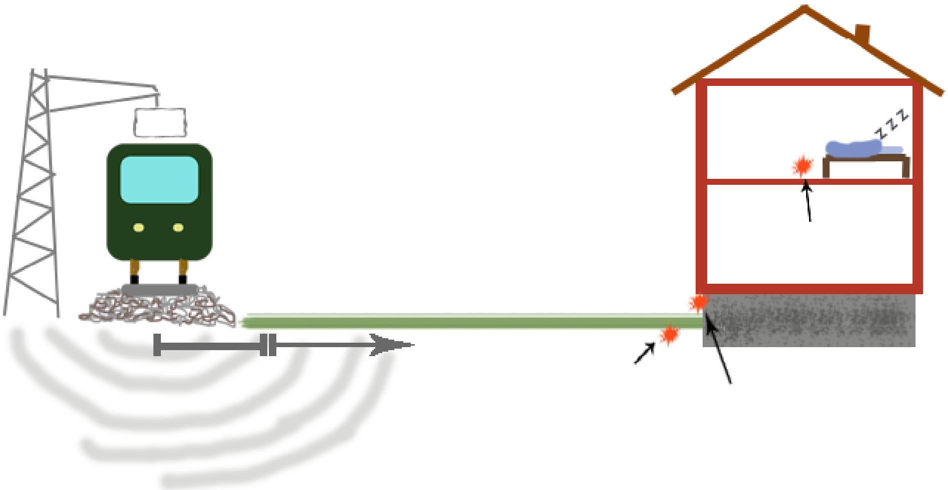
CHALMERS
UNIVERSITY OF TECHNOLOGY



Analysis and Estimation of Residential Vibration Exposure from Railway Traffic in Sweden

Master's thesis in Sound and Vibrations

MATILDA ARNESSON

Department of Civil and Environmental Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

Master's thesis BOMX02-16-146

Analysis and Estimation of Residential Vibration Exposure from Railway Traffic in Sweden

MATILDA ARNESSON

CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Civil and Environmental Engineering
Division of Applied Acoustics
Chalmers University of Technology
Gothenburg, Sweden 2016

Analysis and Estimation of Residential Vibration Exposure from Railway Traffic in Sweden
MATILDA ARNESSON

Supervisor: Alf Ekblad, Trafikverket
Examiner: Patrik Höstmad, Department of Civil and Environmental Engineering

Master's Thesis BOMX02-16-146
Department of Civil and Environmental Engineering
Division of Applied Acoustics
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Railway line with vibration source as well as the measurement positions inside building, outside on foundation of building and in ground close to the building that are used to calculate transfer factors for vibrations between different positions of a building.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2016

Analysis and Estimation of Residential Vibration Exposure from Railway Traffic in Sweden
MATILDA ARNESSON
Department of Civil and Environmental Engineering
Chalmers University of Technology

Abstract

Ground-borne vibrations generated by train pass-byes affect the people living close to railways in Sweden. Not since year 1990 there has been estimates made of the amount of people that are exposed to certain vibration velocities from railway traffic in Sweden. Furthermore there has never been any transfer factors published for the transmission of vibrations between the ground and the foundation of buildings in Sweden. By measuring ground-borne vibrations in the ground while doing measurements in the foundation, data for 51 buildings have been collected from which comparison of transfer factors between ground and foundation have been possible. The data have been analysed as an overall, as well as according to building size and foundation type. The transfer factor between ground and foundation of a building was found to be 0.83 as an overall mean. The majority of the transmission factors are in the range 0.7-1.1 and the transmission factor does not seem to be dependent on if the foundation type is suspended foundation or basement. Multi-dwelling buildings seems to have much lower transfer factor than one-dwelling buildings, but more data for Multi-dwelling buildings is needed to establish if this is statistically correct. In order to estimate the amount of people that are exposed to certain vibration velocities from railway traffic in Sweden, almost 3 000 measurements of vibrations have been classified according to geology at the receiving building. A simple model have been made based on the attenuation of vibrations with distance and on the geology-classified data. Based on geological maps and a database of all properties close to railways, the total number of exposed individuals in Sweden could be estimated. The amount of people where the rms-weighted comfort values are exceeding the vibration levels 0.4, 0.7, 1.0 and 1.4 mm/s were estimated to 54 100, 25 000, 14 200 and 7 300 people respectively. The model for estimation of exposed people could be improved by using more precise soil class information and by including the soil class under the railway in the model. The model could be used to simplify analyses of vibration exposed buildings and to make rough estimates of what vibration level that might affect a building.

