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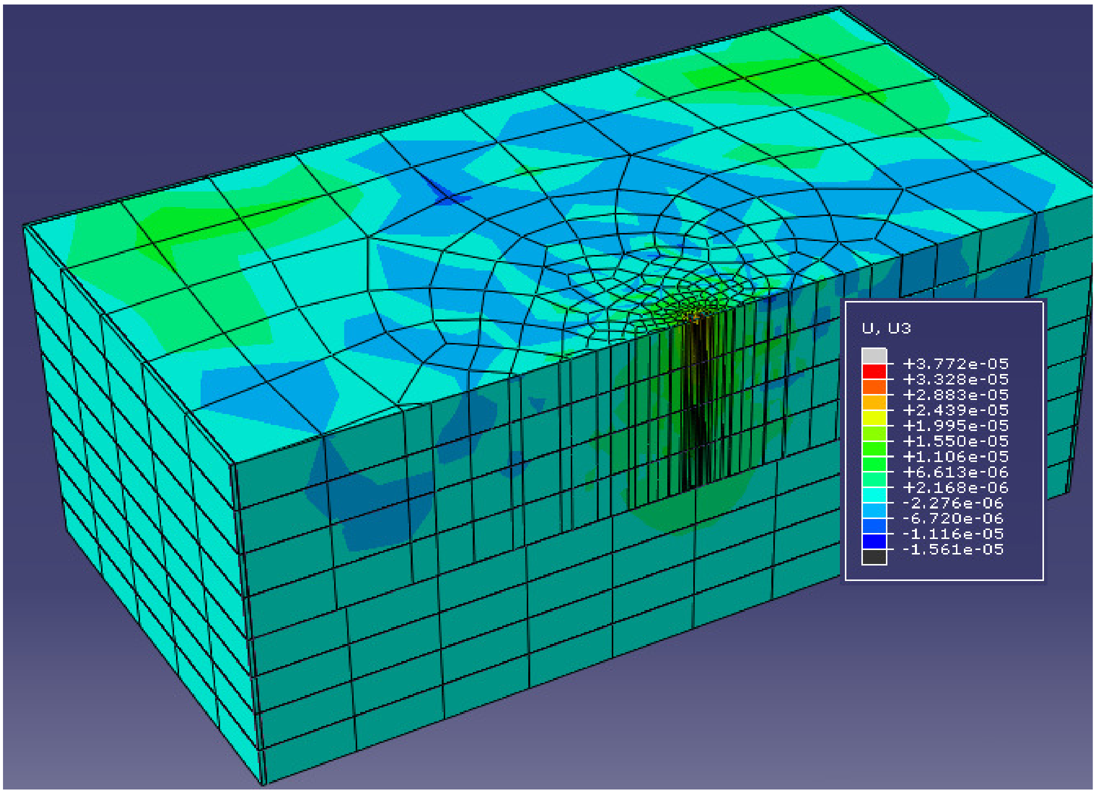

Simulating the dynamic response of a soil-pile system using ABAQUS

Master of Science Thesis in the master's Programme Geo and Water Engineering

PETROS FEKADU

Department of Civil and Environmental Engineering
Division of GeoEngineering

Geotechnical Engineering Research Group

CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Illustration of a response at a section of the soil-pile model

Chalmers Reproservice
Göteborg, Sweden 2010

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ABSTRACT

The football stadium of Gamla Ullevi in Gothenburg, Sweden was opened in 2009. The arena is established on 55-85 metres of clay with cohesion piles reaching a depth of 44 metres. Jumping audiences at football games induced dynamic loads which caused wave propagations. The waves then resulted in vibrations in the surrounding buildings by passing through soft plastic clay. This has brought an interest in the field of geo-dynamics.

The objective of this thesis is to study the response of a soil-pile foundation subjected to a dynamic loading. From this the soil-pile stiffness can be easily obtained.

As a basis for the analysis, the soil has been assumed to be linear elastic and the loading is described as harmonic. For the analysis FE-models are developed in Abaqus to simulate a vertical cyclic load of 5 kN at the head of each cohesion pile. A pile load of 5 kN is aimed to represent the dynamic load caused by a jumping audience. The amplitude of vertical displacement of the pile head as a function of the loading frequency is set as a major output of the model. The frequency was varied between 0-5 Hz where measured frequencies at the stadium where close to 2 Hz.

Results from the model are discussed. Also comparisons between a single pile and a pile group are made. Furthermore, the dynamic response is checked against the static one. Then, a parametric study is carried out to determine to what extent variations of different soil-pile parameters would affect the soil-pile response. The parametric study has indicated that the E-modulus of the soil and pile spacing have larger impact on the soil-pile response than the hysteretic damping property. Finally, velocity from field measurement is compared with a velocity values from Abaqus.

Key words: Abaqus, Complex-harmonic analysis, Damping, Dynamic response, Linear elastic model, Soil-pile system.

Contents

Preface

This master's thesis deals with simulation of the dynamic response of a soil-pile system. It was initiated by Norconsult in Gothenburg, Sweden.

It was carried out at the Department of Civil and Environmental Engineering, Division of GeoEngineering, Geotechnical Engineering Research Group, Chalmers University of Technology, Sweden.

Bernhard Eckel, Jimmy He and Gunnar Widén (Geotechnical Department and Akustikon of Norconsult) were supervisers. Claes Alén (Chalmers University of Technology) was an advisor and examiner.

The thesis had been planned to be done by a partner (David Rudbeck) and me. Some of the theoretical parts, especially the first three chapters were done together with him. However, because of time constraints, we had to work independently using our own models.

Acknowledgements

In doing the thesis, many made considerable contributions for which I would like to extend heartfelt thanks.

Above all, I should forever glorify the Almighty God who holds my life and all my ways in his hands. Many thanks for the indescribable and unconditional love and help in each and every aspect of my life.

It is an honor for me to thank my teacher, advisor and examiner Claes Alen for his invaluable contribution starting from inception to end of the thesis work. Especially, his extraordinary readiness and capability to help and give matured ideas is unforgettable. In a nut shell, it is a big privilege to have such a whole rounded professor as a course teacher and as an advisor in a research in order to accomplish meaningful works and hit the goal.

I would like to acknowledge the wonderful people at Norconsult. Bengt Askmar and Bernhard Eckel made available their support in a number of ways such as thesis provision, facility provision, giving constructive feedbacks and welcoming spirit are worth mentioning. Jimmy He had a vital role in giving vital ideas and challenging questions which pushed me to dig deeper. Gunnar Widén played a major role in giving guidance and valuable ideas with regard to wave mechanics. Without him the thesis would not have had the present quality. Also, some other friends at Norconsult helped in one or other ways. I am heartily grateful to all of them.

I owe my deepest gratitude to Swedish Institute for granting me a scholarship within the Guest scholarship program. Without this my study would not have been possible.

I am indebted to Doctoral students at Geo Engineering division (Mats Olsson) and at Structural Engineering, Steel and Timber Structures (Alann André & Mustafa Aygul) for their help in answering questions related to FEM programs.

To run Abaqus software safely, we had to enhance the capacity of computers. Karin Holmgren, Master's thesis coordinator, facilitated this kindly and timely for which I am very grateful.

I offer my regards and blessings to all of those who supported me in any respect during the study time and the thesis work in particular.

Last, but by no means least, special thanks to my family and relatives for their relentless support and encouragement throughout the study period.

Göteborg, June 2010

Petros Fekadu

Notations and Abbreviations

Roman upper case letters

A	deflection amplitude
C	damping matrix
D	damping factor
Dc	nodal damping coefficient
E	elastic modulus
ΔE	change in elastic modulus
$\mathbf{F}$	complex harmonic load
F	input value of the load
G	shear modulus
H	hysteretic damping coefficient
K	stiffness martix
M	mass matrix
P	applied load
R	radius
S	complex impedance
X, Y	amplitude multipliers

Roman lower case letters

a	areas
c	wave speed
c	imaginary stiffness coefficient
f	frequency
i	$\sqrt{-1}$
k	real stiffness matrix
r	radius
s	element side area
u	displacement
$\dot{u}$	velocity
$\ddot{u}$	acceleration

Greek letters

α	absorption coefficient
γ	unit weight
ε	strain
Φ_0	initial phase angle
ν	Poisson’s ratio
ρ	mass density
σ	normal stress component
σ'_c	preconsolidation presuure
τ	shear stress component
ω	angular frequency

Abbreviations

FEM	Finite element method
OCR	Overconsolidation ratio
SGI	Swedish Geotechnical Institute

1 Introduction

1.1 Background

The phenomenon of ground vibrations in deep layers of clay has been experienced in the Gothenburg a number of times. In 2009 a new football stadium, Gamla Ullevi, was completed and ready for domestic and international football games. In April the same year, it was discovered that cyclic loadings on the standings created vibrations in the surrounding clay. Nearby buildings were exposed to horizontal vibrations up to 11.5mm/s. This has initiated an interest in the field of geo-dynamics.

Most buildings in the area, including Gamla Ullevi, are constructed on a foundation of cohesion piles. This makes them subjected to soil borne wave motions. Therefore, the interest of prediction of soil-pile behaviours has increased. Today, there is little knowledge about the interaction between piles and the Gothenburg clay.

1.2 Objective

The objective of this master's thesis is to determine the dynamic response of an interacting soil-pile foundation. From this the soil-pile stiffness can be easily obtained. Separate analysis results are presented for a single pile and a pile group with input data for a specific location-Gamla Ullevi. The analysis will include parametric studies. Studies will be conducted on soil-pile parameters to determine their specific impact on the dynamic response. Velocity from field measurement is compared with a velocity values from Abaqus.

1.3 Delimitations

The thesis focuses on predicting the dynamic stiffness of a soil-pile system considering both single pile and pile group cases. In addition, static response is determined for the sake of comparison. Only vertical stiffness is dealt with and the lateral stiffness is recommended for further studies.

In the real scenario, piles are subjected to different loading conditions such as vertical forces, horizontal forces and moments. However, the predominant component is the vertical loading in the Gamla Ullevi case. Thus, this study is limited to consider only a dynamic vertical force which could reasonably represent many practical situations.

The location in consideration is Gamla Ullevi where the soil condition is clay which is the prevailing soil condition in Gothenburg. The existing soil type is clay with some varying parameters with depth. Besides these, only undrained condition is set since the phenomenon is known to happen in a short period of time. Furthermore, concrete piles are in consideration because they are preferably used very often.

Depending on the stress amount, soil can exhibit different stress-strain behaviors such as elastic and plastic. Plasticity is known to reduce the stiffness of the soil-pile system as different studies done so far testify (Maheshwari 1997). But, the study is limited to an elastic model with a linear case by making the system subjected to a small amplitude of loading.

