical-mathematical modelling. The model's equation for observation *i* on building *ID* = *k*, is

$$E(y_i) = a_o + b_1x_{i1} + \ldots + b_rx_{ir} + a_k \quad (4)$$

where

$E(y_i)$	is the mean of the *suhde* (apartment sale price per square metre divided by Statistics Finland mean price per square metre) variable
x_{ij}	is the quantitative explanatory variables *skaala* (difference between sale date and underpinning completion date),..., *ura* (underpinning cost, price per square metre*floor area)
b_j	is the explanatory variable coefficient
a_o	is a constant
a_k	is the difference between the levels of the categorical variable *ID* (represents the running ID number of the building), i.e. the housing companies.

Fairly extensive data on residential property prices were used to determine market values. Statistical methods can be used for areas with a sufficient number of property sales (Halomo 1995). The market values of properties depend on the different characteristics of individual properties (location, age and condition of the building, the condition of the apartment, views, storey), the different criteria of the parties and chance (Halomo 1995).

The research was carried out by examining apartments in Turku where ownership is based on the residents' association (housing company, in Finnish: *asunto-osakeyhtiö*) and whose properties have been underpinned in the period from 1994-2004. The property value is described using the sale prices of individual apartments. Sale prices for apartments in buildings which have been underpinned were retrieved from the Finnish Tax Administration statistics for 1994-2004 (Tax Administration 2005). The properties were identified based on the DATU database. The data includes 23 housing companies and 799 individual sales of properties. The average price per square meter for the area is the mean price for the quarter in the centre of Turku as determined by Statistics Finland (Statistics Finland area "Turku-1", which covers post codes 20100, 20110, 20120, 20140, 20500, 20520, 20700, 20900, 20960).

The sale prices for apartments in underpinned properties were compared to the average prices of the areas in question based on the price per square meter (Statistics Finland 2008). The method eliminates the effect of cyclical fluctuation in demand and the related fluctuation in selling prices.

The main finding of the research was an accelerated fall in the value of apartments before the underpinning. The research data did not provide material to determine what happened to the value after the reconstruction work. The data contained fewer observations on post-underpinning sale prices than on sale prices before underpinning. One obvious explanation for the fact that the repair work was not found to increase the sale prices is that some properties' values were affected by a housing company loan taken out for the underpinning work. Research literature provides various results which show that property values improve as a result of refurbishment. Additional data on price trends of underpinned properties may be available for future studies, as more observations on post-reconstruction prices are collected over time.

3. Discussion

3.1 Research questions and results

RQ1. What alternative design solutions are available on the basis of the life cycle stage of the foundation?

The research is limited to design solutions which are comparable to piling and which have been previously used in Turku. Based on the life cycle classification of wood foundations, certain design solutions can be excluded which may pose risks in foundations at that particular stage of the life cycle. In other words, more design solutions are available in the early stages of the life cycle of wood foundations than in the later stages. The research proposes that driven micropiles should only be used in stages C1/E1, that drilled piles should be avoided in stage C3/E3, and that LTC Category B (beam – no jack) should be avoided at least in stage C3/E3. The research supports the view that underpinning work is best carried out in the early stages of the life cycle.

RQ2. How can the costs of underpinning be assessed; what are the costs of different design solutions?

The research found that existing research literature does not address the costs of underpinning. Two costing models were used in the research. The resource-based Model 2 provides a reasonably accurate cost forecast method. Modelling is based on the classification of load transfer structures presented in Appendix I and Section 2.1 of the Summary. The cost model indicates that the early stages of the life cycle provide more affordable repair costs than the later stages of the life cycle.

RQ3. How can the duration of the repair work based on the chosen design solution be estimated?

The research provides initial evidence that the design solution has an effect on the duration of the work. The results are presented in Appendix IV. The duration is examined based on the pile type and the load transfer structure classification. The results are rough estimates, and the number of observations is small. The research proposes a resource-based forecasting model to scheduling of underpinning.

RQ4. What effect does the repair work have on the property value?

The examined projects were extensive reconstruction works. A significant finding in the research is the observation of the accelerated decrease in the property value prior to the commencement of repair work. Existing research literature provides general descriptions of the decrease in property values during the life cycle of buildings, and observations on the increase in value after reconstruction work. The identification of repair needs and the preparation of underpinning work result in a decrease in the property value up until the time the work begins. Repair work carried out early is more beneficial to property values than work carried out at a later stage.

3.2 Novelty value and impact of the results

This research provides new technical-financial perspectives into the commissioning of underpinning works. Existing research literature has focused on the technical aspects of underpinning methods. The results of this research can be used by owners to assess the need for underpinning, to compare alternative design solutions and to evaluate contractors' bids. A summary of the novelty value of the research is provided in Table 10.

This research proposes a new model and classification of damage in wood foundations which can be used in the evaluation of the usability of alternative underpinning methods and in the planning of the timing and the costs of underpinning works. The research supports the view that settlement occurs during underpinning works in wood piling foundations; the magnitude varies depending on the condition of the piles and the chosen support method. Decisions on how construction-related settlement is controlled has a bearing on the choice of underpinning methods, as some methods are not an option in the late stages of the life cycle of the foundations. In terms of individual methods, this means that the early stages of the life cycle are more advantageous in terms of reducing settlement than the later stages of the life cycle. The research supports the view that there are benefits to carrying out underpinning in the early stages of the life cycle of wood piling.

This research develops and compiles a new classification for load transfer structures in underpinning. The classification can be used in the estimates and planning of project duration. Further, a new method of classifying load transfer structures based on UML (Unified Modeling Language™) modelling is also presented. The applied UML model provides a new form of simultaneously presenting both the project process and the compression/tension loads in the foundations. Load transfer structures are classified under 13 cases which are further grouped under four main categories. The four main categories provide a new method of describing the load transfer structures in an underpinning project, which facilitates a new approach to estimating the project costs and duration.

This research introduces cost models which provide reasonable accuracy in forecasting the costs of underpinning projects. The models have been developed based on the classification of load transfer structures as described in Appendix II. The new models can be applied in the early stages of the project, during project planning, in the different stages of construction planning, and during bid comparison. Previously, estimates have been solely based on empirical data from previous projects, which provide an approximate range of costs. More accurate cost estimates have previously required cost accounting procedures which are difficult to carry out at the owner's end. Model 2, the more accurate of the two, includes an input structure which enables the costs to increase as the reconstruction work becomes more complex; for example, if jacking is used to minimise settlement. This also supports the view that underpinning is more affordable in the early stages of the foundations' life cycle.