Keywords: ground-borne vibration, transfer factor, residential vibration exposure.

Analysis and Estimation of Residential Vibration Exposure from Railway Traffic in Sweden
MATILDA ARNESSON
Department of Civil and Environmental Engineering
Chalmers University of Technology

Sammanfattning

Markburna vibrationer orsakade av tågpassager påverkar de personer som bor nära järnvägsspår i Sverige. Uppskattningar av hur många personer som utsätts för vibrationer, orsakade av järnvägstrafik, över specifika nivåer har inte gjorts sedan år 1990 och överföringsfaktorer för vibrationer mellan mark runt och grundmur på byggnader har aldrig publicerats i Sverige. Genom att mäta markburna vibrationer i marken då grundmursmätningar gjorts har data samlats in från 51 byggnader för jämförelse av överföringsfaktorer mellan mark och grundmur. En överföringsfaktor har beräknats för samtliga byggnader samt uppdelat efter grundmurskonstruktion och byggnadens storlek. Det totala medelvärdet för överföringsfaktorn mellan mark och grundmur beräknades till 0,83. Huvuddelen av överföringsfaktorerna för de analyserade byggnaderna var i spannet 0,7-1,1 och överföringsfaktorn verkar inte vara beroende av om byggnaden är byggd med källare eller torpargrund. Flerfamiljshus verkar ha mycket lägre överföringsfaktor än enfamiljshus, men fler data för flerfamiljshus behövs för att fastslå att det är statistiskt korrekt. För att uppskatta antalet personer som utsätts för vibrationsnivåer orakade av järnvägstrafik i Sverige över specifika nivåer har nära 3 000 mätresultat från vibrationsmätningar klassats utifrån geologi under den utsatta byggnaden. En enkel modell har gjorts baserad på vibrationsdämpning med avstånd för jordartsklassad data. Baserat på geologiska kartor och en databas innehållandes alla fastigheter belägna nära järnvägar i Sverige har det totala antalet vibrationsexponerade personer i Sverige kunnat uppskattas. Det antal personer som utsätts för rms-vägda komfortnivåer över 0,4, 0,7, 1,0 respektive 1,4 mm/s har uppskattats till 54 100, 25 000, 14 200 respektive 7 300 personer. Modellen över antal vibrationsutsatta personer kan förbättras med mer precis information om jordarter och genom att inkludera jordarten under järnvägen i modellen. Modellen kan användas för att förenkla analyser där sannolikheten ska bestämmas att en viss vibrationsnivå påverkar en byggnad.

Nyckelord: markburna vibrationer, överföringsfaktor, *`residential vibration exposure`.

List of publications

This thesis is an introduction to the appended paper as listed below in Roman numerals:

I Arnesson, M. Ekblad, A. Ögren, M. (2016) Residential Vibration Exposure from Railway Traffic in Sweden. In *INTER-NOISE 2016, 45th International Congress and Exposition on Noise Control Engineering*; August 21-24, 2016, Hamburg.

Acknowledgements

This report is a result of a master thesis written at the Department of Civil and Environmental Engineering - Division of Applied Acoustics, Chalmers University of Technology in collaboration with Trafikverket between the fall of 2015 and the fall 2016. The idea of this master thesis have been to use the big set of vibration data that Banverket and Trafikverket have collected throughout the years. There is probably at the moment nowhere else in the world where such large amounts of measurements have been performed and stored in one place.