Analysis of dynamic stiffness involves multidiscipline and comprehensive procedures which may be geotechnical and non-geotechnical in nature. However, the thesis is principally concerned in analysis of the geotechnical matters, viz., the soil and the foundation.

1.4 Methodology

The work encompasses numerous methods and steps to carry out the task systematically. It entails literature survey, incorporation of available data, modeling the scenario and using of a FEM program.

First, a literature survey from different books, papers and theses on the topic are done. This serves as a good plat form to begin and frame the thesis properly.

Then, all characteristics of clay at the specific location are collected as input data. Furthermore, the basic dynamic soil properties, viz., shear modulus and damping are modeled by employing the linear elastic model. The measured data from the site investigation carried out are incorporated in the model. The basic soil parameters and others are determined to be used in the subsequent steps.

Afterwards, a realistic scenario is conceptualized and a model of the soil-pile system is produced. This is carried out for both single pile and pile group cases. This is the most important step in the thesis and serves as a bridge between the input data and the FEM analyses.

A FEM program-Abaqus is used to analyze the problem. Models are developed and simulated in Abaqus to perform 3D complex-harmonic analyses. From the analysis, displacement values for different cases are determined as major output. Finally, comparisons and conclusions are drawn.

2 Site characterization

The arena is constructed on a foundation consisting of nearly 1200 cohesion piles reaching a depth of 44 meters. The superstructure of concrete is casted at the site and the framework consists of concrete columns and beams. The roof is a steel construction made by welded I-beams which stretches 22 meters from the fixed attachment. (Figure 2.1)

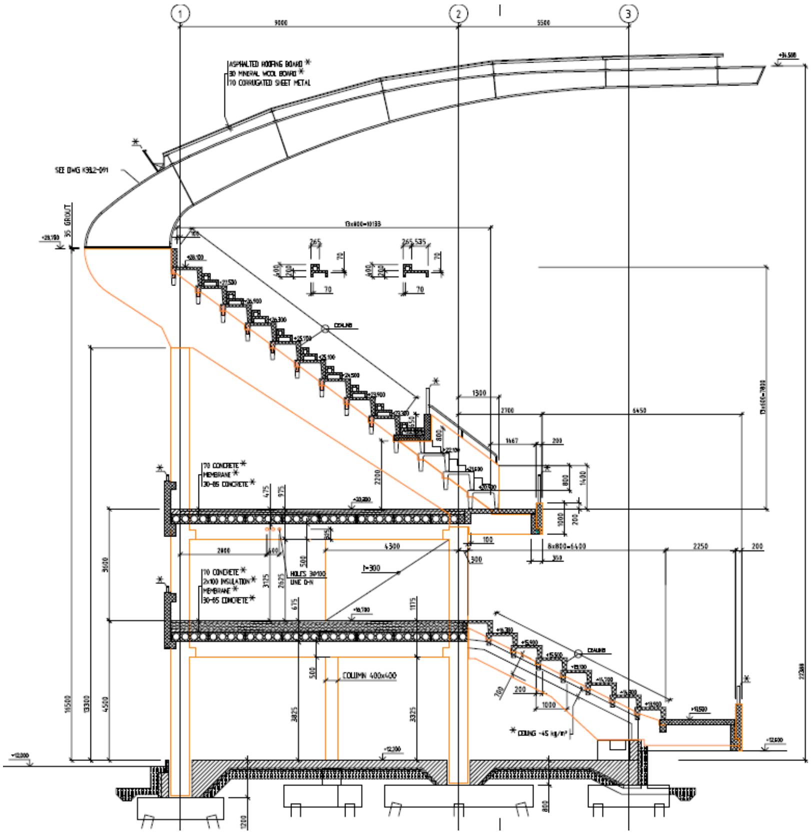


Figure 2.1 A section of a structure at Gamla Ullevi.

At the site of Gamla Ullevi the ground level varies between +11.5 and +12.6 m. In the local level system,i.e. about 1.5-2.6 m above sea level. In the south, the area borders to Ullevi tennis club, to the east it borders to Rättscentrum Göteborg and to the north runs Fattighusån with office buildings, apartment buildings and passing tram lines. A long the north side, the buildings of Rättscentrum Göteborg are constructed with a foundation of end bearing piles. The other surrounding buildings are built on cohesion piles. From previous occasions of concerts high levels of vibrations have been measured in Katolska kyrkan situated south of Gamla Ullevi. There is risk for development of fractures.

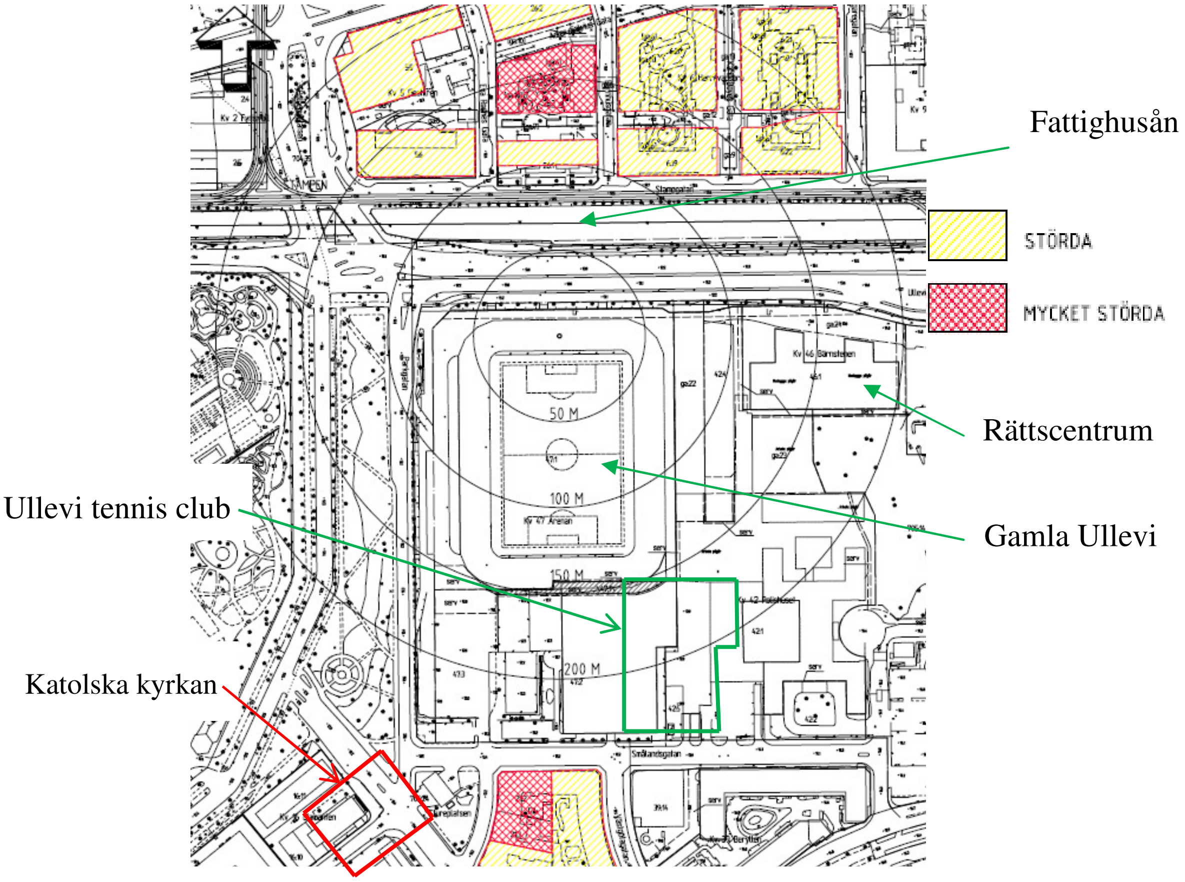


Figure 2.2 Area plan of Gamla Ullevi.

The soil consists of soft plastic clay with varying depths between 52–84 meters. In a report made by Norconsult in 2009 the top 10 meters of the layer was described as "very soft". The surface layer consists of 0.5-2 meters filling material and dry crust. The filling material consists of sand, gravel, stones and crushed bricks. Beneath the clay there is an estimated 3 meters layer of friction material. The estimation is based on an average value for the site according to Gatubolaget (2006).

For the analysis, already collected and organised data are used. However, some of the field tests and laboratory tests made are mentioned here in subsequent subsections.

2.1 Field tests

Data from field tests have been recorded several times at Gamla Ullevi. In 1985 Gatukontoret carried out tests in 9 different locations.

Static penetration was performed at 6 points.

Compilation of undisturbed soil samples in 1 point.

Measurements of the ground water surface level were measured from an open pipe at 2 points.

Pore pressure measurements were taken by a piezometer at 4 levels at a station.

(Gatukontoret, 1985)

Compilation of disturbed soil samples was made using helical auger.

Seismic investigations were made at 4 points to determine the approximate soil depth.

In addition another 5 investigations were carried out between 1961and 2005. A more recent is dated to 2006 and complements the other investigations. It was carried out by Gatubolaget on behalf of HIGAB to provide geotechnical results for the arena project. It comprised the following tests.

Static penetration test was performed at 3 points.

Cone penetration test was carried out at 3 points

Field vane shear test was made at 2 points

2.2 Laboratory tests

In 1985 the geotechnical laboratory of the roadwork department studied the undisturbed soil samples regarding soil type, density, water content, liquid limit, sensitivity and shear strength. The disturbed samples were studied to determine the soil types. Odometer tests were carried out at three depths, 10 m, 20 m, and 30 m below the ground surface. In addition to the geotechnical investigation, a number of analyses were carried out to determine the content of different metals and chemicals in the soil. (Gatukontoret, 1985)

Consolidation tests at 5 levels were made 2 at points.

The moisture content is measured to be 20% in the filling material, 32% in the dry crust and 45-100% in the clay.

The clay is overconsolidated with an OCR between 1.3 - 1.9 decreasing with depth.

The undrained shear strength is estimated to be 12 kPa at the top of the clay layer. The shear strength increases with depth by 1.2 kPa/m.

The liquid limit varies between 60-85 % (Norconsult, 2009)

The sensitivity varies between 10-30.

3 Dynamics of a soil-pile system

3.1 General

If the long-term response of a structure to applied loads is sought, a static analysis has to be performed. However, if the loading has a short duration as in the cases of machine vibrations, compaction, pile driving, wave loading and earthquake, the loading is dynamic in nature. Thus, a dynamic analysis ought to be executed.