The research produced a finding on changes in property values prior to extensive reconstruction projects. Existing research literature has provided evidence of increases in property values after refurbishment. The finding of this research shows that there is an accelerated decrease in property value as the time for the repair work approaches. This finding supports the view that underpinning should be carried out as early as possible in the life cycle of piling foundations.

The research provided several findings which indicate that the timing of underpinning works should be as early as possible in relation to the life cycle of wood foundation piling. The choice of repair methods, reconstruction costs, the duration of works, and the effect of underpinning on the property value all point to the same conclusion: that early reconstruction is more affordable than work carried out in later stages. The return on investment was not taken into account in the comparison of timing options; if interest rates are high, postponing repair works may be more affordable in financial terms.

The results of this research improve the owner's possibility to make efficient decisions in terms of different methods and timing options in underpinning projects. The results are primarily applicable to city centre properties in Finland. In addition, the results can be calibrated for use in other underpinning projects, for example in St. Petersburg, Amsterdam and other old town environments in Holland.

Table 10. Summary of the results' novelty value.

Paper	Finding	Other novelty value
Summary		- new technical-financial approach to underpinning - the owner's perspectives to design solutions, costs, duration and timing of underpinning projects
I	- new load transfer cases - new classification into main categories which can be used in the assessment of costs and duration	- new method (applied UML modelling) for the classification of load transfer structures
II	- choice of piling methods and load transfer structures has an effect on the magnitude of settlement during reconstruction - in the late life cycle stages of wood foundation piling, the number of available design solutions decreases both in terms of piles and load transfer structures	- new model and classification for the determination of the life cycle stage of wood foundation piling
III	- resource-based input structure for load transfer structures supports the view that it is beneficial to carry out underpinning as early as possible in the life cycle of the foundations	- the cost model provides a more accurate method for estimating the costs of underpinning projects
IV	- the effect of the pile type and the load transfer structure on the duration of the underpinning project	- the duration model provides a tool for estimating duration of underpinning projects
V	- accelerated decrease in property value as the time of repair approaches	- statistical-mathematical model for the determination of the property value in relation with the timing of repair works

3.3 Reliability of the results

The reliability of this research is subject to a common problem in construction-related research: the low availability of observation data. By its nature, underpinning is incidental reconstruction work which provides observations mainly from single individual projects. On the other hand, this research benefits from the large-scale underpinning project currently underway in Turku; internationally, the project is unique in its scale. The DATU database contains data on an exceptionally large number of projects, and the number of available observations (N) is reasonable in some statistical parts of the research. Some results are indicatory only due to the limited number of observations.

The research problem was approached from the point of view of underpinning in Turku. The nature of the projects is dictated by local geology and construction methods. The problem at the focus of this research, namely the know-how about underpinning required by the owner or the developer, is of a universal nature, and the exceptionally large project base in Turku provides an exceptionally large amount of observation data for research purposes. The research questions only cover some parts of the entire scope of the problem. The commissioning of underpinning works is a vast topic, and one study can only provide results for a very limited area. Nevertheless, the research questions cover knowledge areas about underpinning which are highly relevant to the research problem.

Research methods were chosen to provide answers to the research question as efficiently as possible. The identification of the need for underpinning and the determination of the foundations' life cycle stage are based on observations about the settlement of the building. Other possible methods, such as the monitoring of cracks (e.g. Thorburn 1993) and sampling of wood piles (e.g. Pitkänen et al. 1999) are addressed only superficially. In possible further research, additional methods could be used to develop the identification of repair needs. Nevertheless, this research has provided the means to develop a new, easy method for the assessment of settlement observations to determine the need for underpinning and its timing.

Cost estimates for alternative design solutions have been drawn up using cost models which are based on the resource-based cost structure of piles and load transfer structures. Load transfer structures are classified into categories using applied UML modelling which is based on descriptive research into the projects. Other potential methods of cost estimation include floor area-based statistical data or project cost accounting. The former is a relatively easy method, but the deviation of data is high. The challenge inherent to the latter method is that it is laborious.

The results on the estimation of the duration of underpinning works are preliminary and rough by nature. Research into duration estimations was based on limited data with high deviation. The data could be better interpreted by modelling the duration in terms of key parameters, such as the scope of works and the piling depth. Owners can obtain more accurate information about the project duration from the contractor, for example, in the contract negotiation stage.

The research provided a new finding about the effect of underpinning on the property value. An accelerated decrease in the property value prior to the time of repair was modelled using reasonably extensive data. Further research into property values could be carried out by hedonic research methods (e.g. Knight and Sirmans 1996). In this research, statistical-mathematical modelling was chosen due to the exceptional availability of data.

The research into the timing of underpinning works was based on research results on the life cycle of wood piles, design solutions, costs and property values. The results related to timing are indicatory only. They indicate that it is beneficial to carry out reconstruction work before the wood piles reach the end of their life cycle. The research did not address the effects of market conditions on the costs; however, it is evident from the results that the refurbishment plan should be drawn up as soon as possible once the need for repairs has been identified. This way, the eventual timing of underpinning works can be based on favourable market conditions. For example, this can involve a recession or a project carried out in the same area, which could provide savings in site establishment works and logistics.

The research data is mainly focused on residential apartment blocks in the centre of Turku. Data have been collected by topic to varying degrees, and more data are gathered all the time in the DATU database. This research was based on the following numbers of data:

- observations of settlement in wood piling, properties N=22
- classification of load transfer structures, pile observations N=8,598
- cost modelling, properties N=22
- duration of underpinning works, properties N=49 in analysis, N=22 in modelling
- the effect of underpinning works on property values, properties N=23.

Observations of settlement in wood piling are limited for the different categories described, and no settlement observations are available for class C2. The link between settlement observations and the pile type and the load transfer structure used in the underpinning works is based on a low number of observations; category C (no beam - jack) contains only one property. Observations about high-magnitude settlement during underpinning works are also isolated and only provide an initial base for recommendations regarding different piling or load transfer methods.

Deviation in cases identified by UML modelling is uneven. The largest observation of the number of piles (Case 2) is 3,025, and the lowest (Case 7) is 5. When combined by category, the number of observations is 2,412 (Category A, no beam – no jack), 3,025 (Category B, beam – no jack), 316 (Category C, no beam – jack) and 2,333 (Category D, beam – jack). Although the number of observations in Category C is significantly lower than in the other categories, UML modelling can be used satisfactorily to provide cost modelling.

