KTH ROYAL INSTITUTE
OF TECHNOLOGY

Licentiate Thesis in Civil and Architectural Engineering

Prediction and experimental validation of dynamic soil-structure interaction of an end-bearing pile foundation in soft clay

FREDDIE THELAND

Stockholm, Sweden 2021

Prediction and experimental validation of dynamic soil-structure interaction of an end-bearing pile foundation in soft clay

FREDDIE THELAND

Academic Dissertation which, with due permission of the KTH Royal Institute of Technology, is submitted for public defence for the Degree of Licentiate of Engineering on Monday the 29th March 2021, at 1:00 p.m. in M108, Brinellvägen 23, Stockholm.

Licentiate Thesis in Civil and Architectural Engineering
KTH Royal Institute of Technology
Stockholm, Sweden 2021

ISBN 978-91-7873-796-3
TRITA-ABE-DLT-217

Printed by: Universitetsservice US-AB, Sweden 2021

Abstract

In the built environment, human activities such as railway and road traffic, construction works or industrial manufacturing can give rise to ground borne vibrations. Such vibrations become a concern in urban areas as they can cause human discomfort or disruption of vibration sensitive equipment in buildings. In Sweden, geological formations of soft clay soils overlying till and a high quality bedrock are encountered in densely populated areas, which are soil conditions that are prone to high levels of ground borne vibrations. Under such soil conditions, end-bearing piles are often used in the design of building foundations. The dynamic response of a building is governed by the interaction between the soil and the foundation. It is therefore essential that models used for vibration predictions are able to capture the dynamic soil-structure interaction of pile foundations.

The purpose of this thesis is to experimentally and numerically investigate dynamic soil-structure interaction of an end-bearing pile group in clay by constructing a test foundation of realistic dimensions. The small-strain properties in a shallow clay deposit are estimated using different site investigation and laboratory methods. The results are synthesised into a representative soil model to compute the free-field surface response, which is validated with vibration measurements performed at the site. It is found that detailed information regarding material damping in the clay and the topmost soil layer both have a profound influence on the predicted surface response, especially with an increasing distance from the source.

Dynamic impedances of four end-bearing concrete piles driven at the site are measured. Pile-soil-pile interaction is investigated by measuring the response of the neighbour piles when one of the piles in the group is excited. The square pile group is subsequently joined in a concrete cap and measurements of the impedances of the pile group and acceleration measurements within the piles at depth are performed. A numerical model based on the identified soil properties is implemented and validated by the measurements. A good agreement between the predicted and measured responses and impedances of the pile group foundation is found, establishing confidence in the ability to predict the dynamic characteristics of end-bearing pile foundations under the studied soil conditions.

Keywords: Dynamic soil-structure interaction; Pile group; End-bearing piles; Dynamic impedance; Environmental vibration; Experimental validation

Sammanfattning

Mänsklig verksamhet i urbana miljöer så som väg- och järnvägstrafik, byggnation eller maskindrift inom industri kan ge upphov till vibrationer som sprider sig via marken i närområdet. Dessa vibrationer kan ge upphov till kännbara vibrationer eller påverka vibrationskänslig utrustning i byggnader. I Sverige förekommer ofta mjuka lerjordar ovanpå berg, och inte sällan i tätbebyggda områden. Under sådana jordförhållanden används ofta spetsbärande pålar för grundläggning av byggnader. Det dynamiska verkningssättet för byggnader är beroende av interaktionen mellan jorden och byggnadens grund. Det är därför viktigt att modeller som används för vibrationsanalys i byggnader kan beskriva denna interaktion mellan jord och byggnadsfundament.

Syftet med denna avhandling är att experimentellt och via numeriska modeller studera dynamisk jord-struktur-interaktion av ett spetsbärande pålfundament i lera. Jordens mekaniska egenskaper vid små töjningar utvärderas för en lerjord som är avsatt på morän och berg genom både fältförsök och laboratorieanalyser av prover. Informationen kombineras för att konstruera en lagerförd jordmodell av platsen för att beräkna jordens dynamiska respons till följd av en punktlast. Modellen valideras med vibrationsmätningar som utförts på platsen. Studien visar att detaljerad information angående lerans materialdämpning och de mekaniska egenskaperna av jordens översta lager har en stor inverkan på förutsägelser av jordens dynamiska respons vid ytan, speciellt vid stora avstånd från vibrationskällan.

Experimentella tester utförs för att mäta dynamiska impedanser av fyra slagna spetsbärande betongpålar. Interaktionen mellan pålarna utvärderas genom att utföra mätningar av de omgivande pålarnas respons till följd av excitering av en påle. Pålgruppen sammanfogas därefter i ett betongfundament och impedanserna samt accelerationer inuti pålarna uppmäts. En numerisk modell baserad på de identifierade mekaniska egenskaperna av jorden upprättas och valideras genom mätningarna. De numeriska resultaten är i god överensstämmelse med de uppmätta vilket styrker användningen av numeriska modeller för att förutsäga interaktionen mellan jord och spetsbärande pålar under de studerade jordförhållandena.

Keywords: Dynamisk jord-struktur-interaktion; Pålgrupp; Spetsbärande pålar; Dynamisk impedans; Omgivningsvibrationer; Experimentell validering

Preface

The research presented in this licentiate thesis was conducted during 2018 to 2021 at the Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, Sweden. The research was funded by the Swedish Building, Development and Research fund (SBUF) and the funding for experiments was received from Trafikverket, Vinnova and the Richerska foundation. The financial support is gratefully acknowledged.

I would like to express my gratitude towards my main supervisor Jean-Marc Battini for his support, encouragement and many suggestions during the research project. I would also like to express my sincere gratitude towards my co-supervisor Geert Lombaert and Stijn François of KU Leuven for their support, encouragement and many valuable discussions. I also direct my gratitude to my co-supervisors Costin Pacoste and Peter Blom for their support and advice and to Fanny Deckner for her advice on geotechnical matters. A special thanks is also directed to Raid Karoumi for reviewing the thesis.

A thanks goes to all my friends and colleagues at the Department of Civil and Architectural Engineering for creating an open environment making KTH an enjoyable and fun place to work.

Lastly, I would like to thank my beloved wife Jennifer for her endless love and support, and our son Alfred for always putting a smile on my face.

Stockholm, January 2021

Freddie Theland

List of Publications

Two journal papers form the basis of this thesis. Throughout the thesis, these are referred to by their Roman numerals:

Paper I: Theland, F., Lombaert, G., François, S., Pacoste, C., Deckner, F., Battini, J-M. Assessment of small-strain characteristics for vibration predictions in a Swedish clay deposit. Submitted to *Soil Dynamics and Earthquake Engineering*, November 2020.

Paper II: Theland, F., Lombaert, G., François, S., Pacoste, C., Deckner, F., Blom, P., Battini, J-M. Dynamic response of driven end-bearing piles and a pile group in soft clay: an experimental validation study. Submitted to *Soil Dynamics and Earthquake Engineering*, January 2021.

Both papers were written by the first author whereas the co-authors contributed to the planning the work and the reviewing of the papers. The numerical and experimental works presented in the two papers were performed by the first author.

Contents

Chapter 1

Introduction

1.1 Background

Human activities such as traffic, construction activities or industrial manufacturing can give rise to vibrations spreading through the ground, causing disturbance among residents or to vibration sensitive equipment in nearby buildings. Issues related to such environmental vibrations have received increasing attention in recent years. Emphases have been put specifically on vibrations emanating from railways due to development of new railway lines, increased axle loads and utilisation of previously unbuilt land in close proximity to existing tracks [1]. A variety of different models have been developed for predicting the levels of ground borne vibrations to aid in the design and planning of new buildings and infrastructure, ranging from early stage scoping models [2–5] to strategies for more detailed vibration assessment. Predictions can be based on site measurements and empirical relationships [6, 7], numerical models based on physical principles or a combination thereof [8–10].

One of the main difficulties in making predictions of ground borne vibrations is the large variability of soil conditions and the influence it has on the vibration response of soils [11]. Local soil conditions have been shown to influence the frequency content and the attenuation of vibrations in the free-field [11–13]. Furthermore, the soil type has a significant influence on the transmission of vibrations into buildings [10]. Therefore, it is important that the site specific conditions are taken into account when predicting vibration responses in buildings. However, determination of in situ small-strain soil properties required for these analyses is based on indirect measurements, laboratory analyses or model assumptions and is therefore subject to limitations of the methods applied [14].

The dynamic response of a building subjected to ground borne vibration is governed by the interaction between the building's foundation and the soil. This interaction can be divided into two parts; the kinematic response of the massless building due to an incident wave field, and the response of the building subjected to inertia forces [15]. In inertial interaction analyses, foundations are commonly represented by dynamic stiffness and damping values which are generally frequency dependent. In particular, pile foundations arranged in groups with closely spaced piles show a strong dependency on frequency due to interaction between the piles through the soil [16]. Moreover, the response of pile foundations due to incident loading can be substantially different from the free-field motion at the soil's surface [17, 18]. To predict the vibration response of a building, it is therefore important to be able to capture the incident wave field and the dynamic stiffness and damping of the foundation, which are both strongly dependent on the site specific soil conditions.

In Sweden, the general geological conditions consist of soft clay, silt or sand overlaying a densely compacted moraine (till) and crystalline bedrock. Along the national railway tracks and in densely populated urban areas in Sweden, shallow formations of soft clay deposits overlying till and bedrock are encountered. These soil conditions are prone to high levels of ground borne vibrations [2, 7, 19]. In these soils, driven end-bearing piles are commonly used for foundation design, where prefabricated concrete piles are predominantly used [20, 21]. The vertical motion of stiff end-bearing piles in soft soils have a significantly higher vertical and rotational stiffness than floating piles due to the contribution from the axial stiffness of the piles [22]. The horizontal motion is less affected by the end-bearing condition but more so by the stratification of the soil, resulting in resonances at particular frequencies [23].

To the present date, no experimental studies have been presented for soil-structure interaction of driven end-bearing piles and pile groups. Experimental investigations are necessary to confirm the correctness of modelling assumptions and the ability of models to capture observed phenomena. Validation of numerical models based on soil properties obtained from site investigations is essential to be able to rely on predictions made at a design stage.

1.2 Aim and scope

The aim of this research is to assess the ability of numerical models to predict the small-strain dynamic responses of the soil's free surface and of end-bearing pile foundations, for soil conditions consisting of soft clays underlain by a stiff bedrock. The objectives of the research presented in this thesis are to:

- Investigate the ability of site investigation methods to provide the small-strain soil properties necessary to model a shallow clay deposit for analysis of environmental vibrations.
- Perform measurements to validate the use of numerical models in predicting the dynamic characteristics of end-bearing piles and pile foundations.

The results are of interest for a range of applications in the field of soil dynamics, but the focus of the research is on ground borne vibrations in buildings in the frequency range 1-80 Hz and the following limitations of the research applies.

- Experimental investigations are carried out at a single site and results can only be expected to be applicable to sites with similar soil conditions.
- The deformations in the soil are in all cases considered to be small and the soil is considered as a linear viscoelastic medium.
- Measurements of the free-field response at the soil's surface are limited to the vertical direction.
- No loss of contact between the soil and the piles is assumed in the numerical models.
- Horizontal layering of the soil is assumed in the numerical models.

1.3 Scientific contributions

The research presented in this thesis together with the appended papers address the objectives by considering the two fundamental problems of predicting the free-field response of the soil and the impedances of a pile group in an experimental setting and have resulted in the following scientific contributions:

- An assessment of methods for determining the small-strain soil properties in a Swedish clay, required for modelling the soil's dynamic free-field response.
- Physical insights and experimental evidence of the influence of near-surface soil conditions on the surface response in shallow clay deposits.
- Presentation of a comprehensive set of experimental results of the dynamic response of end-bearing piles and a 2×2 pile group.
- Validation of the ability of a linear elastic numerical model to predict the impedances of an end-bearing pile foundation, based solely on small-strain soil properties available prior to the construction of the foundation.

1.4 Outline of thesis

This thesis consists of two scientific papers preceded by an introductory part. Chapter 2 presents a brief review of elastic wave propagation in stratified soil and different methods to estimate the small-strain soil properties characterizing elastic soil models. Chapter 3 gives a review of the concepts of dynamic soil-structure interaction of foundations with an emphasis on piles and pile groups. Chapter 4 thereafter summarizes the main results and findings in the two appended papers. Chapter 5 presents the conclusions of the performed research and presents suggestions for further research.

Paper I presents an evaluation of the small-strain properties in a shallow clay deposit using different investigation methods, followed by an analysis of how the uncertainties on the estimated properties influence the computed free-field response at different source-receiver distances.

Paper II presents numerical predictions of the dynamic characteristics of driven end-bearing concrete piles and a pile group based on the identified soil properties. These predictions are validated by measurements performed in two stages of construction; when the piles are driven and when the pile cap is cast, joining the piles at the soil's surface.

Chapter 2

Determination of small-strain soil properties

Mechanical models are commonly used for the analysis of ground borne vibration under the assumption that the soil undergoes small deformations. This is often a justified assumption for environmental vibrations such as those induced by railways or road traffic, and allows for treating soils and rock as linear elastic materials. However, to represent the soil, the small-strain soil properties associated with the level of deformations in the soil are required. In practice, the elastic properties are obtained from empirical correlations with index parameters obtained from conventional geotechnical tests or dynamic laboratory or in situ measurements. This chapter briefly presents an overview of methods to estimate the elastic parameters required to perform model predictions of wave propagation in soils. The general principles and limitations of the methods used in Paper I to estimate the small-strain dynamic soil properties are outlined. For a comprehensive overview of investigation methods the reader is referred to the international standard ISO 14837-32:2015 [14].

2.1 Wave propagation in soil

In a linear elastic, isotropic, homogeneous solid, two types of plane body waves can exist, travelling at speeds characterised by the materials elastic properties. These waves consist of the dilatational wave (P-wave) and the shear wave (S-wave). The material wave speeds are related to elastic material properties by:

$$C_\mathrm{p} = \sqrt{\frac{M_0}{\rho}} \tag{2.1}$$

$$C_\mathrm{s} = \sqrt{\frac{G_0}{\rho}} \tag{2.2}$$

with M_0 the initial constrained modulus, G_0 the initial shear modulus and ρ the bulk density. Boundary conditions and impedance mismatch at material interfaces can lead to the existence of other types of waves, such as surface waves propagating along a traction free boundary [24].