Dynamic stiffness of soil including both elastic stiffness and damping can be represented by a complex quantity of the data. Thus, it needs to use a FE-program capable of running complex-harmonic analyses. In the complex data, the real part represents the spring stiffness and the imaginary part represents damping. *(*Maheshwari 2005*)*

3.2 Linear elastic model

The soil is modelled to be linear elastic which is governed by Hooke's law. Thus the elastic properties can be described by two parameters, the E-modulus and Poisson's ratio. Hooke's law is not appropriate for soils because soils are neither linear elastic nor isotropic. Nevertheless, sometimes it needs to idealize soils as being linear elastic and isotropic materials—only then Hooke's law can be used to estimate the elastic strains associated with applied stresses within a soil mass.

If the E-modulus and Poisson's ratio are constant, the equation is linear. This assumption implies that there is no limit of failure which makes the linear elastic soil model a limited model. In practice, clay is not an elastic material and has a non linear behaviour. However, the cyclic loads that will be applied in the simulations are assumed to be small enough not to exceed any stress limits causing any significant non linear behaviour. Therefore the assumption of linearity is supposed to generate results with sufficient accuracy for the actual loading case.

Poisson's ratio

Poisson's ratio describes how a material deforms laterally when exposed to compressive or tensile stress. When a force is applied along one axis the material is strained parallel and orthogonally to that axis. The relation between these strains is represented by the ratio which is defined between -1 – 0.5. If the figure is set to 0.5 it means that the volume is unchanged during deformation. The analysis is an undrained condition and the ratio is set to 0.495. To avoid numerical problems with Abaqus it is recommended to use a value near 0.5. (Gabrielsson, 2007)

Isotropy

Isotropy is assumed for concrete piles instead of the more accurate orthotropic assumption. With small deformations is it reasonable to describe the pile behaviour as elastic. Isotropy is also assumed for the clay instead of a more realistic anisotropy.

3.3 Basic Equation of Dynamic Behavior

According to *Abaqus manual (2010)*, the fundamental equation for the movement of a volume under dynamic load is:

$$M\ddot{u} + C\dot{u} + Ku = P \tag{3.1}$$

where, C = damping matrix

K = stiffness matrix

M = mass

$\ddot{u}$ = acceleration

$\dot{u}$= velocity

u= displacement

P= applied load

The basic difference between static and dynamic analyses is the inclusion of the inertial forces ($M\ddot{u}$) in the equation of equilibrium. Another difference between the two types of simulations is in the definition of the internal forces ($C\dot{u} + Ku$). In a static analysis the internal forces arise only from the deformation of the structure, while in a dynamic analysis the internal forces contain contributions created by both the motion and the deformation of the structure.

3.4 Waves

The definition of a wave is a motion around a state of equilibrium. In soil, it can be caused by tectonic movement resulting in earth tremors or in more extreme cases, earthquakes. In this case the vibrations are caused by vertical cyclic loads on the surface that dislocates the soil particles from equilibrium. If the impact is large enough the dislocation can be permanent which densifies the soil. In the field of ground improvement, the technique of dynamic compaction is a commonly used method to densify soil. The magnitude of the impact for this case is limited to 3 kPa on undrained soil. Under these circumstances no permanent dislocation of soil particles will occur.

There are mainly three wave types that are studied in dynamic soil tests. The pressure wave (P-wave), shear wave (S-wave) and the surface bound Rayleigh wave are described below. (SGI, 2000)

3.4.1 Pressure wave

P-wave is a propagation of compression and extension (variation of pressure and volume change).The P-wave has higher velocity than the S- wave and has a particle motion in the same direction as the propagation of the wave. The term used for this kind of wave is longitudinal. Shear wave

S-wave is a propagation of shear deformation that arrives at earthquake observation station after (second to) the primary (P-wave). The S-waves are transversal wave, which means that the particle movement is perpendicular to the direction of the propagation. (SGI, 2000)

Figure 3.1 illustrates the appearances of a P- and an S-wave. The P-wave is characterized as a longitudinal wave. (SGI, 2000)

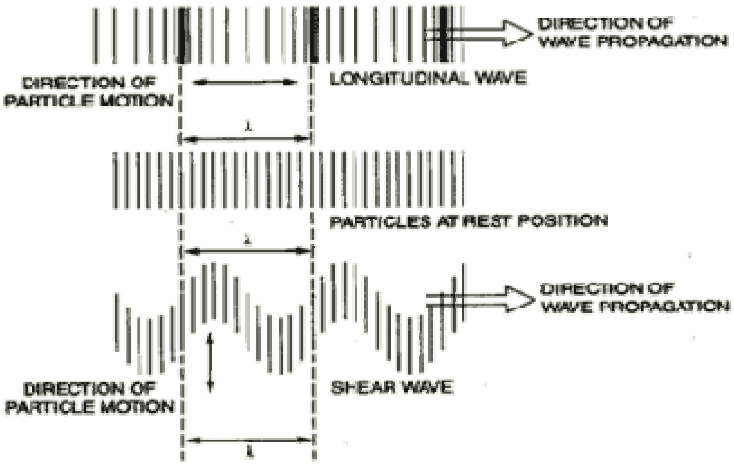


Figure 3.1 A P-wave is illustrated at the top of the figure and an S-wave at the bottom.

3.4.2 Rayleigh wave

Rayleigh waves are categorized as surface waves since they mostly propagate at the ground surface. It is a combination of a transversal and longitudinal wave and the particle motion path is close to elliptic. The amplitude decreases rapidly with depth and can be measured to a depth of one wave length. (SGI, 2000) Since the waves primarily are surface bound and the simulated soil depth is 84 meters the Rayleigh waves are neglected in the model.

3.5 Damping

If an undamped structure is allowed to vibrate freely, the magnitude of the oscillation is constant. In reality, however, energy is dissipated by the structure's motion and the magnitude of the oscillation decreases until the oscillation stops. Every nonconservative system exhibits some energy loss that is attributed to material nonlinearity, internal material friction, or to external (mostly joint) frictional behavior. This energy dissipation is known as damping. Damping is usually assumed to be viscous or proportional to velocity. Damping is a convenient way of including the important absorption of energy without modeling the effects in detail.

When waves propagate through soil a certain amount of absorption occur. The waves are damped and wave energy is converted to heat. The soil damping properties are dependent of wave velocity and frequency.

In soil dynamics, two different kinds of damping properties can be estimated which determine the decay of the wave by distance. They are material damping and geometrical damping.

3.5.1 Material damping

The damping type determines how damping is applied to a dynamic system. Two primary types of damping are available in Abaqus (2010):

- velocity proportional viscous damping; and
- displacement proportional structural damping, which is for use in frequency domain dynamics.

Viscous Damping
The most common approach is to use viscous damping or Rayleigh damping, in which it is assumed that the damping matrix is proportional to the mass M and stiffness matrices K, or:

$$[C]=\alpha[M]+\beta[K] \tag{3.2}$$

For large systems, identification of valid damping coefficients α and β for all significant modes is a very complicated task.

Structural Damping
When the materials are deformed, energy is absorbed and dissipated by the material itself. The effect is due to friction between the internal planes, which slip or slide as the deformations take place. When a structure having material damping is subjected to vibration, the stress-strain diagram shows a hysteresis loop. Therefore, the structural damping is also called hysteretic damping. The area of this loop denotes the energy lost per unit volume of the body per cycle due to the damping. The cyclic stress-strain curve forms hysteretic loop, as seen in Figure 3.2 below.

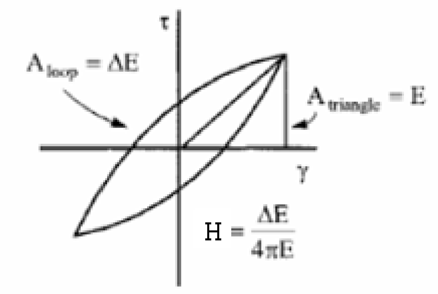


Figure 3.2 Cyclic stress-strain curve.

The area enclosed by the ellipse, A_{loop}, is related to the amount of energy dissipated by the material during a cycle of harmonic loading. $A_{triangle}$ is the maximum strain energy stored during that cycle. Strain energy is the work done on an elastic body causing it to deform, which makes it a form of potential energy. The deforming energy is provided by the propagating wave. A relation between A_{loop} and $A_{triangle}$ gives the material damping ratio H.

$$H = \frac{\Delta E}{4\pi E} \tag{3.3}$$

3.5.2 Geometrical damping

In many applications of damping theory it is important to estimate the vibrations at a given distance from the source. The geometrical damping property describes the decay of amplitude as a function of distance from the source. The decay occurs due to dispersion of wave energy over an increasing volume. For P- and S-waves the theoretical amplitude decay is 1/r. (SGI, 2000)

3.6 Non-reflecting boundaries

For dynamic calculations, the boundaries should be much further away than those for static calculations, because, otherwise, stress waves will be reflected leading to distortions in the computed results. However, locating the boundaries far away requires many extra elements and therefore a lot of extra memory and calculating time.

To counteract reflections, special non-reflecting boundary conditions have to be defined to account for the fact that in reality the soil ought to be modeled as a semi-infinite medium. Without these special boundaries the waves would be reflected on the model boundaries. Hence, to avoid these unrealistic reflections, non-reflecting boundaries need to be specified at pertinent boundaries.

3.7 Impedance function

The dynamic stiffness of the soil-pile system at the pile head is known as an impedance function. They are obtained by applying a load in a specific direction on the pile head and measuring the complex displacement in the direction of the load at the same point. The complex impedance function is defined as:

$$S(\omega) = \frac{F_0}{U_0} \tag{3.4}$$

where F_0 and U_0 are the amplitude of the force excitation and complex displacement amplitude, respectively for a particular direction for which the impedance function is sought. The impedance function is a complex quantity and can be separated in to real parts (corresponding to stiffness) and imaginary parts (corresponding to damping). Both are frequency dependent i.e.

$$S(\omega) = k(\omega) + ic(\omega) \tag{3.5}$$

4 Analysis using Abaqus

4.1 General

The finite element method is a common tool within various fields of engineering. It is used for advanced numerical calculations and is developed from the theories of continuum mechanics, which studies equilibrium, motion and deformation of physical solids. FEM prerequisites that the mathematical models which describe the motions of the media has to be based on continuous functions.

In FEM the continuous functions are approximated by a discrete model where the body to be studied is divided into several smaller parts, so-called elements. The discretisized model is composed by a number of element functions that are continuous over each separate element. These elements are connected in nodes, which is primarily where the calculations are made. Numerical values for the nodes are compiled to make the element functions an accurate approximation of the global function. Accuracy improves when the number of nodes increases.

The element functions are gathered in the global equation system containing material and geometrical data. The forces applied on the element geometry are represented by load vectors that act in the nodes. The matrixes quickly increase in size and demand high computer performance to be solved. The nodal deflections are the solution to the equation system. The values between the nodes are received by interpolation with either linearly approximations or polynomials of n degrees.