Some of the research results are preliminary by nature. Their reliability could be improved with the use of more extensive research data. The wood pile damage model which has been developed for the identification of foundation repair needs could be more accurate if further observations were available. Repair needs can also be identified based on other indicators, such as the monitoring of cracks in the superstructure or the sampling of the wood foundation piling. The cost model, and the resource-based structure for the costs of piles and load transfer structures upon which it is based, is derived from a reasonable number of observations. The reliability of the results could be further improved by more extensive observation data. The applicability of the results in other types of projects could be greatly improved by obtaining observation data from projects in other localities, with different ground soil conditions and different types of buildings.

The conclusions of the research are preliminary to some extent, due to the partial lack of research data. Nevertheless, the existing results provide a basis for the conclusions. Significant new data has been obtained in terms of repair needs, timing, methods, costs and scheduling for the purposes of commissioning underpinning works. In addition, the conclusions provide a basis for recommendations on future research into underpinning.

3.4 Scope of applicability

The research data was collected from underpinning projects carried out in apartment blocks in Turku in the 1990s and the first decade of the 21st century. The buildings in question were underpinned using new piles or jet grouting columns which extend to the bearing stratum. The soil is layered, typically with 10m-40m of soft clay under the fill layer (up to 50m in some properties). The layer under the clay is moraine or coarse soil, with intact and solid rock underneath. The results can be best applied in similar projects, but some of the conclusions can be extended to cover other types of underpinning projects and repair work in general. The results can be generalised for all underpinning projects in terms of the life cycle assessment of wood piles, the UML modelling of repair works, the general principles of cost models, the duration of the project and the value trend of the property. The results can be seen as universal for all types of repair work in terms of the general principles of cost models and the value trend of the property.

3.5 Link between the results and previous research

This research has produced several results which support previous research. The classification of load transfer structures used in underpinning expands on the previously published classification system (Tawast 1993) and strengthens the applicability of said classification system. The previously used classification has been used mainly for design management. The results of the present dissertation expand application of classification to cost and duration modelling of underpinning.

The results of the life cycle assessment of wood foundations are compatible with the Dutch system for the assessment of repair needs in wood piles (Stichting Platform Fundering 2007). This research contributes an overall monitoring system to foundations of buildings instead of earlier practice to collect data from samples of single wood piles. The monitoring method is of the non-destructive type whereas the earlier methods are typically destructive in character.

Research into the cost models of underpinning improves the suitability of the models for use in cost estimation in the early stages of a construction project, in cost planning, in the comparison of design solutions, and in bid comparison. The results of the dissertation contribute fairly accurate estimates of costs compared with the previously used net-area-based information.

Research into the duration of underpinning is in line with the use of modelling in the scheduling of work on the site (Kruus 2008).

The research on property values expands knowledge on value changes prior to the underpinning project. The post-underpinning results on values lack observations but previous literature contributes information on positive price development due to refurbishment.

3.6 Further research

The classification of load transfer structures has been expanded in this research. The classification can be carried out by a new method which applies the principles of UML modelling. The classification could be used to support an assessment of the costs and duration of other types of underpinning projects, including detached houses, terraced houses and industrial and commercial buildings.

This research proposes a new model for assessing settlement in wood foundations and the need for repair on that basis. The model could be developed further by including more properties in the research and by comparing the samples of pile decay collected from properties with the settlement observed in such properties. A procedure based on the Dutch decay analysis could be applied in Finland if a sufficient number of decay samples could be collected to provide a basis for statistical review. Further, research could be extended to cover the observation of cracks in foundations and superstructures; this could provide measurable factors for modelling purposes. Methods for detecting repair needs could be developed based on the sampling of wood foundations; this could produce a multi-factor model including the average rate of settlement, the definition of uneven settlement, the magnitude and location of cracks, samples taken from wood foundations, and environmental impacts (traffic, changes caused by construction work) on wood piling.

The cost estimation models could be developed further by improving the accuracy of the input structure for the computing factors. It is essential that input data can be updated if the models are to be used in the future as the cost level changes.

The duration of underpinning projects was examined based on empirical data. The results provide a rough idea of project duration based on floor area, load transfer structure category, pile length and the number of piles. A forecast model could be developed for project duration with factors representing the key variables of project size.

The research produced a key finding regarding the change in property values in conjunction with underpinning works: there was an accelerated decrease in value prior to the time of repair. On the other hand, the post-repair increase in value suggested in literature was not observed in this research, probably due to the low availability of data. As time passes after the completion of underpinning works, the post-repair change in property values could be investigated further. The expected increase in value could provide useful information in terms of planning the timing of underpinning works.

There are several findings in the dissertation which all indicate the need to start an underpinning project in the early life cycle stages of the wood foundation. Further research could focus on the ideal timing of underpinning regarding technical challenges, costs and the duration of the refurbishment, and in addition, impacts on property values.

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Annex 1: Load transfer structure cases in underpinning