Material damping in soil under small-strain loading is caused by dissipation of energy e.g. due to friction between soil particles. In the low frequency range, the small-strain damping in soils is almost rate independent [14]. For small damping ratios, taking the material damping into account in a linear formulation can be achieved by applying the correspondence principle, resulting in complex elastic moduli [25]:

$$M^* = M_0(1 + \mathrm{i}2\beta_\mathrm{p}) \tag{2.3}$$

$$G^* = G_0(1 + \mathrm{i}2\beta_\mathrm{s}) \tag{2.4}$$

where $\mathrm{i}^2 = -1$ defines the imaginary unit, β_p and β_s are the damping ratios in volumetric and deviatoric deformation, respectively.

Water saturation of soft soils can have a large effect on the properties governing wave propagation. In general, a saturated soil acts as a two-phase poroelastic medium according to Biot's theory [26]. However, in the frequency range of interest for environmental vibrations, the wavelengths of the propagating waves are long compared to the pore structure in the soil. Therefore, the soil can be considered as an equivalent elastic solid medium without any significant loss of accuracy [27].

It should however be recognized that due to the low compressibility of water compared to the matrix of soil particles in soft soils, the P-wave speed of such soils approach the speed of sound in water $C_\mathrm{p} \approx 1500$ m/s when fully saturated [14]. This can lead to large contrasts in P-wave speed at the interface between saturated and not fully saturated soil, causing layer resonances of vertically propagating P-waves [27]. These resonances occur in the dry layer of depth d approximately at the frequencies where standing waves develop in a layer built in at it's base:

$$f_n = (2n+1)\frac{C_\mathrm{p}}{4d} \quad n = 0, 1, 2, \ldots \tag{2.5}$$

Equation (2.5) also holds for resonances of vertically propagating S-waves if the P-wave speed C_p is replaced by the S-wave speed C_s. These soil layer resonances can largely influence the dynamic response of building foundations, which is further treated in chapter 3.

2.2 Investigation methods

The elastic dynamic soil properties can have a large influence on the vibration response in the free-field [11, 12], soil-structure interaction of buildings or infrastructure and the transmission of vibration into buildings [10]. Numerical predictions of vibration transmission and soil-structure interaction require an accurate representation of the soil for the application. However, due to project restrictions and budget constraints, it is important to understand the advantages and the limitations of different methods for estimating the desired small-strain properties of the soil.

2.2.1 Empirical methods

Empirical correlations are useful to obtain estimates of the small-strain properties from information obtained from standard site investigations. A large variety of different empirical correlations have been presented in the literature for estimating the small-strain shear modulus G_0 for different soil conditions. The following presentation is limited to empirical correlations for cohesive soils, mainly based on data from Scandinavian clays.

Larsson and Mulabdić [28] presented and evaluated empirical correlations for cohesive soils based on results from seismic cone penetration and cross-hole tests and recommends for high and medium-plastic clays the relation:

$$G_0 = \left(\frac{208}{I_\mathrm{p}} + 250\right)\tau_\mathrm{fu} \tag{2.6}$$

with I_p the plasticity index (in decimals) and τ_fu the undrained shear strength. For low-plastic clays and clayey gyttja, an alternative correlation based on the liquid limit w_L is suggested:

$$G_0 = 504\frac{\tau_\mathrm{fu}}{w_\mathrm{L}} \tag{2.7}$$

These relations are especially appropriate for Scandinavian clays, as the sites included in the database to establish the relation are located in Sweden and Norway. It should be
tests should be used for the presented relations.

The initial shear modulus can also be estimated from empirical correlations established for cone penetration tests with pore water pressure measurement (CPTu). Mayne and Rix [29] presented an empirical correlation between CPTu and the initial shear modulus for cohesive soils based on data from clays around the world, where the sites considered by Larsson and Mulabdić [28] constituted a significant part of the data set used as a basis for the correlation. The initial shear modulus is estimated from:

$$G_0(z) = p_\mathrm{a}\frac{99.5}{e(z)^{1.13}}\left(\frac{q_\mathrm{t}(z)}{p_\mathrm{a}}\right)^{0.695} \tag{2.8}$$

where $q_\mathrm{t}(z)$ is the corrected cone tip resistance, z is the depth, $p_\mathrm{a} = 100$ kPa is a reference pressure and $e(z)$ is the void ratio as a function of depth. The advantages of using the CPTu data for estimating the initial shear modulus are the same as for the CPTu test in general, i.e. it provides a high resolution with depth and is based on in situ conditions. However, the method is strictly applicable only for cohesive soils and might yield highly inaccurate results if applied to intermediate layers of non-cohesive soil or mixed soils [14].

2.2.2 Seismic cone penetration test

The seismic cone penetration test is a dynamic test performed using a CPT probe equipped with motion sensors and follows the same principle as down-hole surveys

[30]. The test is performed by hitting a pre-loaded beam at the soil's surface with a hammer in the transverse direction, inducing S-waves that propagate from the surface. The arrival of the S-waves are preferably measured at depth using two stations, allowing to determine the interval wave speed in the medium in between the positions of the sensors. Using two stations rather than a single one eliminates the reliance on an accurate trigger, resulting in more accurate wave speed estimation [31].

The time delay of the arrival of S-waves is estimated from the two recorded signals. This can be done by visual inspection, the cross-over method using two signals of reverse polarity or cross-correlation techniques in the time or frequency domain [30, 32]. Cross-correlation have the advantage that the full waveforms are taken into account when computing the time shift between the signals and that they allow for automation, removing user subjectivity [31, 33, 34]. The time domain cross-correlation between the receiver signals $a_1(t)$ and $a_2(t)$ and the estimated time shift Δt are given by:

$$c_{12}(t) = \int_{-\infty}^{\infty} a_1(\tau) a_2(\tau + t)\,\mathrm{d}\tau \tag{2.9}$$

$$\Delta t = \underset{t}{\operatorname{argmax}}\; c_{12}(t) \tag{2.10}$$

Assuming straight ray paths between source and receiver and a source horizontal offset x_s, the S-wave speed can be calculated as:

$$C_\mathrm{s}^\mathrm{SCPT} = \frac{r_{2k} - r_{1k}}{\Delta t_k} \tag{2.11}$$

where $r_{1k} = \sqrt{z_{1k}^2 + x_\mathrm{s}^2}$ and $r_{2k} = \sqrt{z_{2k}^2 + x_\mathrm{s}^2}$ denotes the radial distance to receiver 1 and 2, respectively. Following Verachtert [35] and Areias and Van Impe [36] the shear wave speeds are attributed to the depth $z_{k,\mathrm{SCPT}}$ corresponding to the radial distance $(r_{1k} + r_{2k})/2$ between the source and the bottom receiver, i.e.:

$$z_{k,\mathrm{SCPT}} = \frac{z_{2k}(r_{1k} + r_{2k})}{2 r_{2k}} \tag{2.12}$$

The assumed travel path model is illustrated in fig. 2.1.

The SCPT was extensively used in the investigations of Larsson and Mulabdić [28], where it was found that for Swedish clays, the upper part of the soil might experience shear strains that are outside the range that can be considered as elastic during the test. Therefore, measurements in the upper part of profiles with soft soils should be carefully executed. Moreover, the estimations of wave speeds in the uppermost meters of the soil are less reliable due to the small effective spacing between the sensors in eq. (2.11) [31, 37].

2.2.3 Bender element tests

Bender elements can be mounted into devices for conventional laboratory testing such as oedometer, triaxial and direct simple shear to measure the S- and P-wave

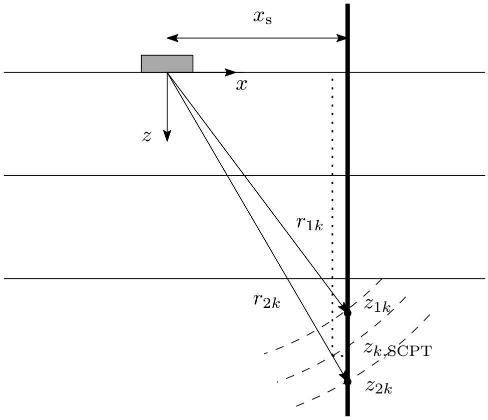


Figure 2.1: *Straight travel path model and interpreted investigation depth $z_{k,\mathrm{SCPT}}$ from the SCPT.*

speeds of a soil specimen under different loading conditions [14]. The bender elements flex when supplied with an electric voltage and likewise produce a voltage when deformed. The piezoelectric benders are mounted to the testing equipment in the top cap and the bottom pedestal, allowing to determine the travel time over the interval to obtain the material wave speed. In addition, anisotropy may also be characterized by mounting elements in the perpendicular direction [38, 39].

The test is fast and considered to be a reliable method to determine the S- and P-wave speeds of samples. However, a general problem with laboratory investigations of small-strain properties is that they require high quality samples. The quality of the samples can have a significant effect on the estimated S-wave speed in Scandinavian clays [40]. Moreover, small specimen evaluated in the laboratory might not be representative for the in situ soil conditions at a site.

The evaluation of material damping with bender elements have been addressed only by a few authors [31, 41, 42]. Karl et al. [31] evaluated different methods to estimate material damping with bender elements. The material damping ratio was overestimated by all the considered methods compared to damping ratios obtained from resonant column tests. Cheng and Leong [42] recently introduced the Hilbert transform method to estimate material damping from the bender element tests. Estimation results were shown to be within a relative error of 10% from numerical simulations and the results were validated against resonant column tests for an Ottawa sand. This method was used to estimate material damping from P-wave signals in oedometer samples in Paper I.

2.2.4 Seismic refraction

Seismic refraction is a non-invasive geophysical method for groundwater exploration and sub-surface mapping of bedrock [43]. The method is based on the measurement of the dynamic surface response due to an impulse load applied at the surface. The loads are in practice generated by a hammer or small explosive loads. The P-wave is the fastest travelling wave and is thus the first to arrive at the receivers. The first arrival time at each receiver is identified, and the arrival time and source-receiver offset data is used to estimate P-wave speeds and depth of soil layers from a model inversion. The model inversion is based on Snell's law and the assumption of a horizontally stratified soil profile where the P-wave speed is increasing with depth. Snell's law is given by:

$$\frac{C_{\mathrm{p}j}}{\sin\theta_j} = \frac{C_{\mathrm{p}j+1}}{\sin\theta_{j+1}} \tag{2.13}$$

where θ_j is the angle of the incident P-wave in layer j travelling with P-wave velocity $C_{\mathrm{p}j}$ and θ_{j+1} is the angle of the refracted P-wave in layer $j+1$ with corresponding P-wave velocity $C_{\mathrm{p}j+1}$. If the condition $C_{\mathrm{p}j+1} > C_{\mathrm{p}j}$ hold, the incident P-wave is critically refracted, travelling with a velocity $C_{\mathrm{p}j+1}$ along the boundary between layers j and $j+1$, whenever the incident angle equals $\theta_{j\mathrm{c}} = \arcsin(C_{\mathrm{p}j}/C_{\mathrm{p}j+1})$.

Figure 2.2 presents a schematic representation of a refraction test where each receiver represents the first arrivals times corresponding to each layer. At the first receiver, a

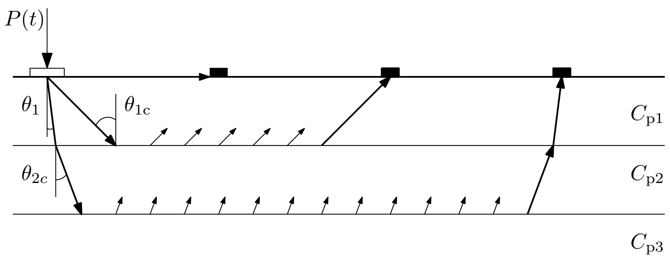


Figure 2.2: *Schematic illustration of a seismic refraction test.*

direct wave travelling in the upper layer arrives first. The first arrival at the second receiver is a wave that is critically refracted at an angle $\theta_{1\mathrm{c}}$ at the interface between the first and the second layer. The wave travels along the upper boundary of the second layer with the velocity $C_{\mathrm{p}2}$ and is refracted back towards the surface. The third ray is refracted at the interface between the first and the second layer with an angle θ_1, and is critically refracted at the interface between the second and third layer at and angle $\theta_{2\mathrm{c}}$, where it is refracted back towards the surface in a similar fashion. For a regular soil profile, where the stiffness is increasing with depth, the first arrivals at the closest receivers will correspond to direct waves in the uppermost layer and refracted waves will be the first to arrive at receivers positioned at larger distances.

The P-wave speed $C_{\mathrm{p}j}$ of a layered soil can be identified from the slopes and intersections of lines of a bilinear curve representing the first arrival times as a function of receiver distance, provided that the P-wave velocity increases with depth at the site, and can be calculated as:

$$C_{\mathrm{p}j} = \frac{r_{j+1} - r_j}{t_{\mathrm{p}j+1} - t_{\mathrm{p}j}} \tag{2.14}$$

where r_j is the source-receiver distance at the jth breakpoint of the bilinear curve and $t_{\mathrm{p}j}$ is the corresponding arrival time of the P-wave. The layer thickness h_j of layer j can then be calculated as [35]:

$$h_j = \frac{\tan\theta_{jj}}{2}\Big(C_{\mathrm{p}j+1}t_{\mathrm{p}j+1} - r_{j+1} - 2\sum_{i=1}^{j-1}\frac{h_i}{\tan\theta_{ij}}\Big) \tag{2.15}$$

with θ_{ij} defined by:

$$\theta_{ij} = \arcsin\Big(\frac{C_{\mathrm{p}i}}{C_{\mathrm{p}j+1}}\Big) \tag{2.16}$$

When the condition of a regular soil profile, i.e. a strictly increasing P-wave speed with depth, is violated, any intermediate softer layer will not be detectable. Moreover, when sharp stiffness contrasts are present, the wave refracted in an underlying much stiffer layer may reach the surface before the wave that is refracted in an intermediate layer, leaving it undetected.