In linear elasticity problems, the stiffness matrix is constant which brings linear element equations. Soil is a non linear material, as previously mentioned, but in this thesis it is assumed to have elastic properties. Thus the problem can be solved by applying all the loads in a single calculation step. (Gabrielsson, 2007)

Abaqus is a powerful FEM tool to analyze 3D problems in various fields. It is also capable of running Complex-harmonic analyses. In this thesis, Abaqus CAE version 6.8-2 is used.

Generally analysis using Abaqus involves two major procedures, viz, preprocessing and postprocessing.

4.2 Preprocessing

It comprises all the steps to create the model with Abaqus/CAE. The following principal steps are taken sequentially:

-Creating a part /defining the model geometry

-Defining the material and section properties

-Creating an assembly

-Configuring the analysis

-Assigning interaction properties

-Applying boundary conditions and applied loads

-Designing the mesh

-Creating, running, and monitoring a job

Below are discussions of procedures and assumptions made for the preceding steps in modeling the soil-pile system:

I- Creating a part /defining the model geometry

The first step in creating the model is to define its geometry. The model is created with a three-dimensional, deformable body with a solid, extruded base feature. The following dimensions are used:

(a) Soil: 202x202x84 m^3

The soil is divided into 8 layers.

(b) Pile: 44.27 m long and 0.27x0.27 m^2 in cross-section.

The analysis is executed for single pile and pile group (2x2) cases to make comparisons. In case of the pile group, the piles are spaced 1.2 m.

At this stage, it is important to decide what system of units to use in the model as Abaqus has no built-in system of units. Thus, the SI system of units is used.

II-Defining the material and section properties

The next step in creating the model involves defining and assigning material and section properties to the part. Each region of a deformable body must refer to a section property, which includes the material definition. In this model linear elastic materials are created for both concrete pile and clay.

Material properties are taken from the report by Gatubolaget (2006). Hereunder the relevant material properties for the concrete pile and clay at different layers are tabulated:

Table 4.1 Properties of concrete pile.

ρ (kg/m^3)	ν	E [GPa]
2400	0.3	37

Table 4.2 Properties of soil layers.

Layer no.	Thickness [m]	Cumulative depth [m]	ρ (kg/m^3)	ν	*E* [MPa]	*H*
1	11	11	1600	0.495	30	0.02
2	11	22	1600	0.495	55	0.02
3	11	33	1600	0.495	80	0.02
4	11	44	1600	0.495	105	0.02
5	10	54	1650	0.495	130	0.02
6	10	64	1650	0.495	150	0.02
7	10	74	1750	0.495	170	0.02
8	10	84	1800	0.495	195	0.02

III-Creating an assembly

Each part created is oriented in its own coordinate system and is independent of the other parts in the model. Although a model may contain many parts, it contains only one assembly. The geometry of the assembly is defined by creating instances of a part and then positioning the instances relative to each other in a global coordinate system. Thus, the soil and piles are assembled together.

IV- Configuring the analysis

Analysis steps can be broadly categorized as an initial step and analysis steps. They are dealt subsequently.

A-The initial step

Abaqus/CAE creates a special initial step at the beginning of the model's step sequence and names it `Initial`. It allows defining boundary conditions, predefined fields, and interactions that are applicable at the very beginning of the analysis.

B-Analysis steps

The initial step is followed by one or more analysis steps. Each analysis step is associated with a specific procedure that defines the type of analysis to be performed during the step.

There are two kinds of analysis steps in Abaqus: general analysis steps, which can be used to analyze linear or nonlinear response, and linear perturbation steps, which can be used only to analyze linear problems. In this case, a static linear perturbation step is defined. Specifically, Direct-solution steady-state dynamic analysis step is used because it is used to calculate the steady-state dynamic linearized response of a system to harmonic excitation. Multiple frequency ranges or multiple single frequency points can be requested for a direct-solution steady-state dynamic step.

Requesting data output

Finite element analyses can create very large amounts of output. Abaqus allows controlling and managing this output so that only data required to interpret the results of the simulation are produced. Thus the analysis is limited to give such a relevant output as displacement.

V-Assigning interaction properties

The interaction between contacting surfaces consists of two components: one normal to the surfaces and one tangential to the surfaces. The tangential component consists of the relative motion (sliding) of the surfaces and, possibly, frictional shear stresses.

The contact constraint is applied in Abaqus when the clearance between two surfaces becomes zero. The surfaces separate when the contact pressure between them becomes zero or negative, and the constraint is removed. This behavior, referred to as “hard” contact.

The system is subjected to a small force which does not induce slip. Thus, for the tangential component, rough interaction is assumed as there is no slip between the surfaces.

Thus, for the normal behavior and the tangential behavior “hard” and rough contacts respectively are used in all interactions.

In addition, a nodal damping coefficient is introduced at lateral exterior nodes to prevent reflections of energy back to the system from the lateral surfaces. Thereby an amplitude that is undisturbed by reflected horizontal waves can be obtained. Calculation of the damping coefficient is based on the theory of equilibrium between the soil wave force and the damping force. The damping coefficient is specified as force per velocity (N/(m/s)) where the velocity is the relative motion between two nodes. (Abaqus manual, 2010)

$$c = \sqrt{\frac{E}{\rho}} \tag{4.1}$$

$$A_n = \frac{S}{2} \tag{4.2}$$

$$Dc = A_n \rho c \tag{4.3}$$

Where Dc = nodal damping coefficient [N/(m/s)]
E = elastic modulus (Pa)

ρ = density (kg/m^3)
c = wave speed (m/s)
s = element side area (m^2)
A_n = area of a node face (m^2)

Table 4.3 Nodal damping coefficient of soil layers.

Layer no.	*Dc* [N/(m/s)]
1	9,859
2	13,349
3	16,100
4	18,730
5	20,841
6	22,724
7	24,545
8	26,660

VI-Applying boundary conditions and applied loads

Prescribed conditions, such as loads and boundary conditions, are step dependent, which means that the step or steps in which they become active is specified accordingly.

Applying boundary conditions

Boundary conditions are applied to those regions of the model where the displacements and/or rotations are known. Such regions may be constrained to remain fixed (have zero displacement and/or rotation) during the simulation or may have specified, nonzero displacements and/or rotations. Thus, a fixed boundary is set at the bottom and at the sides of the model.

Applying a load

The loads are assumed to vary sinusoidally with time over 0-5 Hz of frequencies. Thus,

$$\mathbf{F} = F[X \sin(\omega t + \Phi_0) + iY \cos(\omega t + \Phi_0)] \quad (4.4)$$

In which

F= Complex harmonic load

F= Input value of the load

X,Y= Amplitude multipliers

ω= 2Πf, with f= frequency in Hz

Φ_0= Initial phase angle in degrees in the sine function.

In here, a dynamic load of 5 KN/ pile for a frequency range of 0-5 Hz is used. It is important to note that the static case corresponds to a frequency of zero and a phase angle of an integral multiple of $\Pi/2$.

VII-Designing the mesh

The Mesh module contains tools that allow generating meshes on parts and assemblies created within Abaqus/CAE. In the model, a structure meshing is used. Structure meshing is a technique that gives the most control over the mesh because it applies preestablished mesh patterns to particular model topologies. Considerable care is taken to optimize the mesh size so as to get reliable results. Fig 4.1 shows the mesh of the assembly.

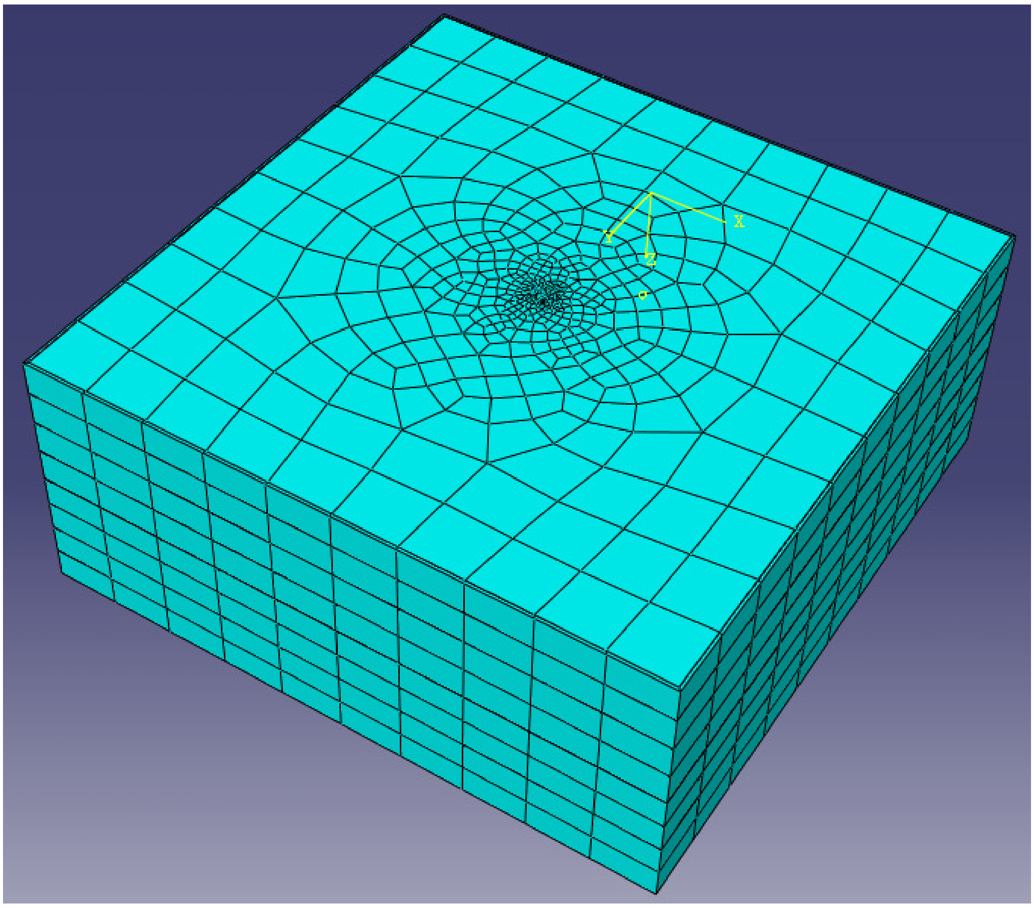


Figure 5.1 Mesh of the assembly.

VIII-Creating, running, and monitoring a job

Once defining a model is finished, the model is analyzed using the Job module. The Job module allows interactively submitting a job for analysis and monitoring its progress.