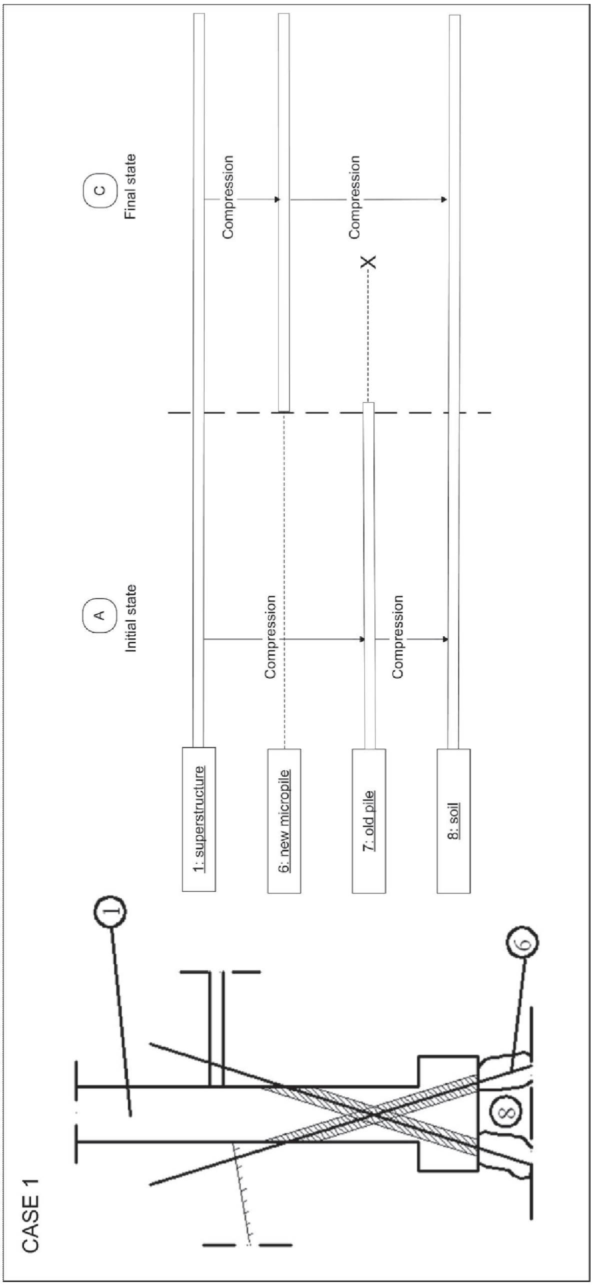

Figure A1. Category A, Case 1: no beam – no jack.

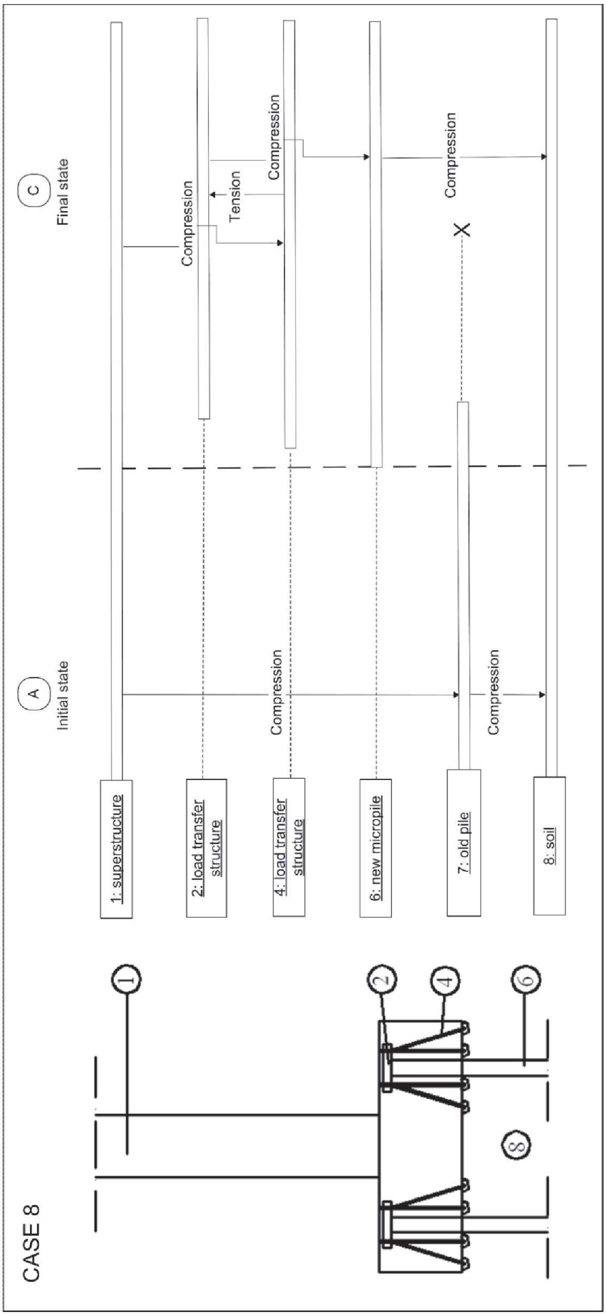

Figure A2. Category A, Case 8: no beam – no jack.

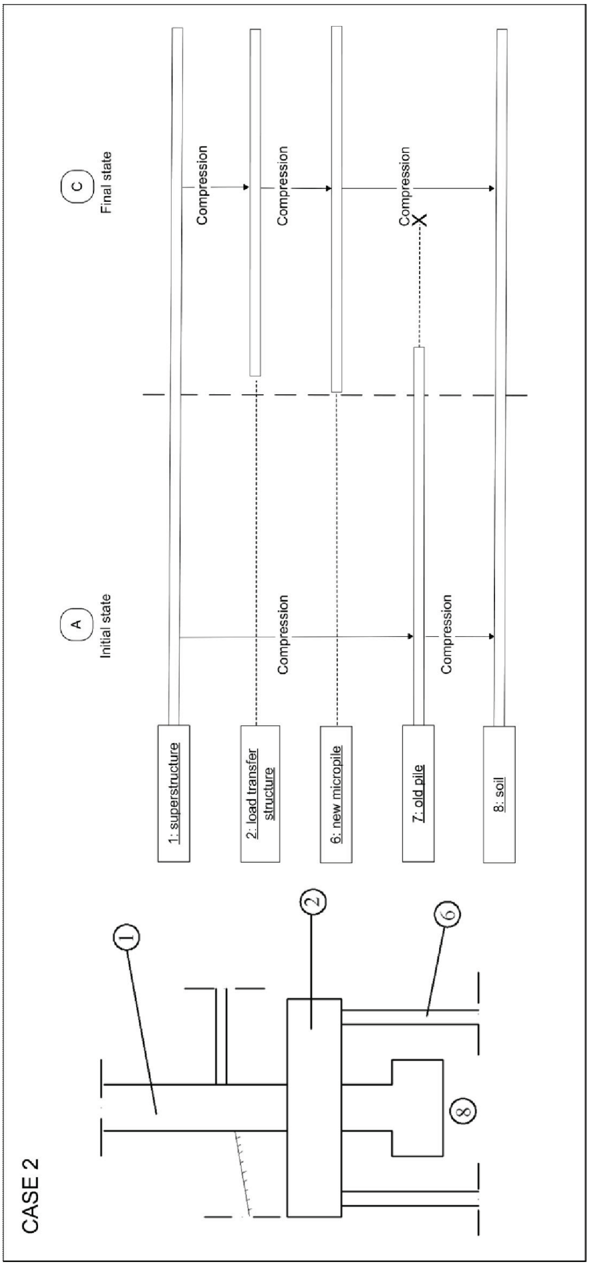

Figure A3. Category B, Case 2: beam – no jack.