2.2.5 Spectral and multichannel analysis of surface waves

At the stress-free boundary at the soil's surface, not only P- and S-waves exist, but also surface waves. The surface waves develop as a consequence of the traction-free boundary condition and propagate along the surface. For a homogeneous halfspace, the surface wave (Rayleigh wave) travel with a constant speed C_{R} that is closely related to the S-wave speed of the soil [24]. Moreover, surface waves are subjected to a lower degree of spatial attenuation than body waves. If layering or variation of the stiffness with depth is introduced in the soil, multiple modes of surface waves might exist and they become dispersive, i.e. the wave speeds are varying with frequency. This can be represented by dispersion curves describing the variation of wave speed with frequency. As the penetration depth of a surface wave is proportional to its wavelength, the dispersion curves contain information about the material properties at depth in the soil profile, where longer wavelengths contain information of the deeper layers and shorter wavelengths of the more shallow soil [44]. This is the foundation for a class of methods referred to as Spectral Analysis of Surface Waves (SASW) or Multi Channel Analysis of Surface Waves (MASW), where the dispersion curves of the surface waves observed in the field are fitted to a computational model of a horizontally stratified soil. The model dispersion curves are commonly obtained either from the transfer matrix method [45, 46] or the direct stiffness method [47], assuming a horizontally stratified soil of linear elastic isotropic layers.

The experimental procedure of the test is the same as in the seismic refraction test. An array of receivers are placed at the soils surface extending from the position where a dynamic load is applied. The responses are measured and transformed to the frequency-wavenumber domain using appropriate integral transform techniques (e.g. [48–50]), where the dispersion curves are identified as distinct peaks in the spectrum [51]. The identified dispersion curves can subsequently be used to estimate the experimental attenuation curves of the surface waves from the spectral peaks using methods from structural dynamics [52, 53]. The attenuation curves describe the spatial attenuation related to material damping in the soil as a function of frequency or wavelength and allows for including the material damping of the soil in the inversion.

The inversion is formulated as a multiobjective non-linear least squares problem, minimizing the misfits between the experimental and theoretical dispersion and attenuation curves in order to obtain the final properties making up the soil profile. This problem suffers from non-uniqueness and the outcome of the inversion strongly depends on the initial number of layers and soil properties assumed. This is especially the case for soils with an irregular variation of stiffness with depth [35]. It is therefore beneficial to incorporate any information available of stratification and soil properties estimated from available site investigations.

Surface measurement methods are non-invasive as they require measurements only on the surface of the soil. Due to the spatial distribution of the measurement points over a larger distance, the identified in situ properties take a larger body of soil into account than point wise investigation methods such as laboratory sampling or SCPT. However, as the methods are based on model inversions, they are sensitive to violations of the fundamental assumptions such as lateral variations of the soil properties or inclined layers of soil or rock. In the case of small layer inclinations, an equivalent horizontally stratified model can still capture the propagation of surface waves at a site [35]. However, the material properties and layer depths are then apparent and do not necessarily reflect the true physical material properties of the soil layers. Therefore, careful consideration should be taken of the validity of an identified soil model when used for prediction purposes.

Chapter 3

Dynamic soil-structure interaction of pile groups

Subjected to dynamic loads, the response of a structure founded on soil is governed not only by the mechanical properties of the structure but also by the soil-foundation system. Soil-structure interaction of foundations is generally frequency dependent and can lead to amplification of the structural response at certain frequencies while for others the response is diminished. In particular, the response of pile group foundations is sensitive to the loading frequency, due to the dynamic interaction between closely spaced piles. This chapter presents the general concepts characterising dynamic soil-structure interaction of building foundations as well as the main characteristics governing soil-structure interaction of pile group foundations. In addition, reviews of models available for computing the dynamic impedances of piles and pile groups and available experimental evidence are presented.

3.1 Dynamic soil-structure interaction

The dynamic soil-structure interaction problem consists of predicting the response of a structure founded on or within a semi-infinite soil domain when subjected to dynamic loads in the form of incident waves and/or external loads applied directly to the structure. Assuming linearity, the soil-structure interaction problem can be represented as the superposition of the kinematic and inertial interactions. The kinematic interaction of the structure consists of the response of the massless structure due to incident loading, whereas the inertial interaction is the response of the structure due to external forces and the inertia forces resulting from the ground motion obtained from the kinematic interaction analysis. In applications where the structural response due to external loads is of interest or the foundation input motion is known, only the inertial interaction is relevant. For such analyses, the influence of interaction between the foundation and the entire outer soil domain can be completely captured in the frequency domain by an impedance matrix $\mathbf{Z}(\omega)$, where ω is the circular frequency. This impedance is defined on the boundary between the soil and the foundation and can be directly added to the impedance matrix of the structure [15].

Discrete shallow foundations and pile caps are often considered as massless and infinitely rigid, such that the motion of the whole foundation can be described by three translations and three rotations. The dynamic forces and moments applied to the rigid foundation cap are related to the translations and rotations through the complex valued impedance matrix:

$$\begin{bmatrix} Z_{xx} & 0 & 0 & 0 & Z_{xry} & 0 \\ 0 & Z_{yy} & 0 & -Z_{yrx} & 0 & 0 \\ 0 & 0 & Z_{zz} & 0 & 0 & 0 \\ 0 & -Z_{yrx} & 0 & Z_{rx} & 0 & 0 \\ Z_{xry} & 0 & 0 & 0 & Z_{ry} & 0 \\ 0 & 0 & 0 & 0 & 0 & Z_{rz} \end{bmatrix} \begin{Bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{Bmatrix} = \begin{Bmatrix} u_x \\ u_y \\ u_z \\ \theta_x \\ \theta_y \\ \theta_z \end{Bmatrix} \tag{3.1}$$

with cross-coupling terms being non-zero only between the horizontal u_x, u_y, and rocking θ_y, θ_x degrees of freedom [16, 54]. The individual terms in the impedance matrix are defined as:

$$Z_{kl}(\omega) = k_{kl}(\omega) + \mathrm{i}c_{kl}(\omega) \tag{3.2}$$

where the real part $k_{kl}(\omega)$ represents the dynamic stiffness and inertia of the foundation and the imaginary part $c_{kl}(\omega)$ the dissipation of energy, incorporating both soil material damping and the radiation of energy through wave propagation in the soil.

As the impedance characterises the local interaction between the foundation and the soil, it is an appropriate measure for model validation of the soil-structure interaction between the foundation and the soil. The experimental validation of interactions between piles, impedances of single piles and a pile foundation are considered in Paper II for the purpose of model validation.

3.2 Impedances of piles and pile groups

3.2.1 Single pile impedance

The impedance of a single pile is governed by the stiffness, geometry and orientation of the pile as well as the elastodynamic properties of the soil. In the lateral directions, single piles are most sensitive to the soil properties closest to the surface [23, 55, 56]. This is due to the localized deformation of flexible piles when subjected to lateral excitation, where at a depth of 10-15 pile diameters, the stresses and displacements of the pile reduce to negligible proportions [23]. In the vertical direction, on the other hand, the pile impedance is influenced by the skin friction along the full length of the pile and the conditions at the pile tip [56, 57].

For end-bearing piles, the horizontal impedance is influenced by the resonance frequencies of the soil overlaying the bedrock, where standing S-waves develop. These frequencies act as cut-off frequencies for the onset of wave propagation in the soil, resulting in a reduction of the dynamic stiffness and an increased amount of radiation damping [23, 58].

3.2.2 Pile group impedance

When multiple closely spaced piles are joined together at the surface in a rigid foundation, pile-soil-pile interactions significantly influence the dynamic impedances of the foundation [59, 60]. This interaction between the piles leads to a strong dependence on frequency of the foundation impedances. This interaction is governed by the ratio between the pile-to-pile spacing and the wavelengths propagating in the soil [60]. A forced vertical motion of a single pile induces vertically polarized S-waves propagating horizontally in the soil. When the pile-to-pile spacing coincides with the half-wavelength of this wave, the motion induced at the neighbour pile is 180 degrees out of phase with the motion of the forced pile. The simultaneous forced motion of multiple piles in a group causes destructive interference due to this pile-soil-pile interaction, resulting in a drastic increase in foundation stiffness for pile groups with equal separation distances between the piles [16, 61, 62]. Similar mechanisms hold for the horizontal impedance of pile groups, where also longitudinal waves are involved in the interaction [63]. These interactions are most pronounced in homogeneous soil, where phase differences of the waves emanating from the periphery of a forced pile are negligible over the pile length. In that case, the piles are moving as a rigid body and the waves induced in the soil are of equal wavelength [64]. However, this is only true for floating piles in homogeneous soils. Non-homogeneous soils and stiff end-bearing piles in a soft soil do not show as pronounced peaks in vertical and rotational foundation impedances [22, 56, 60, 65]. Similar observations of less pronounced interaction effects have been made when the pile cap is embedded in the soil and when soil non-linearity is taken into account [66, 67].

3.2.3 Computation of dynamic pile group impedances

Due to the strong frequency dependence of foundation stiffness and damping properties of pile foundations and the potential beneficial or detrimental effects it can have on the seismic response of structures, machine foundation design and ground borne vibrations, the development of prediction models to estimate the impedances of pile foundations have received much attention in the literature in the past few decades.

Owing to the numerous possible variations of soil stratification and pile group geometries, different numerical methods with varying degrees of accuracy are used to perform predictions of pile group impedances. The most widely used numerical methods consist of the boundary element method (BEM) and the finite element method (FEM). The BEM offers an attractive option to model soil, as it inherently takes the infinite extent of the soil into account and requires only discretization of boundaries and interfaces. However, dense linear systems are obtained when assembling the structural matrices. The FEM allows for arbitrary geometries as well as taking into account non-linearities [68]. However, due to the infinite extent of the soil domain, the finite model geometry requires either a large computational domain, resulting in significant computation times, or the use of absorbing boundary conditions to attenuate waves propagating towards the outer boundary of the model and avoid reflections.

Such boundaries can be achieved by making use of e.g. viscous boundaries [69, 70], infinite elements [71] or perfectly matched layers (PML) [72, 73]. The BEM and FEM strategies can also be combined, where structural components and piles are modelled with finite elements and the soil is modelled with boundary elements, eliminating the need for absorbing boundary conditions [74].

Due to the complexity and large computational demands of advanced models, the practical use for engineering applications is limited. Therefore, results derived from advanced models have been used to publish results for idealized cases of soil properties and sets of different common geometrical configurations. These results are presented as dimensionless quantities in graphs and tables to be applicable for a wide range of soil properties and pile geometries [22, 65]. For a larger degree of flexibility in the geometrical layout of the piles, dynamic pile interaction factors have been established based on the idea of static interaction factors [75, 76]. The influence of the displacement of a single pile on a neighbouring pile is considered in order to obtain the interaction factors. Pairwise interaction factors are then combined by superposition under the assumption that the interaction between two piles are not influenced by the presence of the other piles in the group. These methods have been found to be excellent engineering approximations and interaction factors have been established for physically motivated analytical expressions for pile-to-pile wave propagation [58, 61, 77, 78] and tabulated for specific soil conditions [79]. Moreover, the methods have been extended for use with battered piles [80] and even for non-linear clays [67]. Alternatively, hidden state variable models can be tuned based on a data sets from more rigorous models to obtain simple expressions for large pile group and have been established for floating or end-bearing piles in homogeneous soils [81].

3.2.4 Experimental validation

To confirm the ability to predict impedances from models based on derived soil parameters, validation by experiments is necessary.

A number of experimental studies have been performed under field conditions to validate numerical predictions of the response of floating single piles [82–85], pile groups in cohesive soils [86–90] and non-cohesive soils [91–94]. The majority of the experimental studies available in the literature have been focused on the excitation and response of piles and pile groups in the lateral direction for application in earthquake engineering. Only a limited amount of experimental results have been presented for the vertical response of pile groups. Studies of vertical impedances of pile groups have predominantly been performed on 2×2 pile groups, focusing on investigating non-linear effects [90] and the influence of battered piles [95, 96].

The dependency of lateral group effects on the soil properties and the pile spacing has been validated from both laboratory and in situ measurements [90, 97]. It has been demonstrated that the pile spacing-to-diameter ratio s/d influences the pile-soil-pile interaction in the lateral direction for values up to $s/d = 16$ [88].

While numerical results for end-bearing piles and pile groups have been presented in the literature [22, 23], no experimental studies have been published where a complete set of dynamic impedance functions is presented for an end-bearing pile group foundation.

Chapter 4

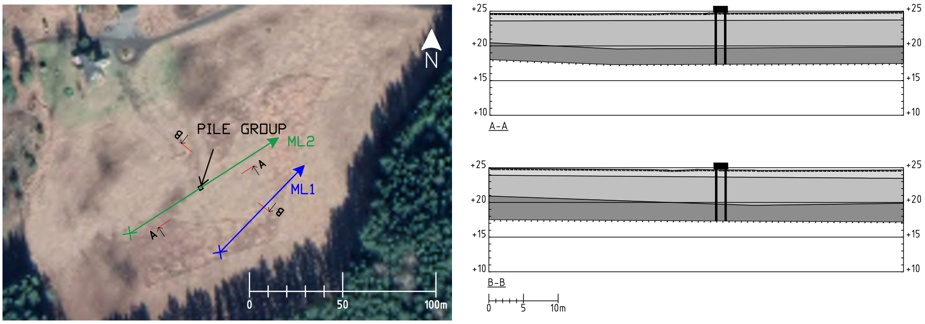
Summary of appended papers

This chapter summarizes the works and conclusions from the two appended papers in this thesis. Section 4.1 presents the results from an extensive measurement campaign to determine the small-strain soil properties in a Swedish clay deposit. The properties estimated from different investigation methods are compared, a synthesised model is established and the influence of remaining uncertainties is investigated by simulations. Section 4.2 treats the experimental validation of the impedances of end-bearing piles and a 2×2 pile foundation. The impedances are predicted using the estimated soil properties and a finite element model, representing the information available at a design stage.