4.3 Postprocessing

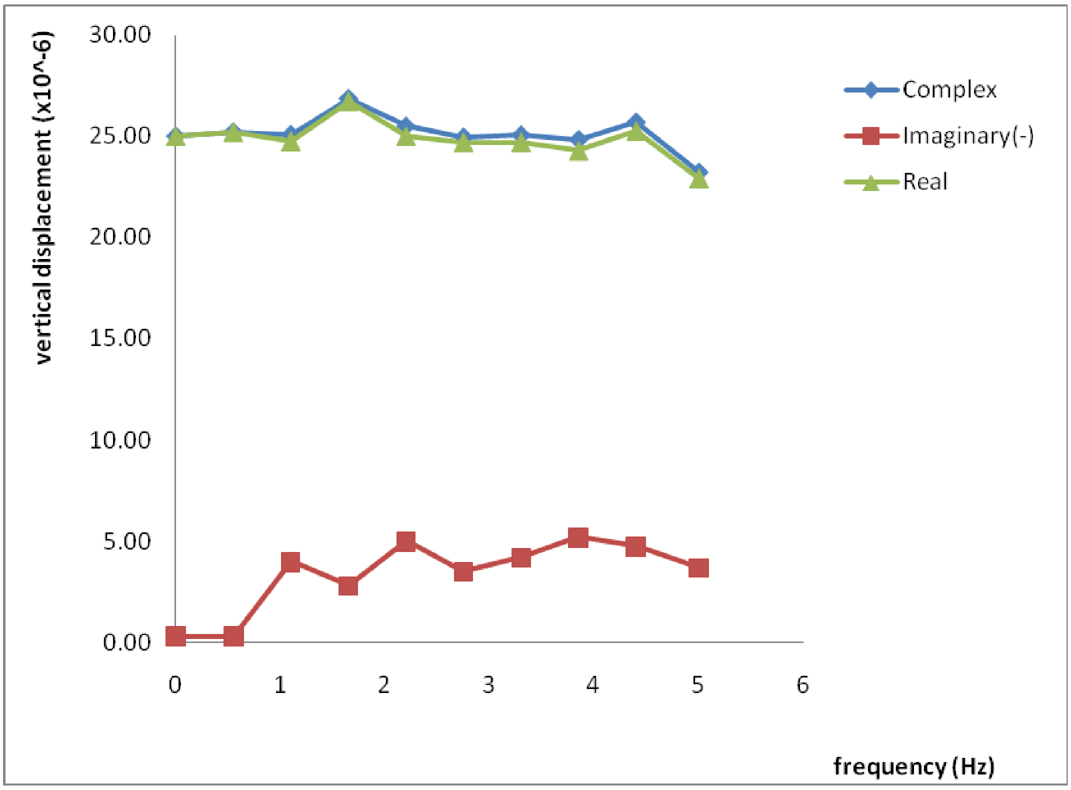
The Visualization module provides graphical display of finite element models and results. It obtains model and result information from the output database; it is controlled what information is written to the output database by modifying output requests in the Step module.

5 Discussions

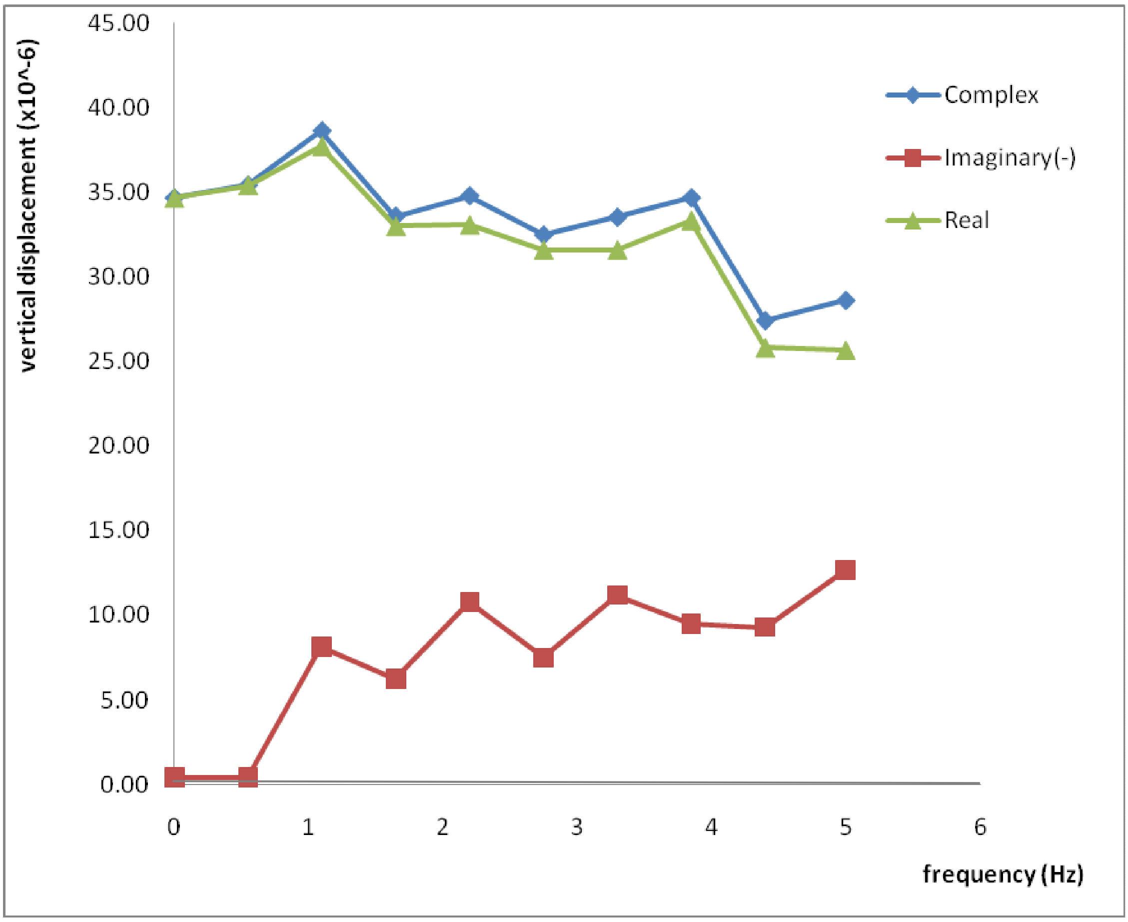
In here the analysis results are compared and verified based on some theoretical and field measured references. As mentioned in the foregoing discussions, displacement of the pile is focused. Because it is direct to imply the stiffness from displacement. The vertical stiffness is the applied force divided by the corresponding vertical displacement.

5.1 Displacement vs. frequency plots

In both single pile and pile group, the complex response of the system has the tendency to decrease as the frequency increases. This is because faster loads cause smaller strains. It could also be seen that the real part is much higher than the imaginary part in the frequency range. See Fig 5.1 below.



(a) single pile



(b) pile group

Figure 5.1 Displacement vs. frequency plot

It is important to note that the static response is the one corresponding to 0 Hz frequency. It can easily obtained by executing static analyses.

Here are the corresponding displacement values:

Single pile: 25 E-06 m

Pile group: 34 E-06 m

Using the static and the dynamic response values, it is very important to plot the normalized curve of the response versus the frequency. The normalized values are obtained by dividing the responses by the corresponding static response. Here are the plots for both single pile and pile group in Fig 5.2.

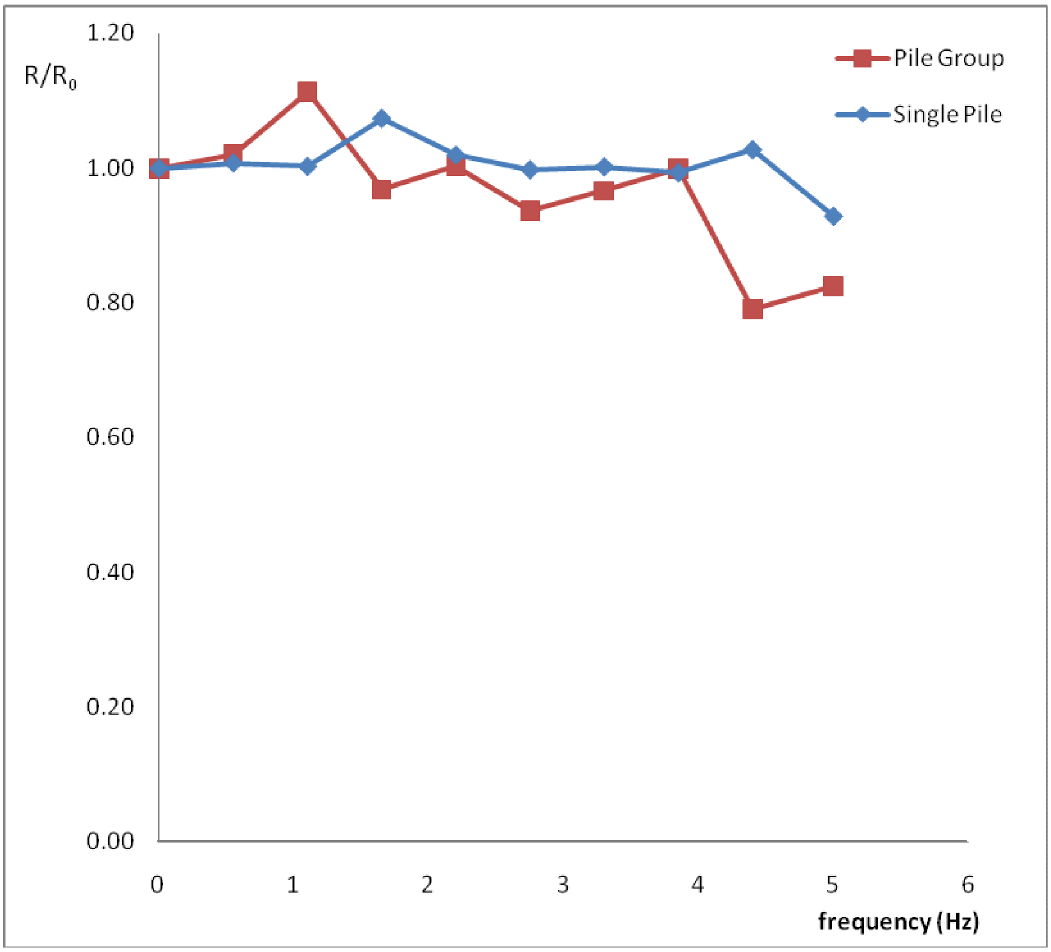


Figure 5.2 Normalized curve.

A point worth mentioning is the natural frequency of the soil-pile system. This is the frequency corresponding to the peak response. In this case it lies in the ranges 1.5-1.75 Hz and 1-1.25 Hz for single pile and pile group cases respectively. At this frequency, the dynamic response is most pronounced. It is important to know that the response increases at the natural frequency increases with the number of calculation steps. However, in this case, it is not important to consider it since the measured frequency is out of these ranges.

5.2 Single pile vs. pile group

Here is the plot of complex responses of a single pile and a pile group in Fig 5.3.