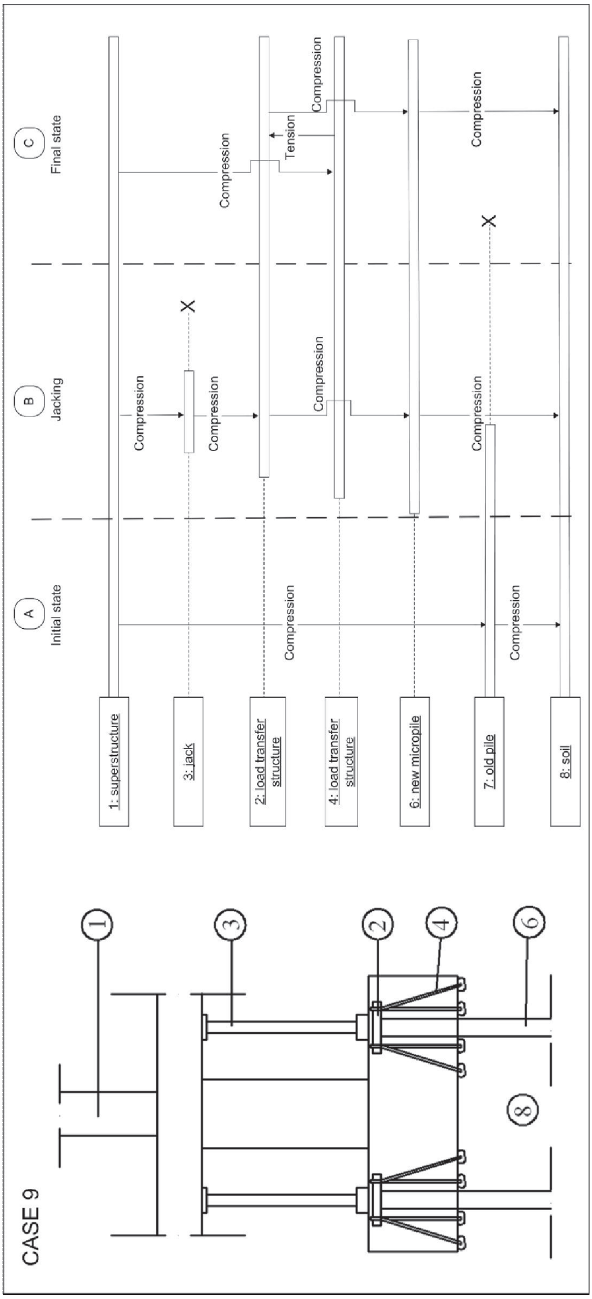

Figure A4. Category C, Case 9: no beam – jacking.

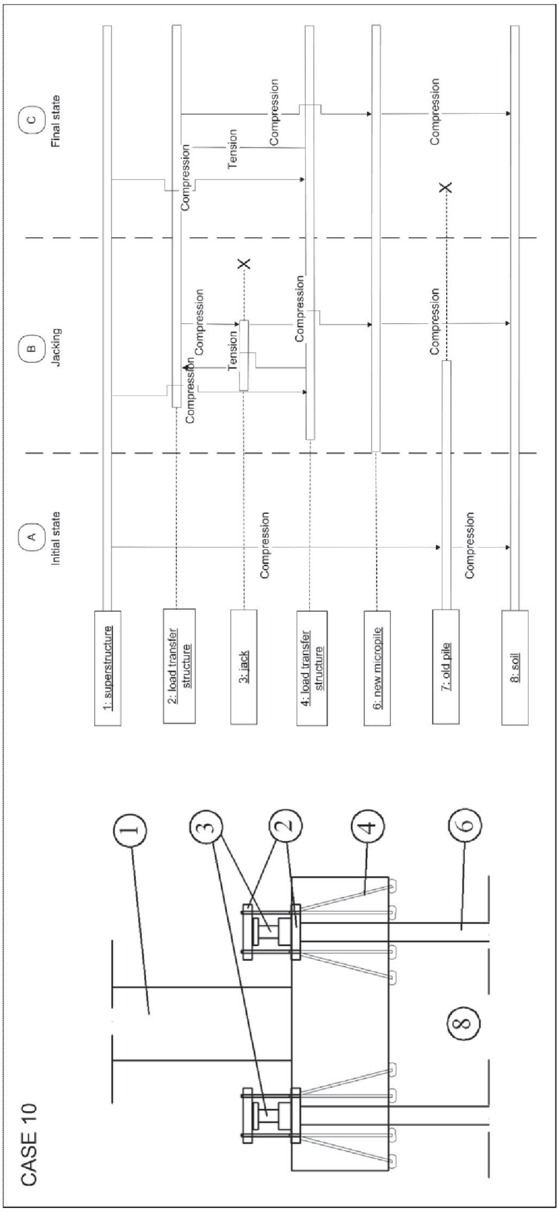

Figure A5. Category C, Case 10: no beam – jacking.