4.1 Paper I: Assessment of small-strain characteristics of a Swedish clay deposit for environmental vibration studies

This paper presents an evaluation of the ability to predict the dynamic surface response in a shallow clay deposit using a layered soil model. Results from extensive geotechnical and geophysical investigations at a designated test site are presented. The test site is located in a remote field in Brottby 40 km north of Stockholm. The site was chosen for its particular stratification and the possibility to represent the soil using a layered soil model. Figure 4.1 presents an overview of the site, the positions of the lines along which dynamic measurements are performed and two sections.

The small-strain properties of the soil are estimated from in situ and laboratory dynamic measurements and are compared to results obtained from empirical correlations with CPT and the undrained shear strength in clay. A representative layered soil model is synthesised from the results, and the influence of uncertainties in the estimated small-strain soil properties is investigated. Figure 4.2 presents a comparison of the small-strain properties estimated from the different methods. The properties in the clay are consistently estimated from the dynamic measurements and the S-wave speeds estimated by available empirical correlations related to the CPT are in good



(a) **(b)**

Figure 4.1: *Test site overview with (a) an aerial photography [98] with the location of the pile group indicated and the lines* `ML1` *and* `ML2` *along which dynamics measurements have been performed and (b) two sections with the stratification interpreted from geotechnical site investigations with a layering of dry crust clay (light gray), saturated soft clay (medium gray) and till (dark gray) on top of a stiff bedrock.*

agreement. The synthesised profile indicated in fig. 4.2 is validated against measure-

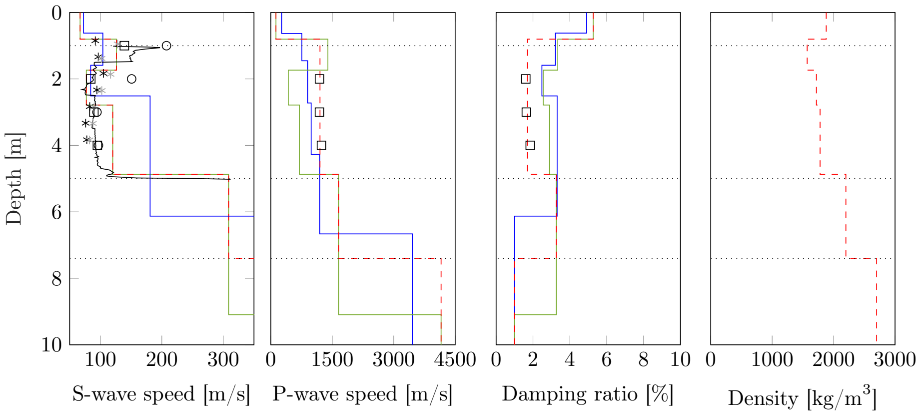


Figure 4.2: *Small-strain dynamic soil properties estimated from bender element tests (..), two SCPT (*), two SASW (green and blue lines) and empirical correlations with CPT (black line) and the undrained shear strength (◯). A representative soil model (red dashed line) is synthesised taking into account the layer boundaries identified from soil/rock probing (dotted lines).*

ments performed at the soil's surface at different source receiver distances and the influence of the properties of the top soil, the material damping ratio in the clay and the presence of an elastic bedrock are addressed.

The small-strain soil properties of the uppermost meter of the soil are consistently estimated by the two SASW tests, except for the P-wave speed. Figure 4.3 compares the measured mobilities and time domain responses due to an impact load to the simulated ones assuming the two P-wave speeds in the top soil layer obtained from the SASW tests. The simulation results demonstrate that the properties of the top soil governs the narrowband response seen in the mobilities. Furthermore, the time domain representation shows that this part of the spectrum is related to the first waves to arrive at the receiver location. It is concluded that a resonance of vertically propagating P-waves in the unsaturated uppermost soil causes this amplification.

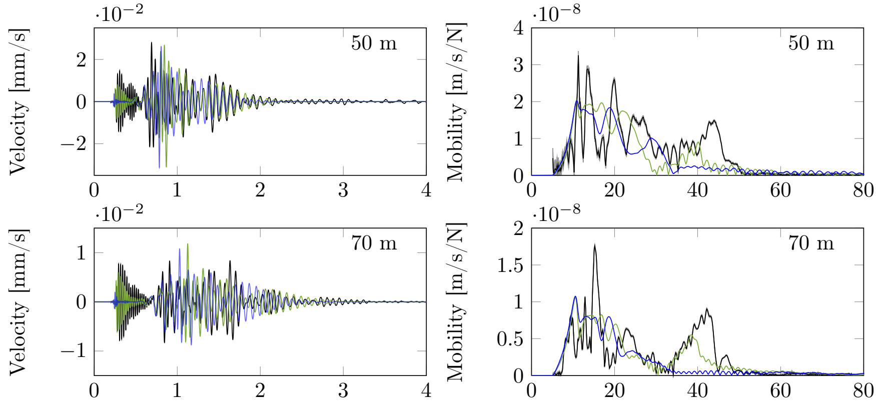


Figure 4.3: *Comparison of experimental and model results of time domain velocity responses due to an impact load (left) and mobilities (right) at 50 and 70 m. The measured mobilities (black) with 95% confidence bounds indicated (gray) are compared to the synthesised soil model (green) and a soil model with an increased top layer P-wave speed (blue).*

The first waves to arrive at a receiver are direct or refracted P-waves. Critically refracted waves travel along the interface between two layers with the speed of the underlying material. Due to the high material wave speeds of the underlying elastic bedrock, this results in significantly longer wavelengths of the refracted waves compared to the waves travelling in the overlying soil material, reducing the effective material damping substantially. A common and often justified model assumption for such high contrasts in stiffness is to consider the bedrock to be rigid. Figure 4.4 compares the computed mobilities and velocity responses at 70 m source-receiver offset assuming the bedrock as elastic and as rigid. Assuming the bedrock as rigid, the resonant response of the uppermost soil is strongly reduced. This demonstrates that the waves refracted in the elastic bedrock significantly contributes to the surface response. Therefore, assuming a rigid bedrock is not always appropriate when considering large source-receiver offsets with respect to the surface wavelengths in the soil, especially whenever potential resonance effects of the unsaturated soil layer falls within the frequency band of interest.

Material damping in the clay was consistently estimated from the two SASW tests while the bender element tests in axial motion resulted in lower values of material damping (see fig. 4.2). Figure 4.5 presents the influence of the clay material damping

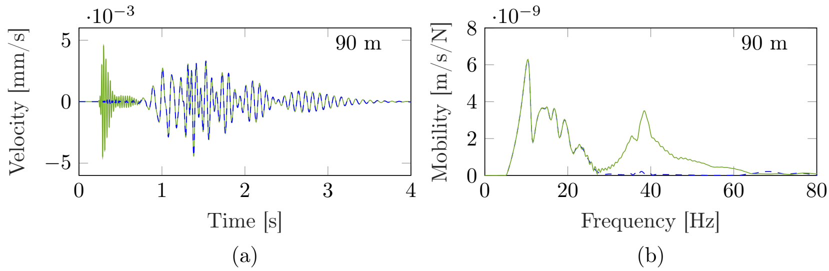


Figure 4.4: *Comparison of simulated (a) time domain velocity responses due to an impact load and (b) mobilities at 90 m from the source point assuming the bedrock as elastic (green solid line) and as rigid (blue dashed line).*

values on the predicted response at the center- and end points of the measurement line `ML2` at the test site. With the measurements as a reference, it is concluded that the

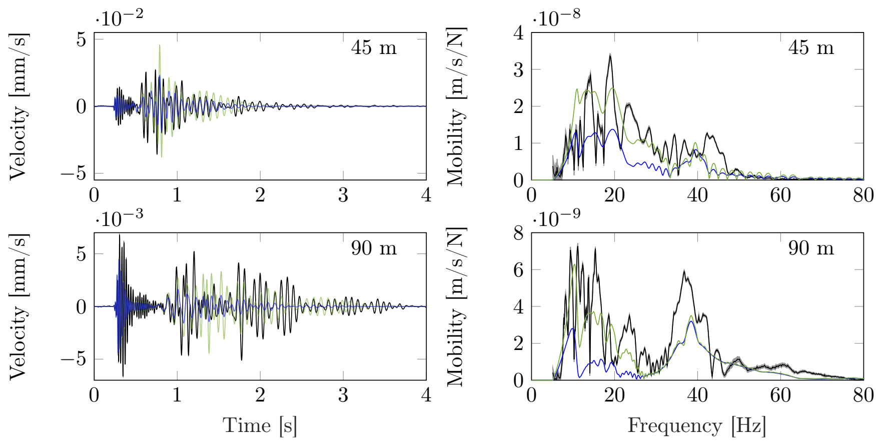


Figure 4.5: *Comparison of experimental and model results of time domain velocity responses due an impact (left) and mobilities (right) at 45 and 90 m source-receiver distances. The measured mobilities (black) with 95% confidence bounds indicated (gray) are compared to soil models assuming damping values in the clay obtained from bender element tests (green) and from the SASW inversions (blue).*

material damping assumed in the clay has a large influence on the predicted response in the lower frequency range associated with the surface waves, and is better predicted using the values obtained from the bender element tests.

4.2 Paper II: Dynamic response of driven end-bearing piles and a pile group in soft clay: an experimental validation study

This paper presents the results from a measurement campaign of the dynamic responses and impedances of end-bearing piles and a pile group in soft clay. The objectives of the study are twofold. First, to provide an extensive set of results as reference for model validation. Second, to assess the accuracy of numerical design calculations under the considered soil conditions.

A 2×2 pile group of dimensions 2×2×0.85 m with a pile separation distance of 1.365 m is installed at the test site at the position where the soil samples where collected and SCPT were performed in Paper I. Measurements are conducted in two stages of construction. First, when only the piles are installed at the site, local excitation is applied to each pile top and measurements are performed on top of each pile in three directions, allowing to obtain the single pile impedances and to study the pile-soil-pile interaction between the free-top piles in the group. Second, measurements are performed on the pile cap after casting the pile cap on top of the piles. In both test setups, measurements are also performed at depth within all of the piles, allowing to capture the global motion of the piles within the soil. These measurements are performed using an equipment originally designed for down-hole and cross-hole measurements, and is achieved by introducing a pipe cast along the center of the cross section of each pile. Figure 4.6 presents the measurement setup for the free-top piles and the down-hole equipment used for instrumenting the piles at depth. Figure 4.7 presents the instrumentation of the pile cap to derive the translational and rotational impedances of the foundation.

(a) **(b)**

Figure 4.6: *Measurement setup for the tests on the free-top piles (a) instrumented with six accelerometers at each pile head head (4 vertical and 2 horizontal) and (b) the down-hole equipment used for measurements at depth within the piles.*

A linear 3D finite element model including the piles, the pile cap and the soil is implemented. The material properties of the soil are obtained from the site investigations performed in Paper I. The predicted responses and impedances are compared to the ones obtained from the measurements.

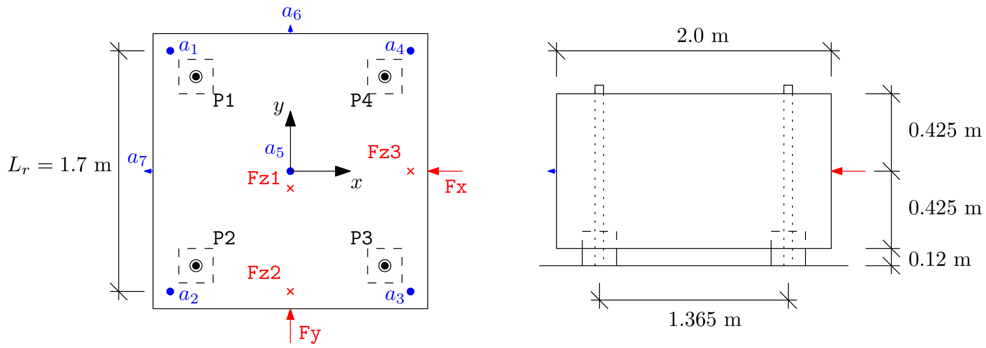


Figure 4.7: *Setup and dimensions for the pile cap. Accelerometers are denoted by a_j, the four piles numbered* `P1-4` *and excitation points are denoted by* `F`.

4.2.1 Global response of the individual piles and the pile group

Figure 4.8 presents snapshots of the measured and simulated harmonic responses at three frequencies for horizontal excitation and one frequency for vertical excitation of one of the piles in the group of piles unrestrained at the surface. The three frequen-

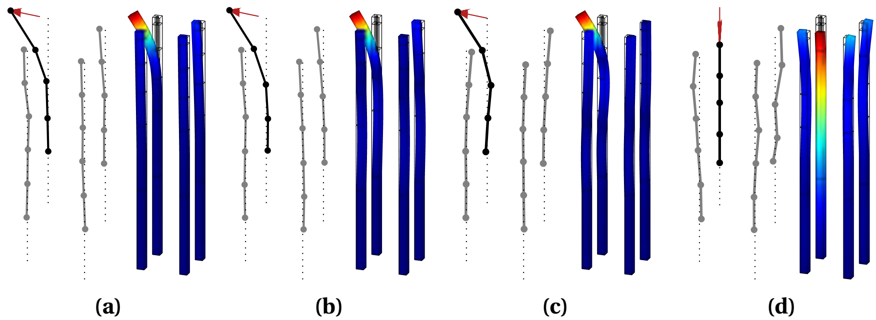
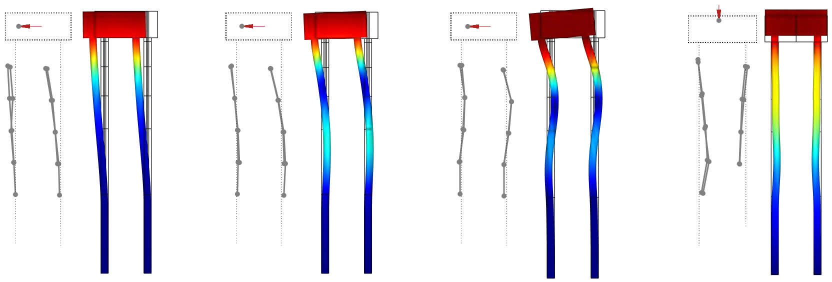


Figure 4.8: *Measured (left) and predicted (right) deflections of free-top piles at excitation frequencies (a) 5, (b) 14 and (c) 26 Hz in the horizontal direction and at (d) 30 Hz in the vertical direction. The displacements are identically scaled for the measured and computed illustrations.*

cies in horizontal excitation correspond to the resonance frequencies of vertically propagating S-waves in the soil. The measurements confirm the predicted deflection patterns of the piles, the phase differences of the non-excited receiver piles and the confinement of the response in the layers of soil closest to the surface. Figure 4.8d shows an out-of-phase motion of the receiver piles in the vertical direction. This 180 degrees out-of-phase motion relative to the excited pile is found in both the vertical and horizontal direction at 30 Hz and is well captured by the numerical model. However, the responses of the excited piles are underestimated in all cases by the numerical model.