The idea has therefore been to, with this amount of data together with new measurements, get a better understanding of how many people that are affected by vibrations in Sweden, and how vibrations are transferred from the ground into a structure. The idea for this research was proposed by Alf Ekblad, senior advisor vibrations at Trafikverket and I, after an internship at Trafikverket during the summer 2014.

First and foremost I would like to thank Alf Ekblad, my supervisor at Trafikverket during this thesis work, for coping with the big diversity of both large and small questions I've asked and for letting this thesis be my own work. Also thanks to Peter Johansson, Jesper Lindgren and Linus Karlsson at Trafikverket for cheering me up during bad days, discussing boring subjects and all the small talk during "fika".

Another huge thanks is sent to Mikael Ögren from the unit for Occupational & Environmental Medicine at Gothenburg University. Without your participation, input and good thoughts this thesis had not been what it is.

Peter Falk and P-O Bjelkström at Metron Miljökonsult have been a great help and thank you for letting me participate while doing measurements and for your hospitality at the office.

I would also like to thank my supervisor at Chalmers, Patrik Höstmad for encouraging help and great discussions. I also appreciate the help with translation, explanation of technical terms and valuable comments from Oscar Pagrotsky, Anna Albertsson and Gustaf Arén. A very warm thank you to Hanna Berglund for reading and commenting the whole thesis work.

Last but not least I would like to thank my Johan for your unfailing support and for helping me out of trouble and doubt whenever I have needed it. Also, thank you mom, dad and Viktor for always having belief in me and the very winding roads I sometimes choose to walk.

Matilda Arnesson, Gothenburg, November 2016

Nomenclature

comfort value velocity level measured indoors at floor in there directions, where the signal is rms-weighted (see below).

FFT analysis Fast Fourier transform analysis. An analysis in the frequency domain.

foundation value velocity level measured on the foundation of a building, often in one direction (vertical).

frequency range the actual span of frequencies included e.g. in analyses or produced by a source.

geophone meter used to measure ground-borne vibrations.

GIS Geographical Information System.

ground-borne vibrations vibrations that propagates in ground from a vibrating source.

the nationwide data a collection of data for all buildings in Sweden situated closer to the railway than 200 m (the term is only used for this thesis).

the new guideline the guideline for ground-borne vibrations caused by traffic used in Sweden between year 1997-2015 (the term is only used for this thesis).

the old guideline the guideline for ground-borne vibrations caused by traffic used in Sweden since year 2016 (the term is only used for this thesis).

p-wave primary waves, propagate through compression of the volumes in the ground.

Rayleigh wave surface wave, a combination of shear deformation and dilatation on the surface of a half sphere.

rms-weighted result/signal that is frequency weighted to a root mean square value.

slab on grade *sv.* platta på mark.

suspended foundation *sv.* torpargrund.

s-wave shear waves, propagate through shear deformation of the volumes in the ground.

Västra stambanan the main railway line between Gothenburg and Stockholm.

Authorities and companies

Banverket the Swedish Railway Administration.

COWI consulting group with competencies within engineering, economics and environmental science.

Geological Survey of Sweden *sv.* Sveriges geologiska undersökning.

Lantmäteriet the Swedish mapping, cadastral and land registration authority.

Metron Miljökonsult AB an independent consulting firm focused on measuring influence from infrastructure and construction work in the adjacent environment.

Region Västra Götaland *sv.* Västra Götalandsregionen

Statistics Sweden *sv.* Statistiska centralbyrån.

Trafikverket the Swedish Transport Administration.

ÅF Infrastructure AB consulting company with technical expertise within e.g. environment, sound and vibrations, installations and civil engineering.

Contents

List of Figures

List of Tables

1

Introduction

In this chapter the short history for the railways in Sweden is presented together with earlier estimations of the amount of people affected by ground-borne vibrations. The research questions and limitations for the project is presented as well as the method used to solve the problems.