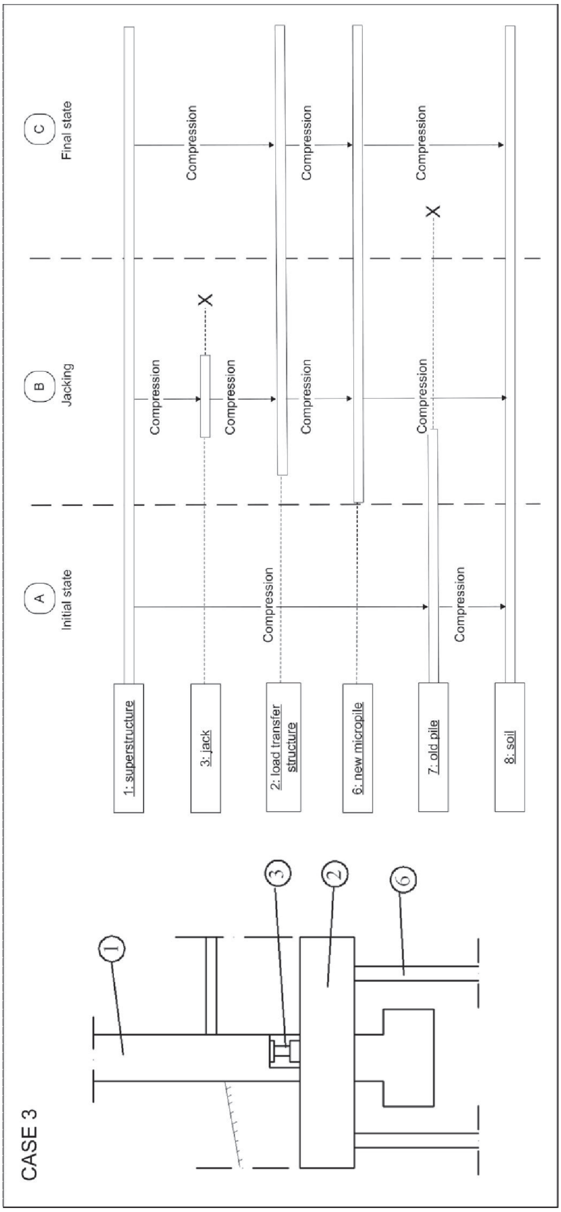

Figure A6. Category D, Case 3: beam – jacking.

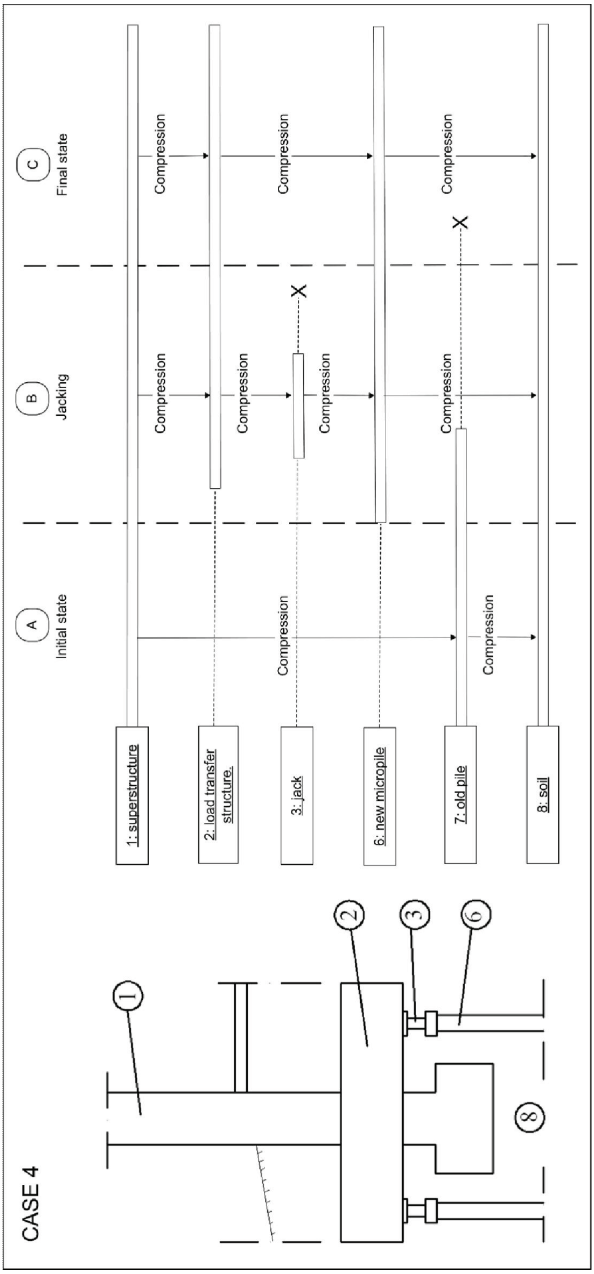

Figure A7. Category D, Case 4: beam – jacking.

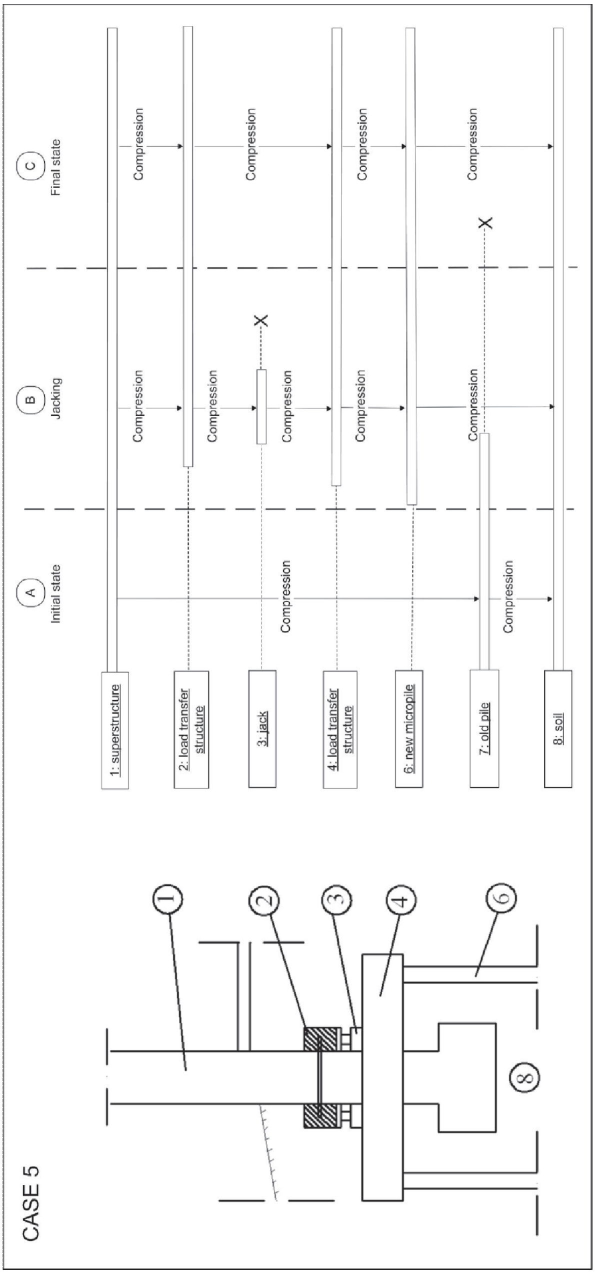

Figure A8. Category D, Case 5: beam – jacking.