Figure 4.9 presents a comparison of the measured and predicted displacements in the piles at the horizontal resonance frequencies of the soil and at 30 Hz in the vertical direction. Comparing figs. 4.8 and 4.9, the displacements are less localized when the piles are joined in the cap and are therefore less sensitive to the properties, potential soil-pile separation or non-linearities of the uppermost soil.



(a) **(b)** **(c)** **(d)**

Figure 4.9: *Measured (left) and computed (right) harmonic displacements at the (a) first (b) second and (c) third resonance frequency of the pile group due to horizontal excitation and (d) at 30 Hz due to vertical excitation. The displacements are identically scaled for the measured and computed illustrations.*

4.2.2 Pile and pile group impedances

The measured responses at the pile tops and the pile cap are used to obtained the impedances of the foundations. Figure 4.10 presents measured and predicted vertical and horizontal impedances of the piles and fig. 4.11 of the pile group.

It should be noted that the same model parameters are used for both cases. The horizontal impedance real and imaginary parts are overestimated for the single piles, but are well estimated for the pile group. This is due to the more even distribution of displacements in the soil for the group of piles, whereas the individual piles that are free at the surface are more sensitive to the conditions close to the surface.

The pile-soil-pile interaction in the pile group is manifested in the real part of the vertical impedance by the peak at 30 Hz. This peak is caused by the destructive interference between the forced motion of the piles and the interaction between the piles, observed in fig. 4.8d, and is accurately captured in both frequency and magnitude.

The results presented in the paper demonstrate that under the present soil conditions, the impedances of end-bearing pile foundations can be accurately predicted if the small-strain soil properties at the site are well known.

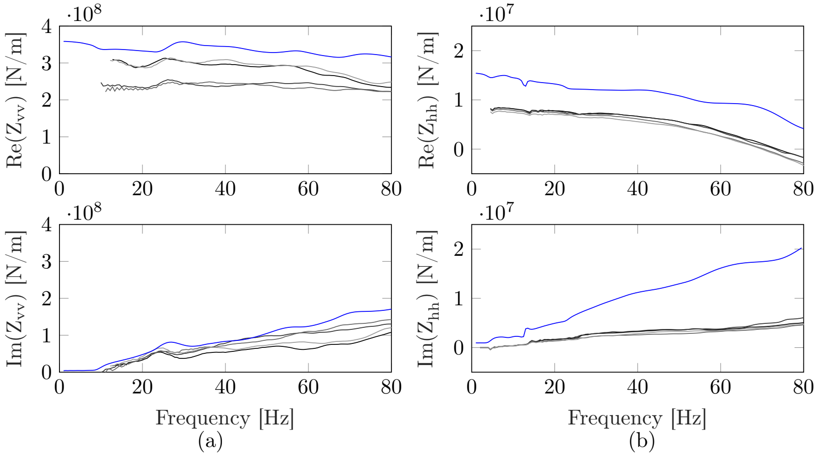


Figure 4.10: *Real (top) and imaginary part (bottom) of the measured pile top impedances for piles* `P1` *to* `P4` *(black to light gray) compared to the numerically predicted impedances (blue line) in the (a) vertical and (b) horizontal direction.*

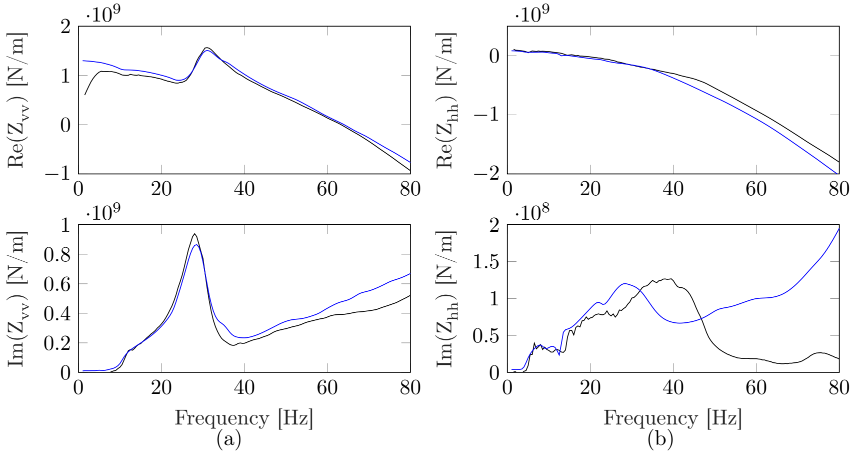


Figure 4.11: *Real (top) and imaginary part (bottom) of the measured (black line) and numerical (blue line) pile group impedance in the (a) vertical and (b) horizontal direction.*

Chapter 5

Conclusions and suggestions for future work

This chapter presents the main conclusions of the performed work in this thesis and suggestions for directions of future research.

5.1 Conclusions

This thesis presents the results from two experimental investigations aimed at assessing the ability of numerical models to predict the dynamic free-field response and foundation impedances in a shallow Swedish clay deposit. The conclusions from each of the studies presented in the appended papers are given in the following:

Paper I: Based on an extensive site investigation, the small-strain soil properties in a shallow clay deposit were obtained using different investigation methods. A good agreement in the estimation of the initial shear modulus in the clay was found from SCPT, bender element tests, surface wave methods and the empirical correlation with CPT cone resistance.

The soil material damping was estimated from surface wave methods and from bender element P-wave tests of clay laboratory samples. The material damping ratios estimated from the laboratory tests were lower than the ones estimated from the surface wave methods and provided a closer agreement between measurement results and predictions made using a horizontally layered soil model.

Only the surface wave methods provided data on properties of the topmost unsaturated layer of soil, but the results were inconsistent between measurements performed in different seasons. The properties of this soil layer in combination with a shallow bedrock was found to largely influence the dynamic response at certain frequencies, caused by layer resonance in the unsaturated soil and P-waves critically refracted in the elastic bedrock. However, variation of the measured response in the related frequency range suggests that the properties of the near-surface soil are not time invariant.

Paper II: The impedances of a 2×2 pile group of driven end-bearing piles were well predicted using a numerical model based on small-strain soil properties obtained from the site investigation. The simulations capture the behaviour of the pile group well even at depth within the piles. Soil layer resonances are clearly manifested in both the computed and measured responses, especially for motion in the horizontal direction.

Pile-soil-pile interaction has a large influence on the vertical impedance of the pile group that is strongly frequency dependent and is well captured in the predictions. The interaction frequency could be experimentally identified from the response of the free-top piles prior to the construction of the pile cap. This frequency is characterised by a phase difference of 180 degrees between the motions of the excited and the neighbour piles.

While the pile group impedances are well captured, the single pile impedances are found to be more difficult to predict. The vertical impedance of the single piles is affected by the final length of the piles due to the difference in penetration depth into the non-cohesive soil. On the contrary, horizontal single pile impedances are unaffected by the differences in pile length for the case at hand, which is explained by the confinement of the pile displacements to the near-surface region in the soil. The horizontal response of the single pile tops are overestimated by the numerical model, which is explained by the sensitivity to the conditions closest to the surface.

The close agreement between predicted and measured impedances for the pile group establish confidence in the ability of linear elastic models to predict foundation impedances for small-strain loading under the considered soil conditions.

5.2 Future work

The research presented in this thesis and the appended papers has addressed the ability of numerical models to capture the vibration characteristics of soil and an end-bearing pile foundation in a shallow clay deposit for the application of predicting levels of ground borne vibration. Conclusions from the performed research and identified further needs have resulted in the following suggestions for further research.

5.2.1 Response due to nearby surface loads

The computation of the vertical free-field response is in satisfactory agreement with the measurements using a horizontally layered soil model. Moreover, the dynamic characteristics of the pile group foundation are well captured from the computational model. However, the prediction of the transmission of vibrations requires an accurate representation of the kinematic response of foundations due to an incident wave field. The response of piles and pile groups subjected to incident body and surface waves can be largely different from the free-field response [17, 18, 99]. The response of pile foundations subjected to nearby surface loads should therefore be evaluated both numerically and experimentally at the test site in order to validate the use of models to predict the transmission of vibrations to piled foundations under the studied soil conditions. This would allow to put a higher degree of confidence into modelling techniques to estimate the transmission of vibrations into buildings on sites with similar soil conditions.

5.2.2 Influence of foundation design on building vibration response

The soil-structure interaction of pile foundations can have significant implications for the dynamic response and impedances of foundations, which both are strongly frequency dependent. The dynamic behaviour of pile foundations are governed by the soil properties at the site and the geometrical design of the foundations. Therefore, based on the model previously developed and assessed for a single foundation, the influence of different feasible geometrical foundation designs on the transmission of vibrations into a building should be evaluated from numerical simulations. This would allow to provide insight into the transmission problem at a larger scale by investigating the influence of the dynamic pile group characteristics in an idealized system.

5.2.3 Transmission of vibrations from resonating top layer

The unsaturated top soil layer at the test site was found to cause resonance of P-waves critically refracted along the bedrock surface. The observed response was shown to attenuate slowly with distance such that it starts to dominate the response at large source-receiver distances. It was further observed that this phenomenon was affected by seasonal variations and governed by the resonance of the topmost layer of soil. It should therefore be investigated weather the observed phenomenon can have a significant contribution to the vibration response of the foundation. This can be evaluated first from numerical simulations and further validated at the test site. This would allow to clarify weather these conditions should be taken into account or can be neglected in vibration assessment studies.

Bibliography

[1] G. Lombaert, G. Degrande, S. François, D. J. Thompson, Ground-borne vibration due to railway traffic: A review of excitation mechanisms, prediction methods and mitigation measures, in: Noise and Vibration Mitigation for Rail Transportation Systems, Springer Berlin Heidelberg, Berlin, Heidelberg, 2015, pp. 253–287.

[2] M. Bahrekazemi, Train-induced ground vibration and its prediction, Ph.D. thesis, KTH Royal Institute of Technology, 2004.

[3] D. Connolly, G. Kouroussis, A. Giannopoulos, O. Verlinden, P. Woodward, M. Forde, Assessment of railway vibrations using an efficient scoping model, Soil Dynamics and Earthquake Engineering 58 (2014) 37 – 47.

[4] D. López-Mendoza, A. Romero, D. Connolly, P. Galvín, Scoping assessment of building vibration induced by railway traffic, Soil Dynamics and Earthquake Engineering 93 (2017) 147 – 161.

[5] L. Auersch, Simple and fast prediction of train-induced track forces, ground and building vibrations, Railway Engineering Science 28 (2020) 232–250.

[6] J. Nelson, H. Saurenman, Prediction procedure for rail transportation ground-borne noise and vibration., Transportation Research Record (1987) 26–35.

[7] C. E. Hanson, J. C. Ross, D. A. Towers, High-Speed Ground Transportation Noise and Vibration Impact Assessment, Technical Report, Federal Railroad Administration, 2012.

[8] C. Madshus, B. Bessason, L. Hårvik, Prediction model for low frequency vibration from high speed railways on soft ground, Journal of Sound and Vibration 193 (1996) 195 – 203.

[9] H. Verbraken, Prediction of railway induced vibration by means of numerical, empirical, and hybrid methods, Ph.D. thesis, KU Leuven, Department of Civil Engineering, 2013.

[10] K. Kuo, M. Papadopoulos, G. Lombaert, G. Degrande, The coupling loss of a building subject to railway induced vibrations: Numerical modelling and experimental measurements, Journal of Sound and Vibration 442 (2019) 459 – 481.

[11] D. Connolly, P. Alves Costa, G. Kouroussis, P. Galvin, P. Woodward, O. Laghrouche, Large scale international testing of railway ground vibrations across europe, Soil Dynamics and Earthquake Engineering 71 (2015) 1 – 12.

[12] G. Lombaert, G. Degrande, D. Clouteau, The influence of the soil stratification on free field traffic-induced vibrations, Archive of Applied Mechanics 71 (2001) 661–678.

[13] G. Kouroussis, C. Conti, O. Verlinden, Investigating the influence of soil properties on railway traffic vibration using a numerical model, Vehicle System Dynamics 51 (2013) 421–442.

[14] ISO 14837-32:2015, Mechanical vibration – Ground-borne noise and vibration arising from rail systems – Part 32: Measurement of dynamic properties of the ground, Standard, International Organization for Standardization, Geneva, CH, 2015.

[15] E. Kausel, Advanced Structural Dynamics, Cambridge University Press, 2017.

[16] G. Gazetas, K. Fan, A. Kaynia, Dynamic response of pile groups with different configurations, Soil Dynamics and Earthquake Engineering 12 (1993) 239 – 257.

[17] N. Makris, Soil-pile interaction during the passage of rayleigh waves: An analytical solution, Earthquake Engineering & Structural Dynamics 23 (1994) 153–167.

[18] N. Makris, D. Badoni, Seismic response of pile groups under oblique-shear and Rayleigh waves, Earthquake Engineering & Structural Dynamics 24 (1995) 517–532.