1.1 Background

The first railway in use in Sweden was opened to traffic in year 1856 (Trafikverket, 2015a). Now the railway system consists of more than 16 500 km of railways, where the Swedish Transport Administration, *Trafikverket*, is responsible for about 14 700 km. Since railways were introduced as a way of transport, the trains have been getting heavier, longer and faster. At the moment (2016) the accepted load per axle is between 22 tons and 25 tons, except on the northern railway *Malmbanan*, where the accepted load per axle is 30 tons (Trafikverket, 2015b). The trend is for even heavier loads per axel and there is also a wish for acceptance of both longer and faster freight-trains.

The traffic load for passenger trains is also increasing a lot, both regarding the amount of journeys and the passenger kilometers travelled (Broberg, 2015). Graphs showing the change of these two parameters quarter-vise since January 2003 are shown in Figure 1.1. As can be seen, the trends for the mentioned parameters are pointing upwards.

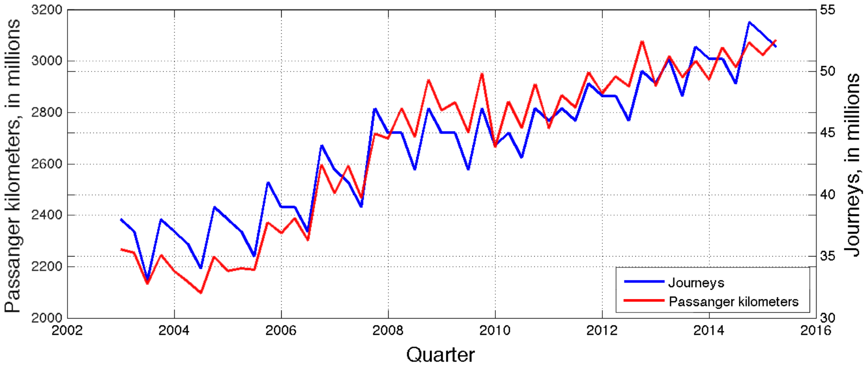


Figure 1.1: *Journeys and the amount of passenger kilometers traveled for each quarter between January 2003 and June 2015 (Broberg, 2015).*

Furthermore, there are also many ongoing European projects dealing with train traffic and the need for increased efficiency on the railways in Europe. One is *Shift2Rail*, were the goals are to cut the life cycle costs of railway, increase the capacity of the railway and make the trains arrive with more punctuality, which will make transportation by railway more reliable (Shift2Rail, 2015). According to *Shift2Rail* there is a need for these changes since Europe and the world faces climate change, a rising traffic demand and security of energy supply as to mention a few challanges.

The Swedish Transport Administration, *Trafikverket*, in charge of the national railway network, have been measuring ground-borne vibrations from trains since before year 1980 (both as Banverket, between 1989-2010 and as SJ, before 1989). The same threshold limit value for *comfort* have been used by the authority since 1997 (Banverket och Naturvårdsverket, 2006). The standard used for measurement is SS 460 48 61, which states that measurements should be performed in a room that is or could be used as a bedroom in three directions for comfort measurements inside the buildings; vertical, along the track and normal to the track (Standardiseringskommissionen i Sverige, 1992). The comfort values are frequency weighted root-mean-square values (rms-value) used for evaluation. A geophone mounted on the foundation of the building is often used to trigger the comfort measurement geophone and usually the foundation geophone only need to measure in vertical direction.

There is no standard in Sweden stating how to measure ground-borne vibrations in the ground. However, this type of measurement is sometimes performed close to an existing building, to find a probable transfer factor for the area between vibration levels in ground and a foundation, to use for estimations of probable comfort levels for new adjacent housing estates. Measurements are also made in ground, with no comparison with vibration levels in foundations for the purpose to establish the vibration level in ground when construction of adjacent buildings are planned. Since no published transfer factors exist for Swedish conditions and railways, the recommendations made for the outcome regarding comfort vibration levels in the planned estates are quite vague. Statistically found transfer factors for Swedish conditions could help make these type of estimations more trustworthy.