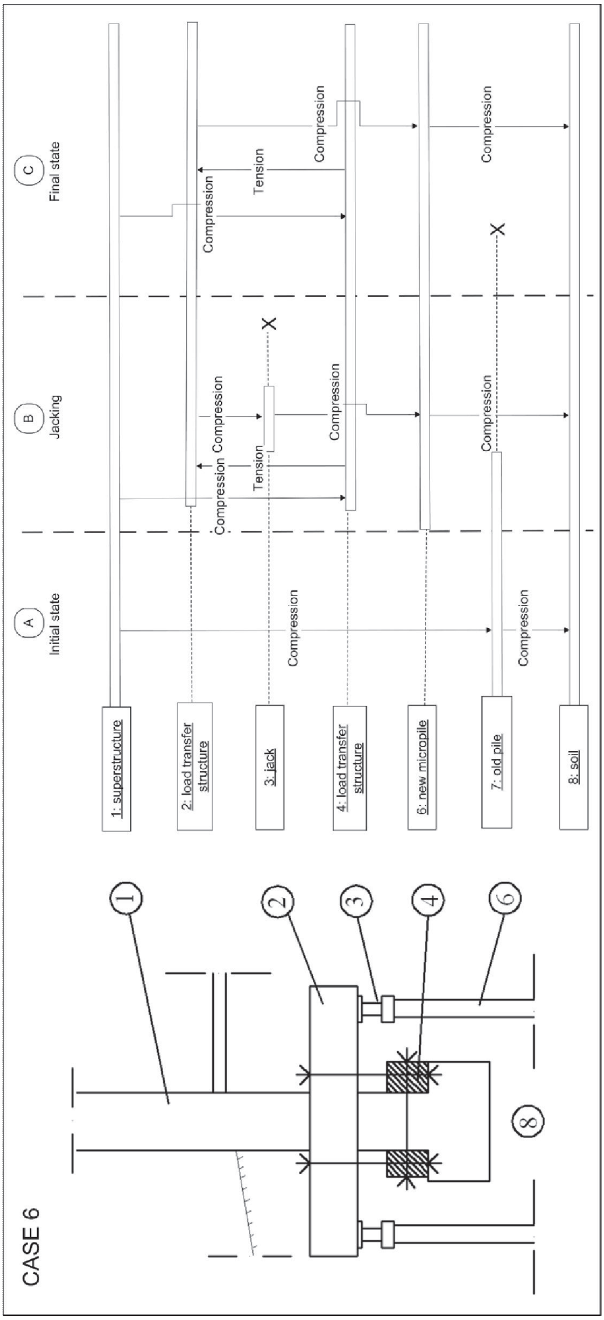

Figure A9. Category D, Case 6: beam – jacking.

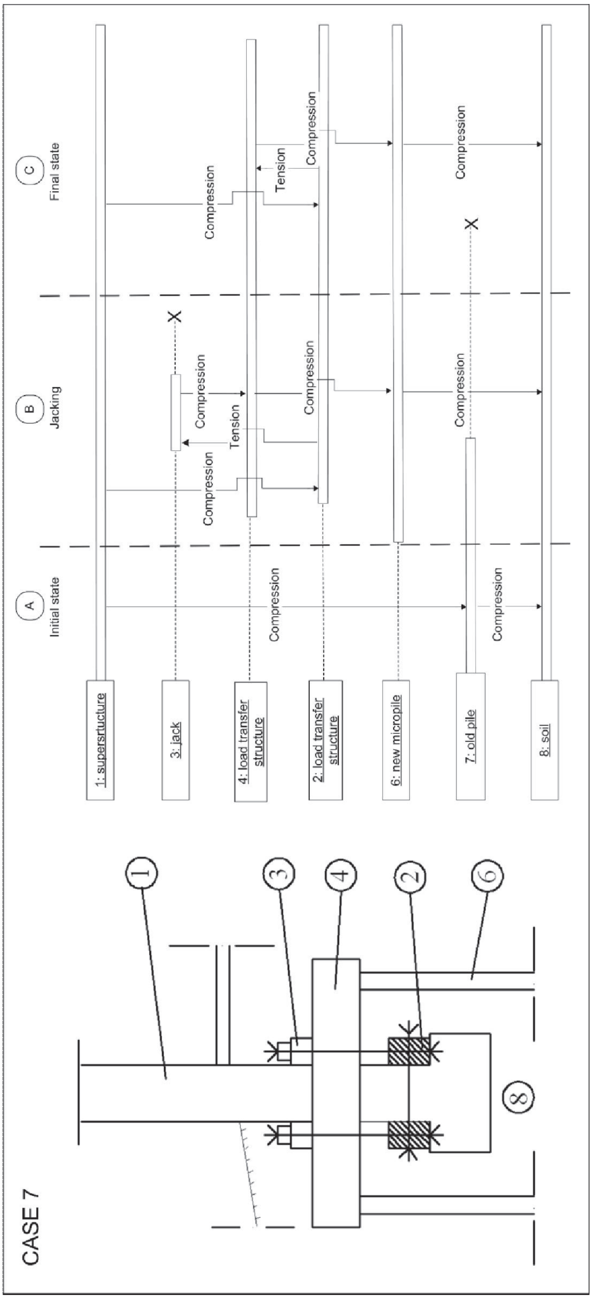

Figure A10. Category D, Case 7: beam – jacking.