[19] O. Hunaidi, M. Tremblay, Traffic-induced building vibrations in Montréal, Canadian Journal of Civil Engineering 24 (1997) 736–753.

[20] G. Axelsson, Design of piles - Swedish practice, in: ISSMGE - ETC 3 International Symposium on Design of Piles in Europe, Leuven, Belgium, 2016.

[21] Comission on Pile Research, Pile statistics for Sweden 2019, 2020.

[22] L. Padrón, J. Aznárez, O. Maeso, M. Saitoh, Impedance functions of end-bearing inclined piles, Soil Dynamics and Earthquake Engineering 38 (2012) 97 – 108.

[23] G. Gazetas, Seismic response of end-bearing single piles, International Journal of Soil Dynamics and Earthquake Engineering 3 (1984) 82 – 93.

[24] J. Achenbach, Wave propagation in elastic solids, Elsevier, 1975.

[25] F. J. Rizzo, D. J. Shippy, An application of the correspondence principle of linear viscoelasticity theory, SIAM Journal on Applied Mathematics 21 (1971) 321–330.

[26] M. A. Biot, Theory of propagation of elastic waves in a fluid-saturated porous solid. i. low-frequency range, The Journal of the Acoustical Society of America 28 (1956) 168–178.

[27] M. Schevenels, G. Degrandec, G. Lombaert, The influence of the depth of the ground water table on free field road traffic-induced vibrations, International Journal for Numerical and Analytical Methods in Geomechanics 28 (2004) 395–419.

[28] R. Larsson, M. Mulabdić, Shear moduli in Scandinavian clays. Measurement of initial shear modulus with seismic cones. Empirical correlations for the initial shear modulus in clay, Technical Report 40, Swedish Geotechnical Institute, 1991.

[29] P. W. Mayne, G. J. Rix, $G_{\mathrm{max}} - q_{\mathrm{c}}$ relationships for clays, Geotechnical Testing Journal 16 (1993) 54–60.

[30] P. K. Robertson, R. G. Campanella, D. Gillespie, A. Rice, Seismic cpt to measure in situ shear wave velocity, Journal of Geotechnical Engineering 112 (1986) 791–803.

[31] L. Karl, W. Haegeman, G. Degrande, D. Dooms, Determination of the material damping ratio with the bender element test, Journal of Geotechnical and Geoenvironmental Engineering 134 (2008) 1743–1756.

[32] R. G. Campanella, W. P. Stewart, Seismic cone analysis using digital signal processing for dynamic site characterization, Canadian Geotechnical Journal 29 (1992) 477–486.

[33] E. J. Baziw, Derivation of seismic cone interval velocities utilizing forward modeling and the downhill simplex method, Canadian Geotechnical Journal 39 (2002) 1181–1192.

[34] L. Areias, W. Van Impe, Interpretation of SCPT Data Using Cross-over and Cross-Correlation Methods, Springer Berlin Heidelberg, Berlin, Heidelberg, 2004, pp. 110–116.

[35] R. Verachtert, Deterministic and probabilistic determination of dynamic soil characteristics, Ph.D. thesis, KU Leuven, Department of Civil Engineering, 2017.

[36] L. Areias, F. W. Van Impe, Effect of travel path in the SCPT test method, in: GeoShanghai International Conference 2006, 2006, pp. 236–242.

[37] L. Areias, Method to reduce variability of s-wave profiles in seismic cone penetration tests, in: International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, 2010.

[38] D. Pennington, D. Nash, M. Lings, Horizontally mounted bender elements for measuring anisotropic shear moduli in triaxial clay specimens, Geotechnical Testing Journal 24 (2001) 133–144.

[39] F.-C. Teng, C.-Y. Ou, P.-G. Hsieh, Measurements and numerical simulations of inherent stiffness anisotropy in soft taipei clay, Journal of Geotechnical and Geoenvironmental Engineering 140 (2014) 237–250.

[40] T. Wood, On the Small Strain Stiffness of Some Scandinavian Soft Clays and Impact on Deep Excavations, Ph.D. thesis, Chalmers University of Technology, 2016.

[41] D. Brocanelli, V. Rinaldi, Measurement of low-strain material damping and wave velocity with bender elements in the frequency domain, Canadian Geotechnical Journal 35 (1998) 1032–1040.

[42] Z. Cheng, E. Leong, Determination of damping ratios for soils using bender element tests, Soil Dynamics and Earthquake Engineering 111 (2018) 8 – 13.

[43] R. W. Lankston, High-Resolution Refraction Seismic Data Acquisition and Interpretation, 1990, pp. 45–74.

[44] S. Foti, F. Hollender, F. Garofalo, D. Albarello, M. Asten, P.-Y. Bard, C. Comina, C. Cornou, B. Cox, G. Di Giulio, T. Forbriger, K. Hayashi, E. Lunedei, A. Martin, D. Mercerat, M. Ohrnberger, V. Poggi, F. Renalier, D. Sicilia, V. Socco, Guidelines for the good practice of surface wave analysis: a product of the InterPACIFIC project, Bulletin of Earthquake Engineering 16 (2018) 2367–2420.

[45] W. T. Thomson, Transmission of elastic waves through a stratified solid medium, Journal of Applied Physics 21 (1950) 89–93.

[46] N. A. Haskell, The dispersion of surface waves on multilayered media, Bulletin of the Seismological Society of America 43 (1953) 17–34.

[47] E. Kausel, J. M. Roësset, Stiffness matrices for layered soils, Bulletin of the seismological Society of America 71 (1981) 1743–1761.

[48] C. B. Park, R. D. Miller, J. Xia, Imaging dispersion curves of surface waves on multichannel record, 1998, pp. 1377–1380.

[49] D. J. Zywicki, G. J. Rix, Mitigation of near-field effects for seismic surface wave velocity estimation with cylindrical beamformers, Journal of Geotechnical and Geoenvironmental Engineering 131 (2005) 970–977.

[50] T. Forbriger, Inversion of shallow-seismic wavefields: I. Wavefield transformation, Geophysical Journal International 153 (2003) 719–734.

[51] C. B. Park, R. D. Miller, J. Xia, Multichannel analysis of surface waves, GEOPHYSICS 64 (1999) 800–808.

[52] S. Badsar, M. Schevenels, W. Haegeman, G. Degrande, Determination of the material damping ratio in the soil from SASW tests using the half-power bandwidth method, Geophysical Journal International 182 (2010) 1493–1508. Cited By 45.

[53] R. Verachtert, G. Lombaert, G. Degrande, Multimodal determination of Rayleigh dispersion and attenuation curves using the circle fit method, Geophysical Journal International 212 (2018) 2143–2158.

[54] F. Dezi, S. Carbonari, G. Leoni, A model for the 3d kinematic interaction analysis of pile groups in layered soils, Earthquake Engineering & Structural Dynamics 38 (2009) 1281–1305.

[55] E. Rovithis, G. Mylonakis, K. Pitilakis, Dynamic stiffness and kinematic response of single piles in inhomogeneous soil, Bulletin of Earthquake Engineering 11 (2013).

[56] G. M. Álamo, Dynamic response of piled structures. Implementation of a model based on the integral formulation of the problem and the use of a fundamental solution for the layered half space, Ph.D. thesis, Universidad de Las Palmas de Gran Canaria, 2018.

[57] C. Zheng, S. Gan, G. Kouretzis, X. Ding, L. Luan, Vertical vibration of a large diameter pile partially-embedded in poroelastic soil, Soil Dynamics and Earthquake Engineering 139 (2020) 106211.

[58] L. Luan, C. Zheng, G. Kouretzis, X. Ding, H. Poulos, A new dynamic interaction factor for the analysis of pile groups subjected to vertical dynamic loads, Acta Geotechnica 15 (2020).

[59] J. P. Wolf, G. A. von Arx, Impedance function of a group of vertical piles, in: Proceedings of ASCE Geotechnical Engineering Specialty Conference, Pasadena, California, 1978, pp. 1024–1041.

[60] T. Nogami, Dynamic group effect in axial responses of grouped piles, Journal of Geotechnical Engineering 109 (1983) 228–243.

[61] R. Dobry, G. Gazetas, Simple method for dynamic stiffness and damping of floating pile groups, Géotechnique 38 (1988) 557–574.

[62] G. Gazetas, N. Makris, Dynamic pile-soil-pile interaction. part I: Analysis of axial vibration, Earthquake Engineering & Structural Dynamics 20 (1991) 115–132.

[63] N. Makris, G. Gazetas, Dynamic pile-soil-pile interaction. part II: Lateral and seismic response, Earthquake Engineering & Structural Dynamics 21 (1992) 145–162.

[64] N. Makris, G. Gazetas, Displacement phase differences in a harmonically oscillating pile, Géotechnique 43 (1993) 135–150.

[65] A. M. Kaynia, E. Kausel, Dynamics of piles and pile groups in layered soil media, Soil Dynamics and Earthquake Engineering 10 (1991) 386 – 401.

[66] P. Emani, B. Maheshwari, Dynamic impedances of pile groups with embedded caps in homogeneous elastic soils using cifecm, Soil Dynamics and Earthquake Engineering 29 (2009) 963 – 973.

[67] K. Kanellopoulos, G. Gazetas, Vertical static and dynamic pile-to-pile interaction in non-linear soil, Géotechnique 70 (2020) 432–447.

[68] B. Maheshwari, K. Truman, M. El Naggar, P. Gould, Three-dimensional nonlinear analysis for seismic soil-pile-structure interaction, Soil Dynamics and Earthquake Engineering 24 (2004) 343 – 356.

[69] J. Lysmer, R. L. Kuhlemeyer, Finite dynamic model for infinite media, Journal of the Engineering Mechanics Division 95 (1969) 859–878.

[70] G. Kouroussis, O. Verlinden, C. Conti, Finite-dynamic model for infinite media: Corrected solution of viscous boundary efficiency, Journal of Engineering Mechanics 137 (2011) 509–511.

[71] P. Bettess, Infinite elements, International Journal for Numerical Methods in Engineering 11 (1977) 53–64.

[72] J.-P. Berenger, A perfectly matched layer for the absorption of electromagnetic waves, Journal of Computational Physics 114 (1994) 185 – 200.

[73] U. Basu, A. K. Chopra, Perfectly matched layers for time-harmonic elastodynamics of unbounded domains: theory and finite-element implementation, Computer Methods in Applied Mechanics and Engineering 192 (2003) 1337 – 1375.

[74] L. Padrón, J. Aznárez, O. Maeso, BEM-FEM coupling model for the dynamic analysis of piles and pile groups, Engineering Analysis with Boundary Elements 31 (2007) 473 – 484.

[75] H. Poulos, Behavior of laterally loaded piles II. pile groups, Journal of Soil Mechanics and Foundation Engineering Division 97 (1971) 773–751.

[76] A. M. Kaynia, Dynamic stiffness and seismic response of pile groups, Ph.D. thesis, Massachusetts institute of technology, 1982.

[77] G. Mylonakis, G. Gazetas, Vertical vibration and additional distress of grouped piles in layered soil, Soils and Foundations 38 (1998) 1 – 14.

[78] S. Zhang, C. Cui, G. Yang, Vertical dynamic impedance of pile groups partially embedded in multilayered, transversely isotropic, saturated soils, Soil Dynamics and Earthquake Engineering 117 (2019) 106 – 115.

[79] G. Gazetas, K. Fan, A. Kaynia, E. Kausel, Dynamic interaction factors for floating pile groups, Journal of Geotechnical Engineering 117 (1991) 1531–1548.

[80] M. Saitoh, L. A. Padrón, J. J. Aznárez, O. Maeso, C. S. Goit, Expanded superposition method for impedance functions of inclined-pile groups, International Journal for Numerical and Analytical Methods in Geomechanics 40 (2016) 185–206.

[81] R. Taherzadeh, D. Clouteau, R. Cottereau, Simple formulas for the dynamic stiffness of pile groups, Earthquake Engineering & Structural Dynamics 38 (2009) 1665–1685.

[82] H. R. Masoumi, G. Degrande, A. Holeyman, Pile response and free field vibrations due to low strain dynamic loading, Soil Dynamics and Earthquake Engineering 29 (2009) 834–844.

[83] K. Tantayopin, P. Thammarak, Effect of soft soil layer on local dynamic response of floating pile under harmonic lateral loading, Canadian Geotechnical Journal 54 (2017) 1637–1646.

[84] E. Esmaeilzadeh Seylabi, A. Kurtuluş, K. H. Stokoe, E. Taciroglu, Interaction of a pile with layered-soil under vertical excitations: field experiments versus numerical simulations, Bulletin of Earthquake Engineering 15 (2017) 3529–3553.

[85] M. Elkasabgy, M. H. El Naggar, Dynamic response of vertically loaded helical and driven steel piles, Canadian Geotechnical Journal 50 (2013) 521–535.

[86] Y. Han, H. Vaziri, Dynamic response of pile groups under lateral loading, Soil Dynamics and Earthquake Engineering 11 (1992) 87–99.

[87] G. W. Blaney, M. W. O'Neill, Dynamic lateral response of a pile group in clay, Geotechnical Testing Journal 12 (1989) 22–29.

[88] J. P. Burr, M. J. Pender, T. J. Larkin, Dynamic response of laterally excited pile groups, Journal of Geotechnical and Geoenvironmental Engineering 123 (1997) 1–8.

[89] S. Biswas, B. Manna, Experimental and Theoretical Studies on the Nonlinear Characteristics of Soil-Pile Systems under Coupled Vibrations, Journal of Geotechnical and Geoenvironmental Engineering 144 (2018) 04018007.

[90] B. Manna, D. K. Baidya, Dynamic nonlinear response of pile foundations under vertical vibration-Theory versus experiment, Soil Dynamics and Earthquake Engineering 30 (2010) 456–469.

[91] B. El Shamouby, M. Novak, Dynamic experiments with group of piles 110 (1984) 719–737.

[92] C. S. Goit, M. Saitoh, Model Tests on Horizontal Impedance Functions of Fixed-Head Inclined Pile Groups under Soil Nonlinearity, Journal of Geotechnical and Geoenvironmental Engineering 140 (2014) 04014023.