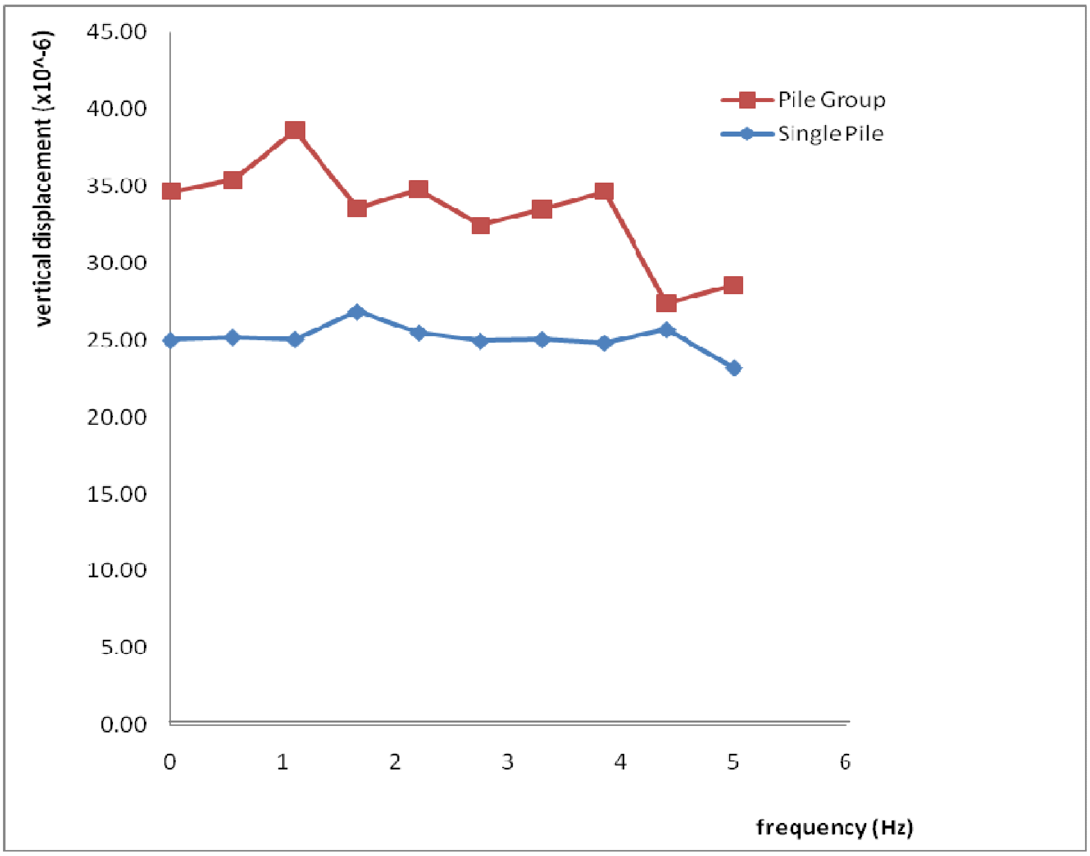


Figure 5.3 Displacement vs. frequency plot comparing pile group and single pile.

To make comparisons, displacements corresponding to 2.22 Hz as in the case of Gamla Ullevi are considered for the two cases:

Single pile: 25 E-06 m

Pile group: 35 E-06 m

At this specific frequency, the displacement in a pile group is greater as compared to that of a single pile by 40% approximately. Thus, the pile group is less stiff than the single pile. This is attributed to overlap of high stresses of the piles in the vicinity.

5.3 Parametric study

To see how variation of results affect the response of the system, parametric studies are made by doing sensitivity analysis on the basic dynamic soil parameters, viz., elastic modulus and structural damping. Also, a parametric study is done based on pile spacing. Consideration is given to the maximum complex response values in the frequency range for nodes at the head of the piles.

(a) Elastic modulus

A sensitivity analysis is done using the single pile system by varying the modulus by ±10%. The following results in Fig 5.4 are obtained.

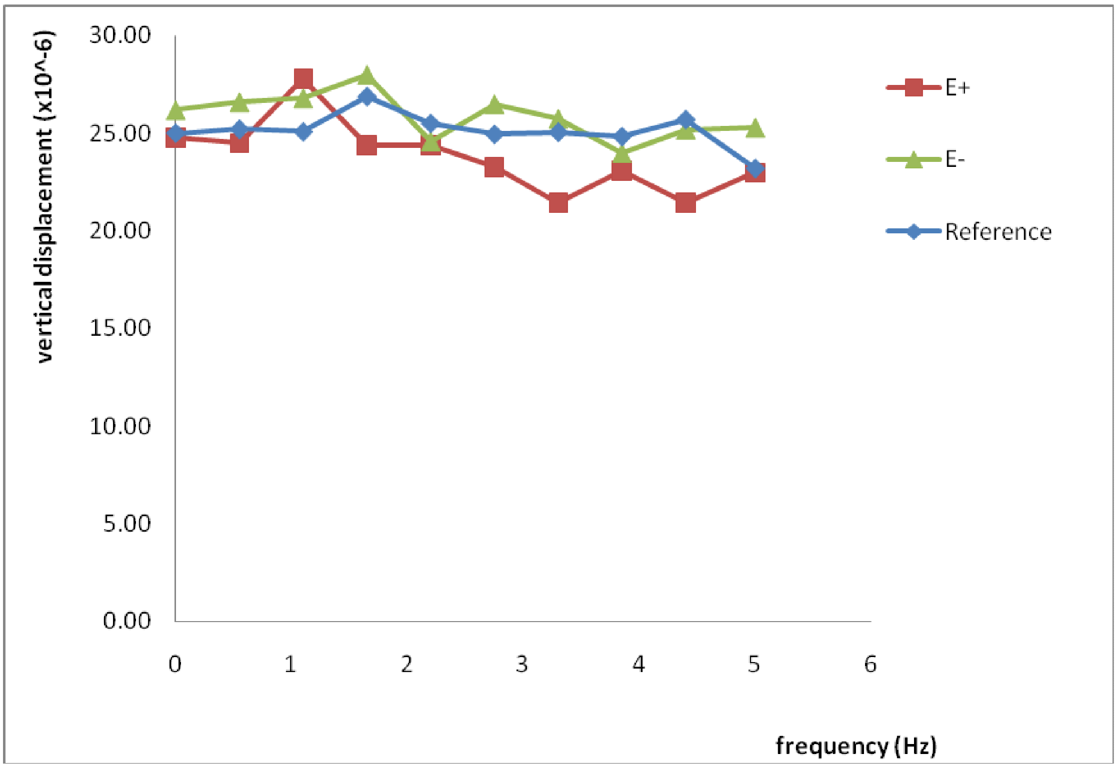


Figure 5.4 Displacement vs. frequency plot for parametric study on E.

Considering the response at 2.75 Hz, the following are obtained as tabulated below:

Table 5.1 Sensitivity analysis on elastic modulus.

Cases	Response (x10^{-6} m)	% Increase of response	Remark on the response
Reference	24.95	-	-
Increase by 10%	23.3	-6.61	decreased
Decrease by 10%	26.5	6.25	increased

(b) Hysteretic damping

In this case, sensitivity is done using the single pile system on hysteretic damping by varying the value by ±50%. The following results in Fig 5.5 are obtained.

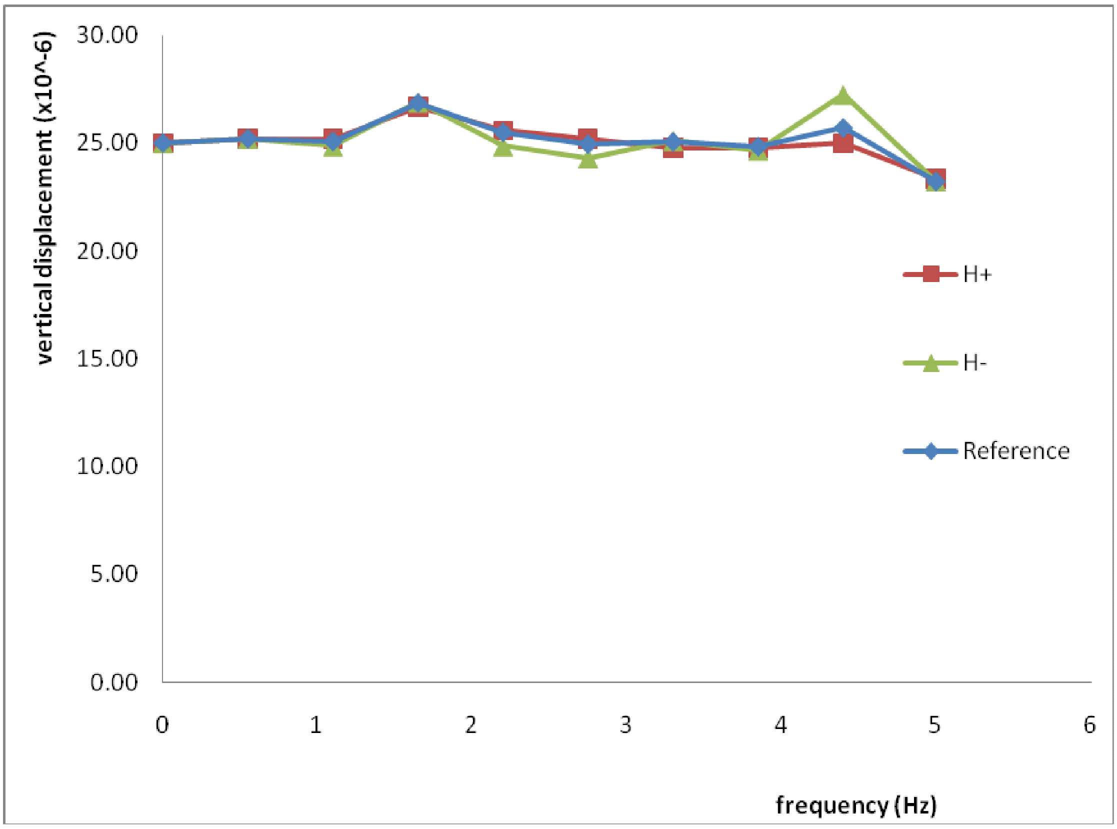


Figure 5.5 Displacement vs. frequency plot for parametric study on H.

Considering the response at 2.75 Hz, the following are obtained as tabulated below:

Table 5.2 Sensitivity analysis on structural damping.

Cases	Response (x10^{-6} m)	% Increase of response	remark on the response
Reference	24.95	-	-
Increase by 50%	25.2	1	increased
Decrease by 50%	24.3	-2.6	decreased

(c) Pile spacing

Obviously the interaction of piles is insignificant when the spacing is large. As a result, pile spacing has got an influence on the response. Now, analysis is done on a pile group system by reducing the spacing from 1.2 m to 0.6 m.