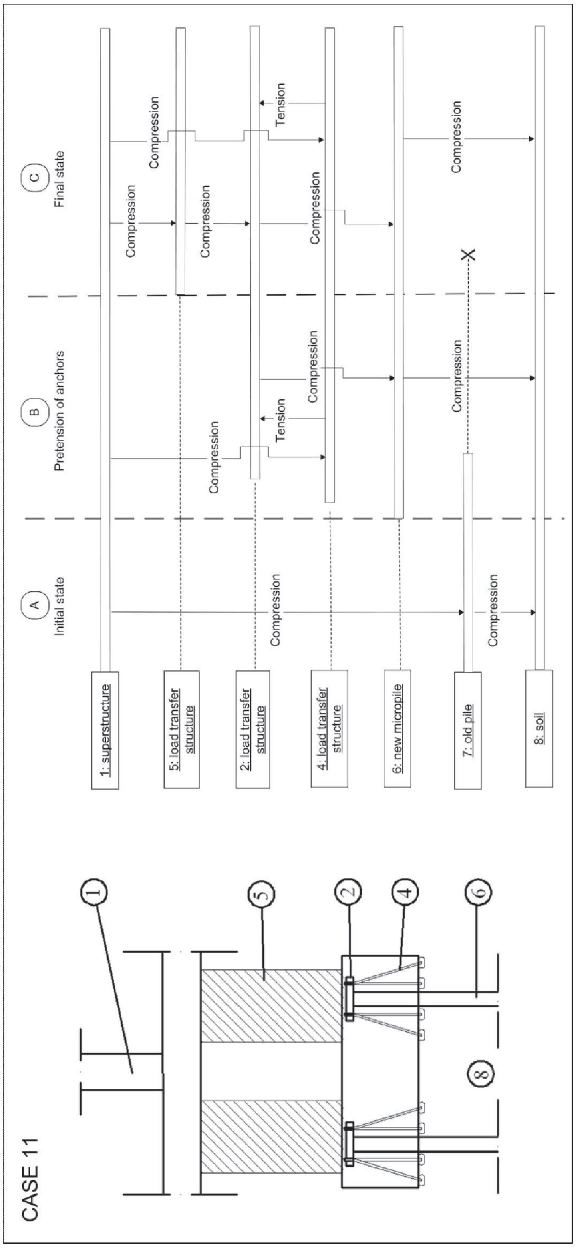

Figure A11. Category D, Case 11: beam – jacking.

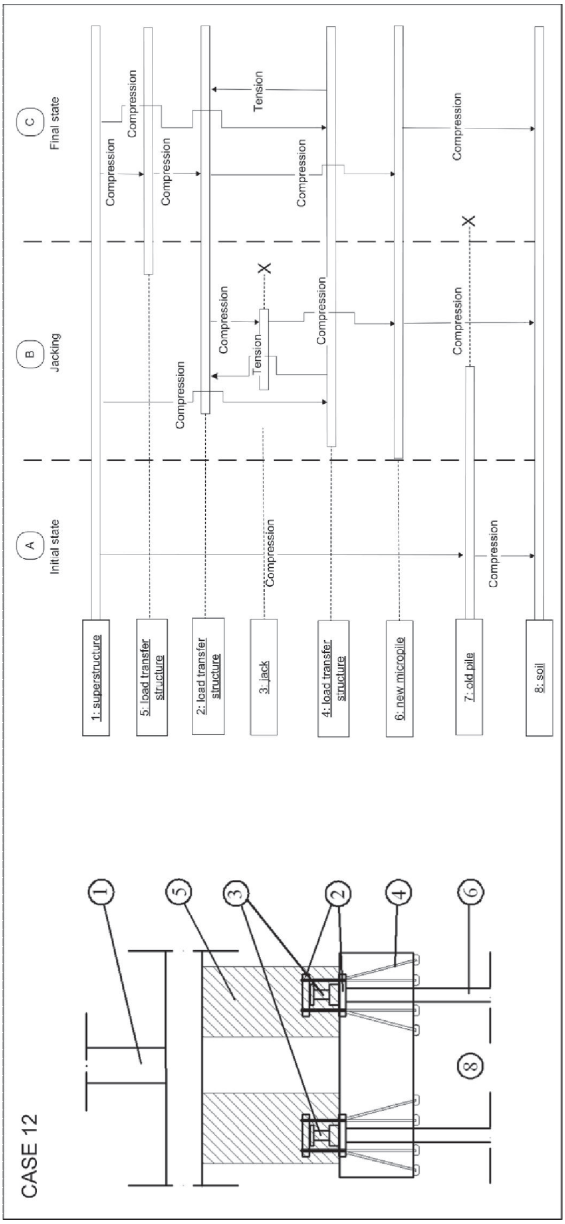

Figure A12. Category D, Case 12: beam – jacking.

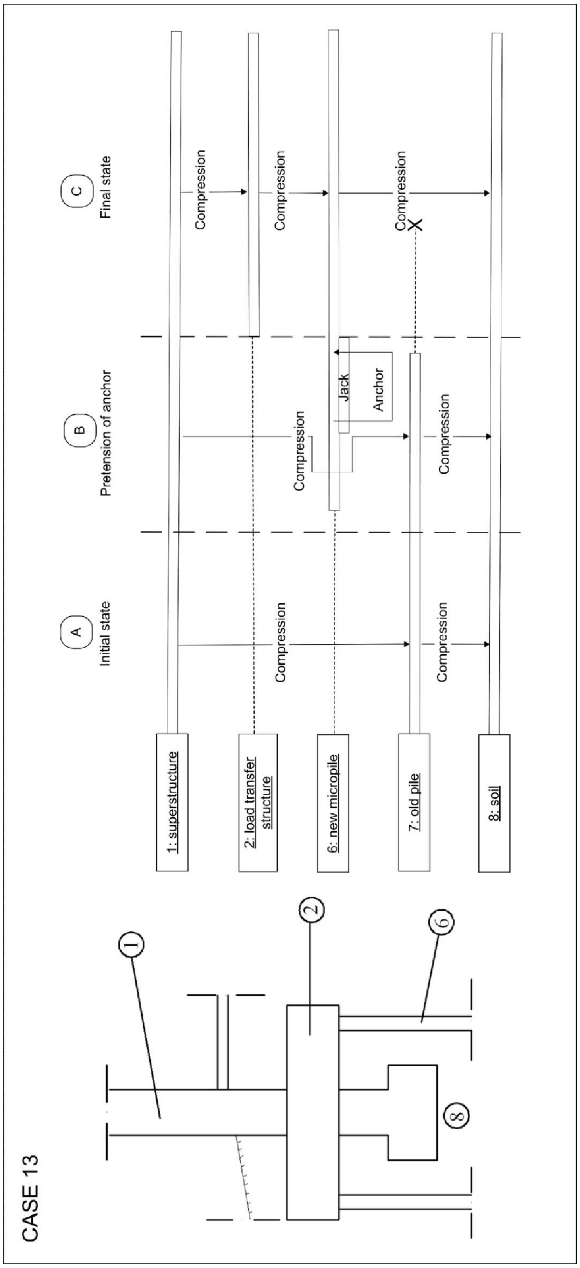

Figure A13. Category D, Case 13: beam – jacking. Case 13 can be classified to Category C (no beam – jacking), too.

Aalto-DD 80/2011

ISBN 978-952-60-4276-3 (pdf)
ISBN 978-952-60-4275-6
ISSN-L 1799-4934
ISSN 1799-4942 (pdf)
ISSN 1799-4934

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