[93] B. H. El-marsafawi, Y. C. Han, M. Novak, Dynamic experiments on two pile groups 118 (1992) 576–592.

[94] B. Manna, D. K. Baidya, Nonlinear dynamic response of piles under horizontal excitation, Journal of Geotechnical and Geoenvironmental Engineering 136 (2010) 1600–1609.

[95] M. Bharathi, R. Dubey, S. K. Shukla, Experimental investigation of vertical and batter pile groups subjected to dynamic loads, Soil Dynamics and Earthquake Engineering 116 (2019) 107 – 119.

[96] M. C. Capatti, F. Dezi, S. Carbonari, F. Gara, Dynamic performance of a full-scale micropile group: Relevance of nonlinear behaviour of the soil adjacent to micropiles, Soil Dynamics and Earthquake Engineering 128 (2020) 105858.

[97] S. S. Chandrasekaran, A. Boominathan, G. R. Dodagoudar, Dynamic response of laterally loaded pile groups in clay, Journal of Earthquake Engineering 17 (2013) 33–53.

[98] Google Earth Pro V.7.3.3.7786, Brottby, Sweden, March 19, 2020. 59°35’24.3”N 18°10’26.0”W, Eye alt 383 m. Maxar Technologies 2020. http://www.earth.google.com [September 21, 2020].

[99] A. M. Kaynia, M. Novak, Response of pile foundations to rayleigh waves and obliquely incident body waves, Earthquake Engineering & Structural Dynamics 21 (1992) 303–318.

List of Bulletins from the previous Department of Structural Engineering,
currently Division of Concrete Structures and Division of Structural Design and Bridges
at
KTH Royal Institute of Technology, Stockholm, Sweden

TRITA-BKN. Bulletin

is from February 2018 replaced by the common publication series of the School of Architecture and the Built Environment (ABE)

TRITA-ABE-DLT-YYX

Pacoste, C., On the Application of Catastrophe Theory to Stability Analyses of Elastic Structures.
Doctoral Thesis, 1993. Bulletin 1.

Stenmark, A-K., Dämpning av 13 m lång stålbalk – "Ullevibalken". Utprovning av dämpmassor och fastsättning av motbalk samt experimentell bestämning av modformer och förlustfaktorer. Vibration tests of full-scale steel girder to determine optimum passive control.
Licentiatavhandling, 1993. Bulletin 2.

Silfwerbrand, J., Renovering av asfaltgolv med cementbundna plastmodifierade avjämningsmassor.
1993. Bulletin 3.

Norlin, B., Two-Layered Composite Beams with Nonlinear Connectors and Geometry – Tests and Theory.
Doctoral Thesis, 1993. Bulletin 4.

Habtezion, T., On the Behaviour of Equilibrium Near Critical States.
Licentiate Thesis, 1993. Bulletin 5.

Krus, J., Hållfasthet hos frostnedbruten betong.
Licentiatavhandling, 1993. Bulletin 6.

Wiberg, U., Material Characterization and Defect Detection by Quantitative Ultrasonics.
Doctoral Thesis, 1993. Bulletin 7.

Lidström, T., Finite Element Modelling Supported by Object Oriented Methods.
Licentiate Thesis, 1993. Bulletin 8.

Hallgren, M., Flexural and Shear Capacity of Reinforced High Strength Concrete Beams without Stirrups.
Licentiate Thesis, 1994. Bulletin 9.

Krus, J., Betongbalkars lastkapacitet efter miljöbelastning.
1994. Bulletin 10.

Sandahl, P., Analysis Sensitivity for Wind-related Fatigue in Lattice Structures.
Licentiate Thesis, 1994. Bulletin 11.

Sanne, L., Information Transfer Analysis and Modelling of the Structural Steel Construction Process.
Licentiate Thesis, 1994. Bulletin 12.

Zhitao, H., Influence of Web Buckling on Fatigue Life of Thin-Walled Columns.
Doctoral Thesis, 1994. Bulletin 13.

Kjörling, M., Dynamic response of railway track components. Measurements during train passage and dynamic laboratory loading.
Licentiate Thesis, 1995. Bulletin 14.

Yang, L., On Analysis Methods for Reinforced Concrete Structures.
Doctoral Thesis, 1995. Bulletin 15.

Petersson, Ö., Svensk metod för dimensionering av betongvägar.
Licentiatavhandling, 1996. Bulletin 16.

Lidström, T., Computational Methods for Finite Element Instability Analyses.
Doctoral Thesis, 1996. Bulletin 17.

Krus, J., Environment- and Function-induced Degradation of Concrete Structures.
Doctoral Thesis, 1996. Bulletin 18.

Editor, Silfwerbrand, J., Structural Loadings in the 21st Century.
Sven Sahlin Workshop, June 1996. Proceedings. Bulletin 19.

Ansell, A., Frequency Dependent Matrices for Dynamic Analysis of Frame Type Structures.
Licentiate Thesis, 1996. Bulletin 20.

Troive, S., Optimering av åtgärder för ökad livslängd hos infrastrukturkonstruktioner. Licentiatavhandling, 1996. Bulletin 21.

Karoumi, R., Dynamic Response of Cable-Stayed Bridges Subjected to Moving Vehicles.
Licentiate Thesis, 1996. Bulletin 22.

Hallgren, M., Punching Shear Capacity of Reinforced High Strength Concrete Slabs.
Doctoral Thesis, 1996. Bulletin 23.

Hellgren, M., Strength of Bolt-Channel and Screw-Groove Joints in Aluminium Extrusions.
Licentiate Thesis, 1996. Bulletin 24.

Yagi, T., Wind-induced Instabilities of Structures.
Doctoral Thesis, 1997. Bulletin 25.

Eriksson, A., and Sandberg, G., (editors), Engineering Structures and Extreme Events – proceedings from a symposium, May 1997. Bulletin 26.

Paulsson, J., Effects of Repairs on the Remaining Life of Concrete Bridge Decks.
Licentiate Thesis, 1997. Bulletin 27.

Olsson, A., Object-oriented finite element algorithms.
Licentiate Thesis, 1997. Bulletin 28.

Yunhua, L., On Shear Locking in Finite Elements.
Licentiate Thesis, 1997. Bulletin 29.

Ekman, M., Sprickor i betongkonstruktioner och dess inverkan på beständigheten.
Licentiate Thesis, 1997. Bulletin 30.

Karawajczyk, E., Finite Element Approach to the Mechanics of Track-Deck Systems.
Licentiate Thesis, 1997. Bulletin 31.

Fransson, H., Rotation Capacity of Reinforced High Strength Concrete Beams.
Licentiate Thesis, 1997. Bulletin 32.

Edlund, S., Arbitrary Thin-Walled Cross Sections. Theory and Computer Implementation.
Licentiate Thesis, 1997. Bulletin 33.

Forsell, K., Dynamic analyses of static instability phenomena.
Licentiate Thesis, 1997. Bulletin 34.

Ikäheimonen, J., Construction Loads on Shores and Stability of Horizontal Formworks.
Doctoral Thesis, 1997. Bulletin 35.

Racutanu, G., Konstbyggnaders reella livslängd.
Licentiatavhandling, 1997. Bulletin 36.

Appelqvist, I., Sammanbyggnad. Datastrukturer och utveckling av ett IT-stöd för byggprocessen.
Licentiatavhandling, 1997. Bulletin 37.

Alavizadeh-Farhang, A., Plain and Steel Fibre Reinforced Concrete Beams Subjected to Combined Mechanical and Thermal Loading.
Licentiate Thesis, 1998. Bulletin 38.

Eriksson, A. and Pacoste, C., (editors), Proceedings of the NSCM-11: Nordic Seminar on Computational Mechanics, October 1998. Bulletin 39.

Luo, Y., On some Finite Element Formulations in Structural Mechanics.
Doctoral Thesis, 1998. Bulletin 40.

Troive, S., Structural LCC Design of Concrete Bridges.
Doctoral Thesis, 1998. Bulletin 41.

Tärno, I., Effects of Contour Ellipticity upon Structural Behaviour of Hyparform Suspended Roofs. Licentiate Thesis, 1998. Bulletin 42.

Hassanzadeh, G., Betongplattor på pelare. Förstärkningsmetoder och dimensioneringsmetoder för plattor med icke vidhäftande spännarmering.
Licentiatavhandling, 1998. Bulletin 43.

Karoumi, R., Response of Cable-Stayed and Suspension Bridges to Moving Vehicles. Analysis methods and practical modeling techniques.
Doctoral Thesis, 1998. Bulletin 44.

Johnson, R., Progression of the Dynamic Properties of Large Suspension Bridges during Construction – A Case Study of the Höga Kusten Bridge.
Licentiate Thesis, 1999. Bulletin 45.

Tibert, G., Numerical Analyses of Cable Roof Structures.
Licentiate Thesis, 1999. Bulletin 46.

Ahlenius, E., Explosionslaster och infrastrukturkonstruktioner - Risker, värderingar och kostnader.
Licentiatavhandling, 1999. Bulletin 47.

Battini, J-M., Plastic instability of plane frames using a co-rotational approach.
Licentiate Thesis, 1999. Bulletin 48.

Ay, L., Using Steel Fiber Reinforced High Performance Concrete in the Industrialization of Bridge Structures.
Licentiate Thesis, 1999. Bulletin 49.

Paulsson-Tralla, J., Service Life of Repaired Concrete Bridge Decks.
Doctoral Thesis, 1999. Bulletin 50.

Billberg, P., Some rheology aspects on fine mortar part of concrete.
Licentiate Thesis, 1999. Bulletin 51.

Ansell, A., Dynamically Loaded Rock Reinforcement.
Doctoral Thesis, 1999. Bulletin 52.

Forsell, K., Instability analyses of structures under dynamic loads.
Doctoral Thesis, 2000. Bulletin 53.

Edlund, S., Buckling of T-Section Beam-Columns in Aluminium with or without Transverse Welds. Doctoral Thesis, 2000. Bulletin 54.

Löfsjögård, M., Functional Properties of Concrete Roads − General Interrelationships and Studies on Pavement Brightness and Sawcutting Times for Joints.
Licentiate Thesis, 2000. Bulletin 55.

Nilsson, U., Load bearing capacity of steel fibree reinforced shotcrete linings.
Licentiate Thesis, 2000. Bulletin 56.

Silfwerbrand, J. and Hassanzadeh, G., (editors), International Workshop on Punching Shear Capacity of RC Slabs − Proceedings. Dedicated to Professor Sven Kinnunen. Stockholm June 7-9, 2000. Bulletin 57.

Wiberg, A., Strengthening and repair of structural concrete with advanced, cementitious composites. Licentiate Thesis, 2000. Bulletin 58.

Racutanu, G., The Real Service Life of Swedish Road Bridges - A case study.
Doctoral Thesis, 2000. Bulletin 59.

Alavizadeh-Farhang, A., Concrete Structures Subjected to Combined Mechanical and Thermal Loading. Doctoral Thesis, 2000. Bulletin 60.

Wäppling, M., Behaviour of Concrete Block Pavements - Field Tests and Surveys.
Licentiate Thesis, 2000. Bulletin 61.

Getachew, A., Trafiklaster på broar. Analys av insamlade och Monte Carlo genererade fordonsdata.
Licentiatavhandling, 2000. Bulletin 62.

James, G., Raising Allowable Axle Loads on Railway Bridges using Simulation and Field Data.
Licentiate Thesis, 2001. Bulletin 63.

Karawajczyk, E., Finite Elements Simulations of Integral Bridge Behaviour.
Doctoral Thesis, 2001. Bulletin 64.

Thöyrä, T., Strength of Slotted Steel Studs.
Licentiate Thesis, 2001. Bulletin 65.

Tranvik, P., Dynamic Behaviour under Wind Loading of a 90 m Steel Chimney.
Licentiate Thesis, 2001. Bulletin 66.

Ullman, R., Buckling of Aluminium Girders with Corrugated Webs.
Licentiate Thesis, 2002. Bulletin 67.

Getachew, A., Traffic Load Effects on Bridges. Statistical Analysis of Collected and Monte Carlo Simulated Vehicle Data.
Doctoral Thesis, 2003. Bulletin 68.

Quilligan, M., Bridge Weigh-in-Motion. Development of a 2-D Multi-Vehicle Algorithm.
Licentiate Thesis, 2003. Bulletin 69.

James, G., Analysis of Traffic Load Effects on Railway Bridges.
Doctoral Thesis 2003. Bulletin 70.

Nilsson, U., Structural behaviour of fibre reinforced sprayed concrete anchored in rock.
Doctoral Thesis 2003. Bulletin 71.

Wiberg, A., Strengthening of Concrete Beams Using Cementitious Carbon Fibre Composites.
Doctoral Thesis 2003. Bulletin 72.

Löfsjögård, M., Functional Properties of Concrete Roads – Development of an Optimisation Model and Studies on Road Lighting Design and Joint Performance.
Doctoral Thesis 2003. Bulletin 73.

Bayoglu-Flener, E., Soil-Structure Interaction for Integral Bridges and Culverts.
Licentiate Thesis 2004. Bulletin 74.

Lutfi, A., Steel Fibrous Cement Based Composites. Part one: Material and mechanical properties.
Part two: Behaviour in the anchorage zones of prestressed bridges.
Doctoral Thesis 2004. Bulletin 75.

Johansson, U., Fatigue Tests and Analysis of Reinforced Concrete Bridge Deck Models.
Licentiate Thesis 2004. Bulletin 76.

Roth, T., Langzeitverhalten von Spannstählen in Betonkonstruktionen.
Licentitate Thesis 2004. Bulletin 77.

Hedebratt, J., Integrerad projektering och produktion av industrigolv – Metoder för att förbättra kvaliteten.
Licentiatavhandling, 2004. Bulletin 78.

Österberg, E., Revealing of age-related deterioration of prestressed reinforced concrete containments in nuclear power plants – Requirements and NDT methods.
Licentiate Thesis 2004. Bulletin 79.

Broms, C.E., Concrete flat slabs and footings New design method for punching and detailing for ductility.
Doctoral Thesis 2005. Bulletin 80.