1.1.1 Banverkets inventory from 1990

In year 1990 the consultant company DNV Ingemansson AB made investigations for Banverket, now Trafikverket, about the amount of dwellings and railway kilometers that were affected by ground-borne vibration levels above the specified values in Sweden (Pagoldh & Bähler, 1990). No similar investigation have been made since then. There have been a need for Trafikverket to know how the situation with ground-borne vibrations have emerged since year 1990.

The results of the investigations of exposed railway kilometers and apartments presented by Pagoldh and Bähler (1990) are published in a 6 page report from Ingemansson AB. The result from the investigation can be seen in Table 1.1 and the levels 0.5, 1.0 and 2.0 mm/s are classified as light, moderate and strong according to Pagoldh and Bähler (1990).

Table 1.1: *Estimations of the amount of apartments and railway kilometers in Sweden affected by vibration levels above 0.5, 1.0 and 2.0 mm/s in year 1990.*

	> mm/s	railway km	apartments
Mainline network for freight trains	0,5	61 km	3 300 st
	1,0	54 km	2 340 st
	2,0	26 km	920 st
Total railway network	0,5	141 km	6 560 st
	1,0	80 km	3 260 st
	2,0	26 km	920 st

In the report there are two plans mentioned with number S-5967/1-3 and S-5967/4. On the first plan (S-5967/1-3) the vibration situation in general is presented. On the second plan (S-5967/4) the apartments affected by vibration levels above 0.5 mm/s are marked out. These two plans, along with the material that the investigations are based on can not be found in the library or archive of Trafikverket, nor in the archive of DNV Ingemansson AB (now ÅF Infrastructure AB). Also, there are no methods presented in the report, showing how the investigations and estimations have been made.

1.2 Purpose

The purpose of this master thesis is to:

- Investigate the amount of vibrational energy, caused by train pass-byes that is transmitted as ground-borne vibrations, between the ground next to a building and the foundation of the same building.
- Estimate the amount of people along the railways in Sweden administered by Trafikverket that are affected by ground-borne vibrations exceeding the limit values stated in the guidelines that are in use year 2016.

1.3 Research questions

The research questions stated for this thesis work have been:

- What is the mean transfer factor between the ground next to the measured buildings and the foundation of the same buildings?
- Does the transfer factor seem to be independent of the foundation type or the size of the building?
- Does the ground properties below a building affect the probability of high ground-borne vibrations in the building?

- How many dwellings and people are affected by ground-borne vibrations above the vibration levels 0.4, 0.7, 1.0 and 1.4 mm/s respectively?

1.4 Limitations

The following limitations have been made for the project:

- Only vibration data from railways are included in the statistic analysis.
- Trains are, throughout the thesis and for simplification, modelled as a point source, since the distance between railway and dwelling is often relatively large.
- The statistics about the amount of people affected by high ground-borne vibrations are based on data in the database `Projektnavet`. The database contains data from measurements performed for two reasons; measurements that have been performed after complaints from resident about disturbance from traffic, as well as when Banverket have made inventories along the railways. For creating the model in this thesis it is presumed that these dwellings are all the ones with intermediate to high vibration levels in Sweden.
- The outcome of the measurements are not correlated or dependent on the time of the year when carried out, thus if the ground was frozen or not.
- The vibrations analysed are pure ground-borne vibrations. Ground-borne noise caused by ground-borne vibrations have been disregarded.
- The only buildings included in both parts of the thesis work are dwellings. Offices, spaces for education, hospitals and laboratory environments are not included.
- The ground properties (soil classes) represented in the model are the ones below buildings within 100 m from the railways in Sweden administered by Trafikverket.
- It is assumed that the dwellings in the model are only affected by ground-borne vibrations propagating as Rayleigh waves.

1.5 Method

The methods used to complete this thesis work have been the following:

- To complete the theory part and to get knowledge about the subject, a literature study have been made.
- To get measurement data, to see how the data used for the thesis work have been collected and to take pictures for the report the author of the thesis have been assisting in field work with the consultant company*Metron Miljökonsult AB*.
- Discussions have been held and phone calls made with people doing research or working within the field of ground-borne vibrations in Sweden.
- The data collected have been handled within Microsoft Excel-files and comparisons of data and creation of the model for estimating the amount of people affected by ground-borne vibrations, like using the linear regression-method, have been performed with MATLAB. The collected data have been sorted manually by the author.