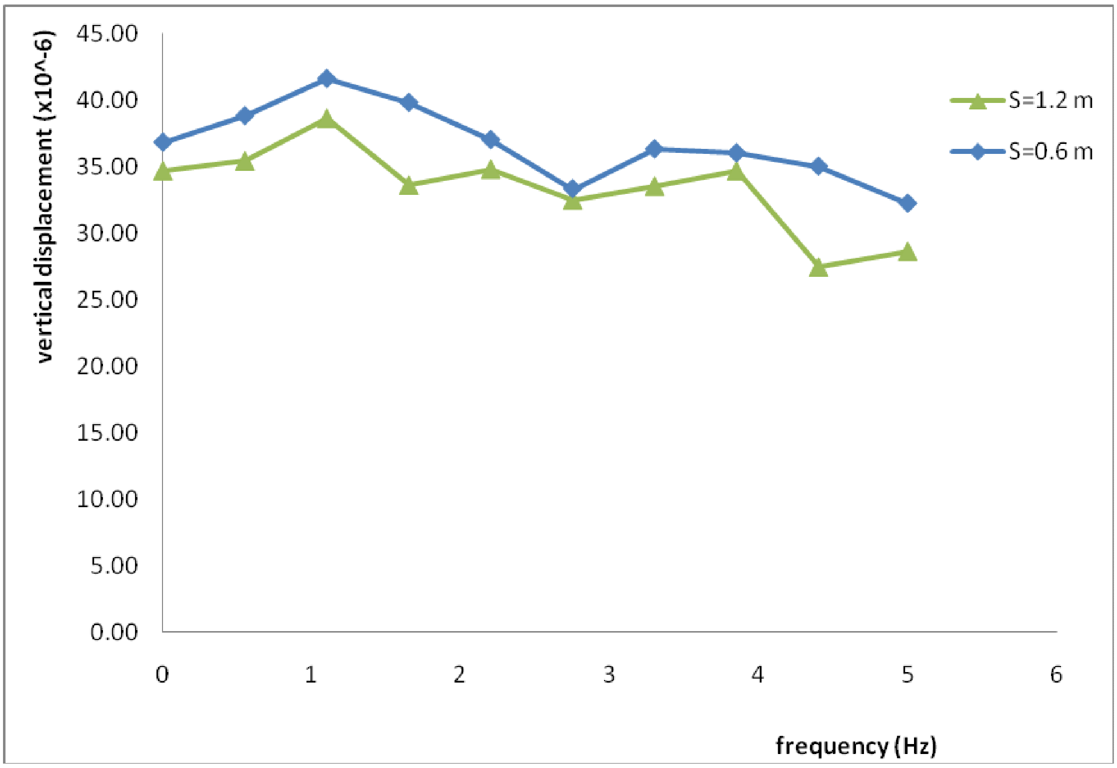


Figure 5.6 Displacement vs. frequency plot for parametric study on pile spacing.

As the pile spacing decreases, the efficiency of each pile in the group decreases.

Considering the response at 0.55 Hz, the following are obtained as tabulated below:

Table 5.3 Sensitivity analysis on pile spacing.

Cases	Response ($x10^{-6}$ m)	% Increase of response	remark on the response
1.2 m spacing	35.42	reference	-
0.6 m spacing	38.8	+9.54	higher

As can be seen from the preceding tables, the response is sensitive to the elastic modulus. On the other hand, the response is not that much sensitive to the change in hysteretic damping since the response is varied by 2.6% only for a change of 50% in damping. Also, it is worth noting that pile spacing has significant impact on pile efficiency.

5.4 Abaqus results vs. field results

It is very essential to make justification of outputs from a FEM program by checking with certain field measurements. Unfortunately, only velocity measurements at a specific spots at Gamla Ullevi are available. The value is tabulated below together with the Abaqus result.

Table 5.4 Velocity values from Abaqus analysis and field measurements.

Cases	Vz (x10^{-3} m/s)
Abaqus analysis	1
Field measurement	2.5

In comparison, it could be seen that the difference is not large. To make sound comparisons, the actual field condition ought to be intercepted and modelled. However, in this case, there are tangible differences between the Abaqus model and the field situation. The lack of accurate value of the load at the field is the major one.

6 Conclusions

In accordance with the preceding discussions, the analysis results obtained from Abaqus are discussed and relevant comparisons such as a single pile versus a pile group, parametric studies and measured values versus Abaqus results are done. The following conclusions are drawn:

In the results, it could be seen that generally the response has a tendency to decrease with frequency since faster loads induce smaller response as a result.

In design of a pile subjected to dynamic loads, it is important to know that the stiffness of a pile group is less than a single pile.

In addition, in design the natural frequency of the system has to be determined. Because it is important to design structures in such a way that the frequencies at which they may be loaded are not close to the natural frequencies which are seen in the discussion.

From the two basic dynamic soil properties, the response is more sensitive to changes in the elastic modulus than changes in hysteretic damping properties. Besides this, pile spacing is seen to have considerable effect on pile efficiency.

It is important to justify FEM results with field measured values or calculated values. Obviously, the field situations have to be intercepted in a reliable accuracy to the FEM model.

7 Recommendations for further studies

Dynamic analysis of a soil-pile system is a vast field which needs plenty time and effort when a comprehensive analysis is sought. So, in this Master's thesis, the focus has been prediction of the vertical stiffness subjected to a reasonably small dynamic load inducing small strains, i.e. linear analysis. However, there are a few areas to be recommended for further work as elaborated next.

Lateral Stiffness

Practically, a pile is subjected to different actions even though the predominant type of loading is an axial force. There are occasions when a lateral load can be considerable in a structure located in areas where earthquake or wind loads are prominent. In such cases, a dynamic lateral stiffness becomes a fundamental part of the pile design. Thus, it is recommended to be studied.

Nonlinearity

In this thesis, the analysis is limited to a linear dynamics by assuming the load to be small enough so as not to induce nonlinear behaviors. Nevertheless, nonlinear behaviors can be induced if the load is large. Also, it is important to notice that soil behaves nonlinearly even in small loads.

A lot of researches have also been made on effects of nonlinearity on dynamic analysis of a soil-pile system. It has been proven that nonlinearity decreases the stiffness significantly. (Maheshwari, 1997). It is not prudent to overlook nonlinear behaviors. Thus, this is highly recommended to be studied.

Permeability

In a report written by Maeso et al. (2004), it is found that permeability has significant effect on the dynamic response. Thus, it is recommended for further studies.

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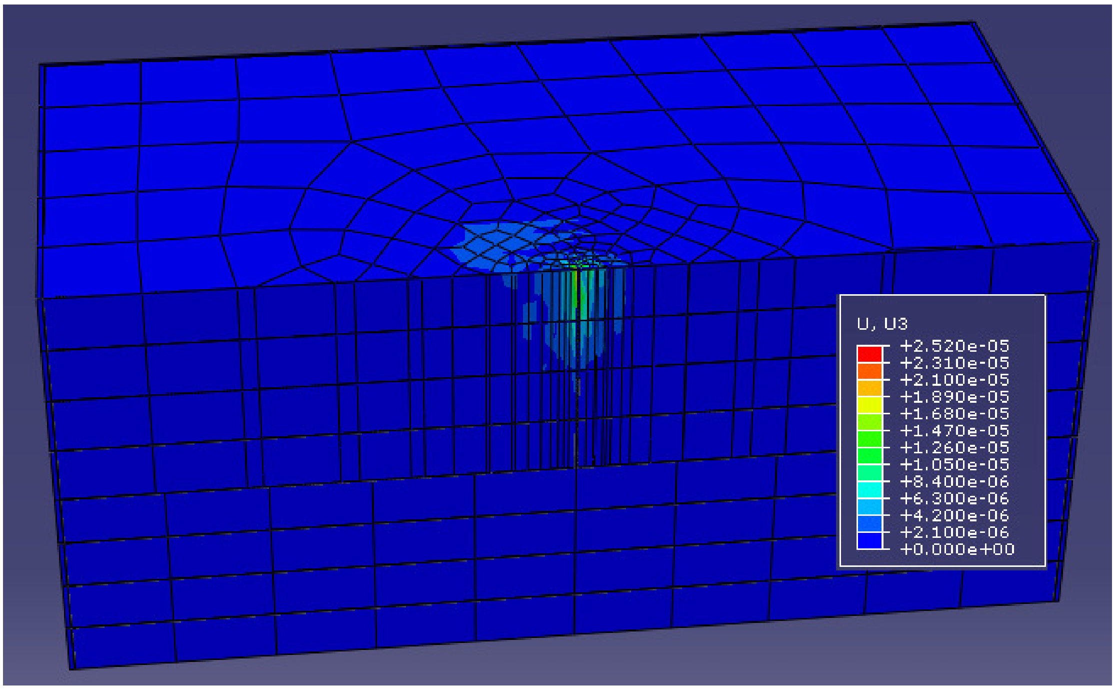
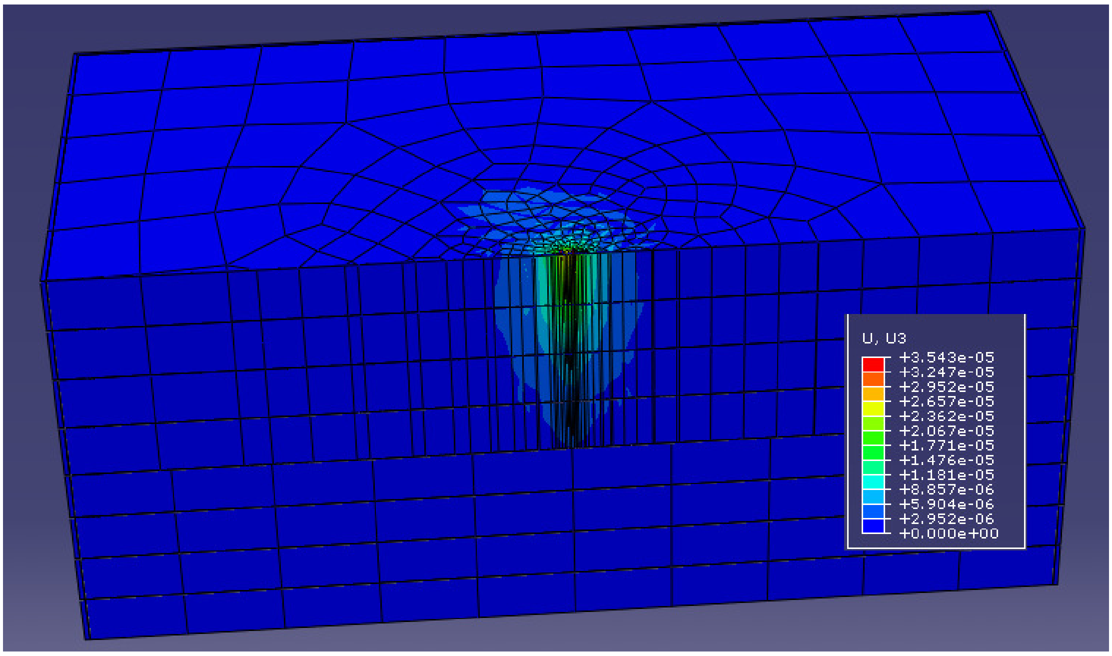
Appendix