Wiberg, J., Bridge Monitoring to Allow for Reliable Dynamic FE Modelling - A Case Study of the New Årsta Railway Bridge.
Licentiate Thesis 2006. Bulletin 81.

Mattsson, H-Å., Funktionsentreprenad Brounderhåll – En pilotstudie i Uppsala län.
Licentiate Thesis 2006. Bulletin 82.

Masanja, D. P, Foam concrete as a structural material.
Doctoral Thesis 2006. Bulletin 83.

Johansson, A., Impregnation of Concrete Structures – Transportation and Fixation of Moisture in Water Repellent Treated Concrete.
Licentiate Thesis 2006. Bulletin 84.

Billberg, P., Form Pressure Generated by Self-Compacting Concrete – Influence of Thixotropy and Structural Behaviour at Rest.
Doctoral Thesis 2006. Bulletin 85.

Enckell, M., Structural Health Monitoring using Modern Sensor Technology – Long-term Monitoring of the New Årsta Railway Bridge.
Licentiate Thesis 2006. Bulletin 86.

Söderqvist, J., Design of Concrete Pavements – Design Criteria for Plain and Lean Concrete.
Licentiate Thesis 2006. Bulletin 87.

Malm, R., Shear cracks in concrete structures subjected to in-plane stresses.
Licentiate Thesis 2006. Bulletin 88.

Skoglund, P., Chloride Transport and Reinforcement Corrosion in the Vicinity of the Transition Zone between Substrate and Repair Concrete.
Licentiate Thesis 2006. Bulletin 89.

Liljencrantz, A., Monitoring railway traffic loads using Bridge Weight-in-Motion.
Licentiate Thesis 2007. Bulletin 90.

Stenbeck, T., Promoting Innovation in Transportation Infrastructure Maintenance – Incentives, Contracting and Performance-Based Specifications.
Doctoral Thesis 2007. Bulletin 91.

Magnusson, J., Structural Concrete Elements Subjected to Air Blast Loading.
Licentiate Thesis 2007. Bulletin 92.

Pettersson, L., G., Full Scale Tests and Structural Evaluation of Soil Steel Flexible Culverts with low Height of Cover.
Doctoral Thesis 2007. Bulletin 93

Westerberg, B., Time-dependent effects in the analysis and design of slender concrete compression members.
Doctoral Thesis 2008. Bulletin 94

Mattsson, H-Å, Integrated Bridge Maintenance. Evaluation of a pilot project and future perspectives.
Doctoral Thesis 2008. Bulletin 95

Andersson, A., Utmattningsanalys av järnvägsbroar. En fallstudie av stålbroarna mellan Stockholm Central och Söder Mälarstrand, baserat på teoretiska analyser och töjningsmätningar.
Licentiate Thesis 2009. Bulletin 96

Malm, R., Predicting shear type crack initiation and growth in concrete with non-linear finite element method.
Doctoral Thesis 2009. Bulletin 97

Bayoglu Flener, E., Static and dynamic behavior of soil-steel composite bridges obtained by field testing.
Doctoral Thesis 2009. Bulletin 98

Gram, A., Numerical Modelling of Self-Compacting Concrete Flow
Licentiate Thesis 2009. Bulletin 99

Wiberg, J., Railway bridge response to passing trains. Measurements and FE model updating.
Doctoral Thesis 2009. Bulletin 100

Athuman M.K. Ngoma, Characterisation and Consolidation of Historical Lime Mortars in Cultural Heritage Buildings and Associated Structures in East Africa.
Doctoral Thesis 2009. Bulletin 101

Ülker-Kaustell, M., Some aspects of the dynamic soil-structure interaction of a portal frame railway bridge.
Licentiate Thesis 2009. Bulletin 102

Vogt, C., Ultrafine particles in concrete
Doctoral Thesis 2010. Bulletin 103

Selander, A., Hydrophobic Impregnation of Concrete Structures
Doctoral Thesis 2010. Bulletin 104

Ilina, E., Understanding the application of knowledge management to safety critical facilities
Doctoral Thesis 2010. Bulletin 105

Leander, J., Improving a bridge fatigue life prediction by monitoring
Licentiate Thesis 2010. Bulletin 106

Andersson, A., Capacity assessment of arch bridges with backfill – Case of the old Årsta railway bridge
Doctoral Thesis 2011. Bulletin 107

Enckell, M., Lessons Learned in Structural Health Monitoring of Bridges Using Advanced Sensor Technology
Doctoral Thesis 2011. Bulletin 108

Hansson, H., Warhead penetration in concrete protective structures
Licentiate Thesis 2011. Bulletin 109

Gonzalez Silva, I., Study and Application of Modern Bridge Monitoring Technique
Licentiate Thesis 2011. Bulletin 110

Safi, M., LCC Applications for Bridges and Integration with BMS
Licentiate Thesis 2012. Bulletin 111

Guangli, D., Towards sustainable construction, life cycle assessment of railway bridges
Licentiate Thesis 2012. Bulletin 112

Hedebratt, J., Industrial Fibre Concrete Slabs – Experiences and Tests on Pile-Supported Slab
Doctoral Thesis 2012. Bulletin 113

Ahmed, L., Models for analysis of shotcrete on rock exposed to blasting
Licentiate Thesis 2012. Bulletin 114

Le, T., N., Corotational formulation for nonlinear dynamic analysis of flexible beam structures
Licentiate Thesis 2012. Bulletin 115

Johansson, C., Simplified dynamic analysis of railway bridges under high-speed trains
Licentiate Thesis 2013. Bulletin 116

Jansson, R., Fire Spalling of Concrete – Theoretical and Experimental Studies
Doctoral Thesis 2013. Bulletin 117

Leander, J., Refining the fatigue assessment procedure of existing steel bridges
Doctoral Thesis 2013. Bulletin 118

Le, T., N., Nonlinear dynamics of flexible structures using corotational beam elements
Doctoral Thesis 2013. Bulletin 119

Ülker-Kaustell, M., Essential modelling details in dynamic FE-analyses of railway bridges
Doctoral Thesis 2013. Bulletin 120

Safi, M., Life-Cycle Costing. Applications and Implementations in Bridge Investment and Management
Doctoral Thesis 2013. Bulletin 121

Arvidsson, T., Train-Bridge Interaction: Literature Review and Parameter Screening
Licentiate Thesis 2014. Bulletin 122

Rydell, C., Seismic high-frequency content loads on structures and components within nuclear facilities
Licentiate Thesis 2014. Bulletin 123

Bryne, L. E., Time dependent material properties of shotcrete for hard rock tunnelling
Doctoral Thesis 2014. Bulletin 124

Wennström, J., Life Cycle Costing in Road Planning and Management: A Case Study on Collisionfree Roads
Licentiate Thesis 2014. Bulletin 125

Gonzalez Silva, I., Application of monitoring to dynamic characterization and damage detection in bridges
Doctoral Thesis 2014. Bulletin 126

Sangiorgio, F., Safety Format for Non-linear Analysis of RC Structures Subjected to Multiple Failure Modes
Doctoral Thesis 2015. Bulletin 127

Gram, A., Modelling of Cementitious Suspensial Flow – Influence of Viscosity and Aggregate Properties
Doctoral Thesis 2015. Bulletin 128

Du, G., Life Cycle Assessment of bridges, model development and Case Studies
Doctoral Thesis 2015. Bulletin 129

Zhu, J., Towards a Viscoelastic Model for Phase Separation in Polymer Modified Bitumen
Licentiate Thesis 2015. Bulletin 130

Chen, F., The Future of Smart Road Infrastructure. A Case Study for the eRoad.
Licentiate Thesis 2015. Bulletin 131

Ahmed, L., Models for analysis of young cast and sprayed concrete subjected to impact-type loads
Doctoral Thesis 2015. Bulletin 132

Albrektsson, J., Durability of Fire Exposed Concrete – Experimental Studies Focusing on Stiffness & Transport Properties
Licentiate Thesis 2015. Bulletin 133

Wallin, J., Systematic planning and execution of finite element model updating
Licentiate Thesis 2015. Bulletin 134

Wadi, A., Flexible Culverts in Sloping Terrain
Licentiate Thesis 2015. Bulletin 135

McCarthy, R., Self-Compacting Concrete for Improved Construction Technology
Licentiate Thesis 2015. Bulletin 136

Veganzones Munõs,J.J., Bridge Edge Beams: LCCA and Structural Analysis for the Evaluation of New Concepts
Licentiate Thesis 2016. Bulletin 137

Abbasiverki, R., Analysis of underground concrete pipelines subjected to seismic high-frequency loads
Licentiate Thesis 2016. Bulletin 138

Gasch, T., Concrete as a multi-physical material with applications to hydro power facilities
Licentiate Thesis 2016. Bulletin 139

Ali, M., M., Use of Macro Basalt Fibre Concrete for Marine Applications
Licentiate Thesis 2016. Bulletin 140

Döse, M., Ionizing Radiation in Concrete and Concrete Buildings – Empirical Assessment
Licentiate Thesis 2016. Bulletin 141

Khan, A., Fundamental investigation to improve the quality of cold mix asphalt
Licentiate Thesis 2016. Bulletin 142

Zhu, J., Storage Stability and Phase Separation Behaviour of Polymer-Modified Bitumen
Doctoral Thesis 2016. Bulletin 143

Chen, F., Sustainable Implementation of Electrified Roads
Doctoral Thesis 2016. Bulletin 144

Svedholm, C., Efficient modelling techniques for vibration analyses of railway bridges
Doctoral Thesis 2017. Bulletin 145

Solat Yavari, M., Slab Frame Bridges, Structural Optimization Considering Investment Cost and Environmental Impacts
Licentiate Thesis 2017. Bulletin 146

Tell, S., Vibration mitigation of high-speed railway bridges, Application of fluid viscous dampers
Licentiate Thesis 2017. Bulletin 147

Elgazzar, H., End-Shield Bridges for Highspeed Railway – Full scale dynamic testing and numerical simulations
Licentiate Thesis 2017. Bulletin 148

Sousa Neves, A. C., Structural Health Monitoring of Bridges: Model-free damage detection method using Machine Learning
Licentiate Thesis 2017. Bulletin 149

Sjölander, A., Analyses of shotcrete stress states due to varying lining thickness and irregular rock surfaces
Licentiate Thesis 2017. Bulletin 150

Heng, P., Simplified Mechanical Models for the Nonlinear Dynamic Analysis of Elasto-plastic Steel Structures Impacted by a Rigid Body
Doctoral Thesis 2017. Bulletin 151

Mohammadi Mohaghegh, A., Structural Properties of High-Performance Macro Basalt Fibre Concrete; Flexure, Shear, Punching Shear and Fire Spalling
Doctoral Thesis 2018. Bulletin 152

Zangeneh Kamali, A., Dynamic Soil-Structure Interaction of Railway Bridges: Numerical and Experimental results
Licentiate Thesis 2018. ABE-DLT-182

Zäll, E., Footbridge Dynamics – Human-Structure Interaction
Licentiate Thesis 2018. ABE-DLT-183

Liu, F., Dynamic analysis of hollow core concrete floors
Licentiate Thesis 2018. ABE-DLT-184

Eriksson, D., Numerical models for degradation of concrete in hydraulic structure due to long-term contact with water
Licentiate Thesis 2018. ABE-DLT-185

Arvidsson, T., Train - Track - Bridge Interaction for the Analysis of Railway Bridges and Train Running Safety
Doctoral Thesis 2018. ABE-DLT-186

Chhang, S., Energy-momentum conserving time-stepping algorithms for nonlinear dynamics of planar and spatial Euler-Bernoulli/Timoshenko beams
Doctoral Thesis 2018. ABE-DLT-1836

Wadi, A. H. H., Soil-Steel Composite Bridges: Research advances and application
Doctoral Thesis 2018. ABE-DLT-1842

Khouri Chalouhi, E., Optimal design solutions of concrete bridges considering environmental impact and investment cost
Licentiate Thesis 2019. ABE-DLT-194

Gasch, T., Multiphysical analysis methods to predict the ageing and durability of concrete
Doctoral Thesis 2019. ABE-DLT-1910

Magnusson, J., Shear in Concrete Structural Elements Subjected to Dynamic Loads
Doctoral Thesis 2019. ABE-DLT-1916

Skoglund, O., Innovative structural details using high strength steel for steel bridges
Licentiate Thesis 2019. ABE-DLT-1933

Hellgren, R., Condition assessment of concrete dams in cold climate
Licentiate Thesis 2019. ABE-DLT-1934

Liu, F., Experimental and numerical analyses of the dynamic behaviour of hollow-core concrete floors
Doctoral Thesis 2020. ABE-DLT-207

Sjölander, A., Structural behaviour of shotcrete in hard rock tunnels
Doctoral Thesis 2020. ABE-DLT-209

Lind Östlund, J., Dynamic soil-structure interaction of simply supported high-speed railway bridges
Licentiate Thesis 2020. ABE-DLT-2025

Sousa Neves, A. C., Structural Health Monitoring of Bridges: Data-driven damage detection method using Machine Learning
Doctoral Thesis 2020. ABE-DLT-2027

Schönbeck, P., Use of configuration information in construction projects to ensure high performance of healthcare facilities
Licentiate Thesis 2020. ABE-DLT-2029

Wang, R., Reliability-based fatigue assessment of existing steel bridges
Licentiate Thesis 2020. ABE-DLT-2031

Veganzones Muñoz, J. J., Bridge Edge Beams - LCCA and Structural Analysis for the Evaluation of New Concepts
Doctoral Thesis 2020. ABE-DLT-2037

Tell, S., Vibrationsdämpning av broar med viskösa dämpare
Doctoral Thesis 2020. ABE-DLT-2046

Li, S., Numerical simulations of flow discharge and behaviours in spillways
Licentiate Thesis 2021. ABE-DLT-211

Colmenares Herrera, D., Footbridge dynamics – running loads, interaction effects and vibration mitigation
Licentiate Thesis 2021. ABE-DLT-215

Markari, A., Experimental investigation on the self-healing capabilities of asphaltic materials using neutron imaging
Licentiate Thesis 2021. ABE-DLT-218