2

Theory

In this chapter ground-borne vibrations are explained as a phenomenon, both how they propagate in ground as well as into a building and how they are measured according to the Swedish standard for ground-borne vibration measurements. The database `Projektnavet` is described, since data from the database is used for calculations and assumptions later in this report. The statistic methods used to build the model, as well as statistics and ground properties for Sweden used in the model, is explained in detail in the end of the chapter.

2.1 Ground-borne vibrations

Vibrations from a vibrating source propagate in a half sphere or half-space from a point source (Lindberg, 1992). There are mainly three types of waves propagating in ground as a result of a passing train; primary waves, secondary waves and Rayleigh waves. Primary waves and secondary waves are the waves present in whole-space and Rayleigh waves are surface waves only present in half-space. Primary waves, p-waves, are also called compression waves and they are the fastest propagating wave type. P-waves propagate through compression of the volumes in the ground. Secondary waves, s-waves, are also called shear waves and propagate through shear deformation of the volumes in the ground. Figure 2.1 shows the propagation of shear and compression waves seen from the side and next to neutral ground.

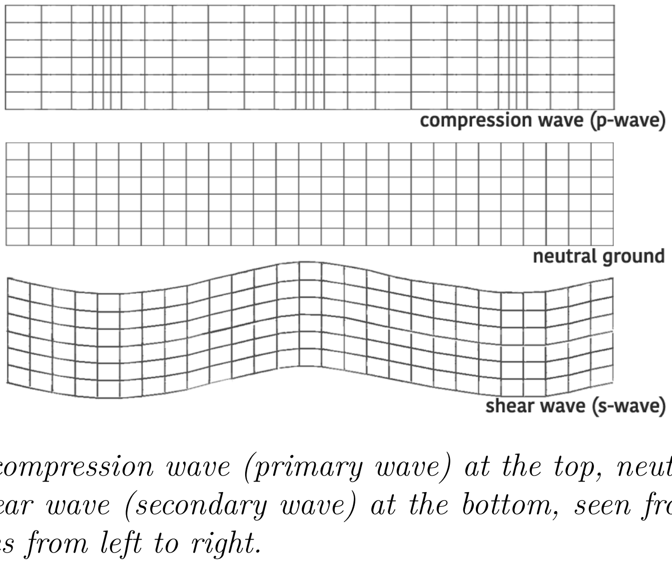


Figure 2.1: *A compression wave (primary wave) at the top, neutral ground in the middle and a shear wave (secondary wave) at the bottom, seen from the side when a wave propagates from left to right.*

The p- and s-waves exist and propagate independent of each other. Their wave speed can be explained as

$$c_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{E}{\rho}\frac{1-\nu}{(1+\nu)(1-\nu)}} \tag{2.1}$$

$$c_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{\rho}\frac{1}{2(1+\nu)}} \tag{2.2}$$

where c_p and c_s are the primary and secondary wave speed respectively, λ and μ are the Lamé constants, E is Young's modulus, ν is Poisson's ratio, G is the shear modulus and ρ is the total density (Lindberg, 1992, Thompson, 2009).

The Rayleigh wave is a combination of shear deformation and dilatation on the surface of a half sphere, since there is a free boundary condition along the surface (Thompson, 2009). The Rayleigh wave propagates from the vibrating source in the same way as the waves on water are rolling from a stone thrown in water (Lindberg, 1992). The particle motion of a Rayleigh wave decrease exponentially with depth, which is why the r-wave mostly affect the surface of the ground. Hence, the r-wave is sometimes referred to as a surface wave. In Figure 2.2 a Rayleigh wave is shown, seen from the side, with the surface rolling in circle-like patterns at the peak in reversed direction from the propagation direction.