3D plots of complex responses

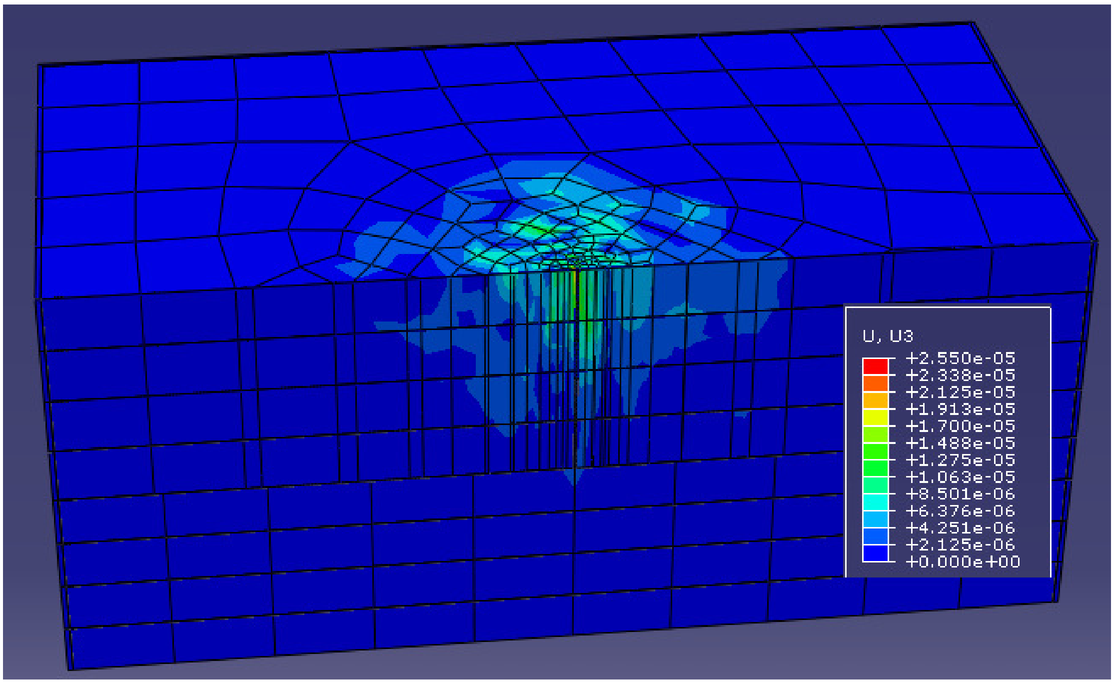


(a) Single pile

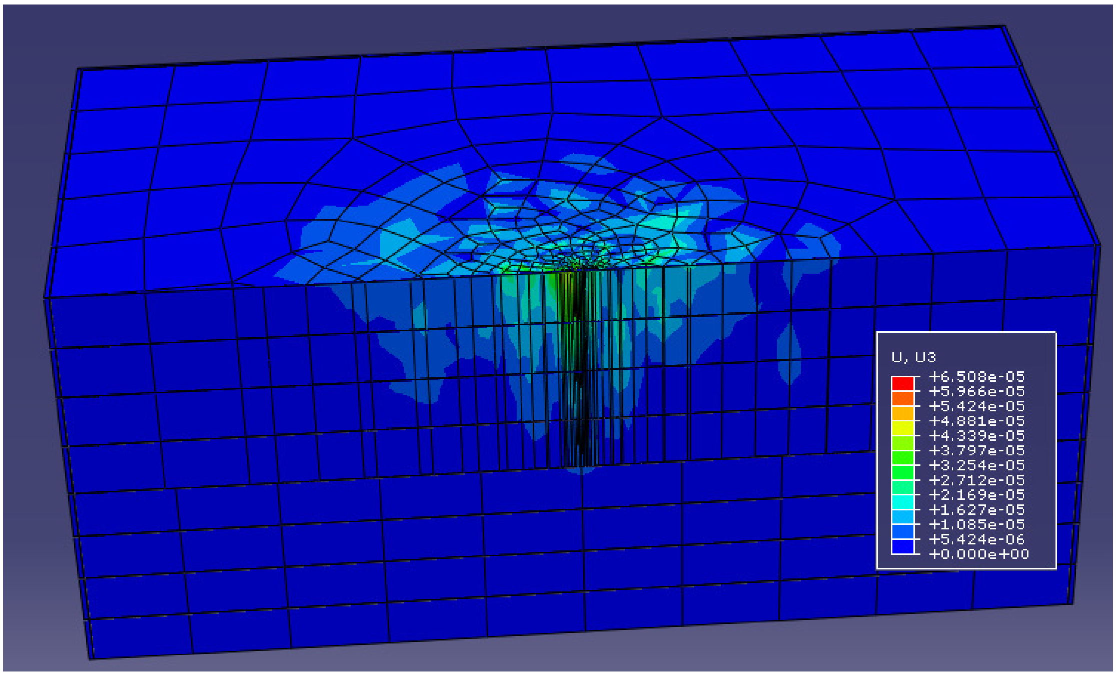


(b) Pile group

A-1 Vertical displacement 3D plot @ f= 0.555 Hz

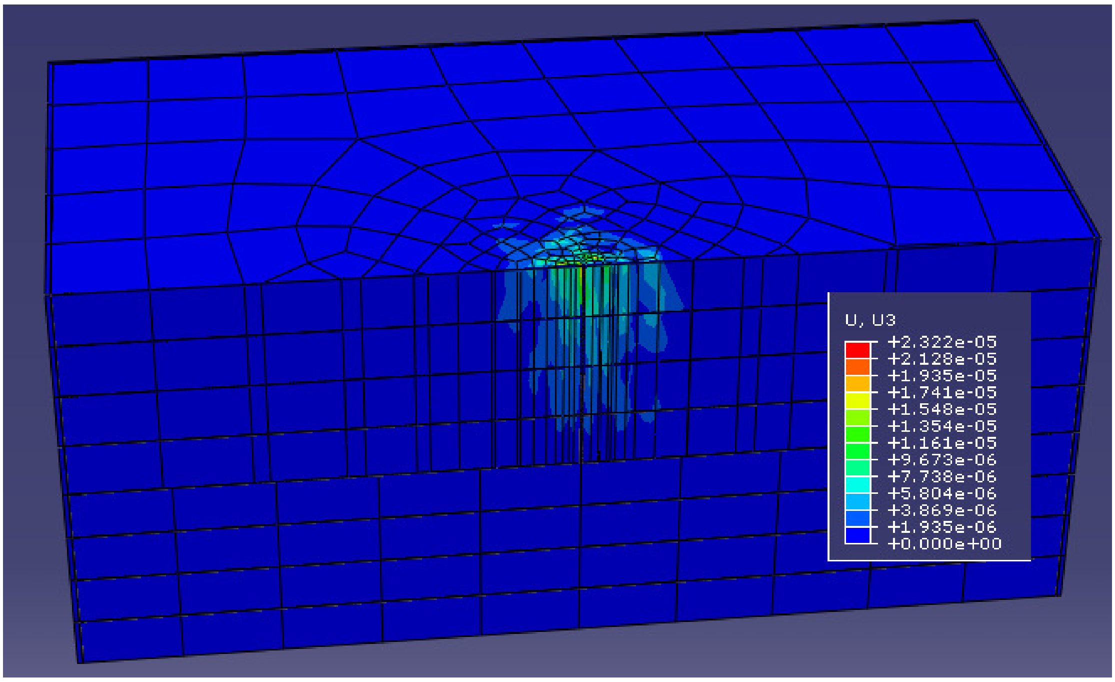


(a) Single pile

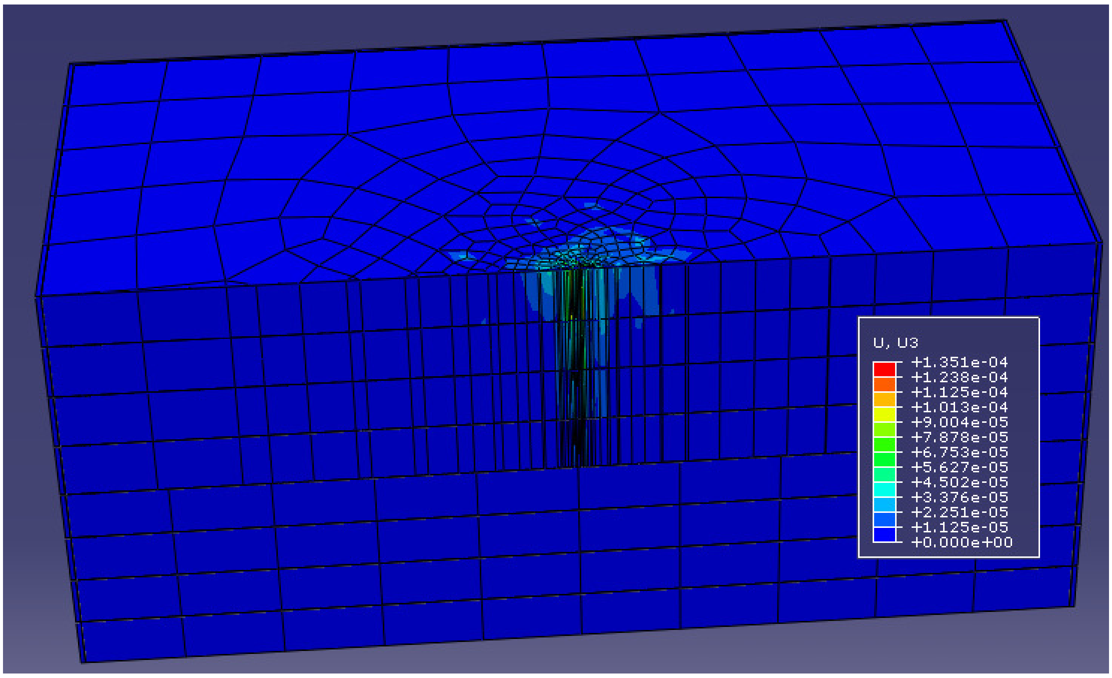


(b) Pile group

A-2 Vertical displacement 3D plot @ f= 2.222 Hz



(a) Single pile



(b) Pile group

A2-3 Vertical displacement 3D plot @ f= 5 Hz