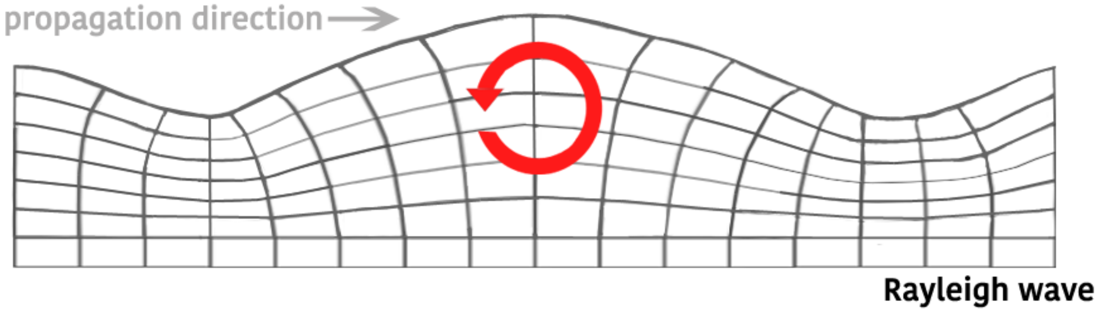


Figure 2.2: *A Rayleigh wave seen from the side.*

Most of the energy from a vibrating source propagates as a Rayleigh wave. According to Lindberg (1992) the energy-relations between the propagating waves are 67 % Rayleigh wave, 26 % s-wave and 7 % p-wave. This holds for a vertical oscillating vibrating source. Rayleigh waves propagates at a velocity around 90 % of c_s, though it depends on poisons ratio, hence $c_p > c_s > c_R$.

The attenuation of a Rayleigh-wave, when the source is seen as an oscillating point source, can be described as the attenuation of energy for an expanding circle. Without material damping and in a perfect elastic material the peak velocity, $\hat{v}$, in ground at the distance r from the source can be described by Equation 2.3.

$$\hat{v} = \hat{v}_1 \left(\frac{r_1}{r}\right)^n, \tag{2.3}$$

where $\hat{v}_1$ is the top velocity at the distance r_1 and n is an attenuation constant. When the particle velocity only depends on the increased distance to the source, the attenuation constant, n, will be n=1/2. When energy losses are included n will increase.

2.1.1 Ground-borne vibration propagation from trains

A train affect the ground underneath with its mass by pushing the ground down, creating a trough (Lindberg, 1992). When the train travels along the railway this trough act like a force in the ground, directed forward from the front of the train and outwards, causing ground-borne vibrations. When the train has passed the mass is taken away which also can give rise to ground-borne vibrations. Both phenomenons are shown in Figure 2.3.

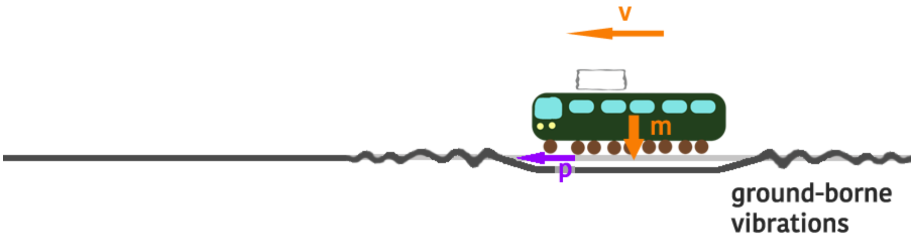


Figure 2.3: *A train travels along a track, pushing the ground below the train down which causes a through in the ground below the train. This through is pushed in front of the train, causing a force which give rise to propagation of ground-borne vibrations.*

The same happens for all the wagons in the train set, which can make the waves of the vibrating volumes to interfere, amplify and reduce each other. Close to the train set both p- and s-waves might exist, making the vibrational pattern uneven. Further from the railway the vibrations have a more sinusoidal pattern, since only Rayleigh waves exist and the highest frequencies are filtered out by the soil. The phenomenon is more common for freight trains, where the wagons and the locomotive are heavy, while for passenger trains the locomotive is heavy, while the wagons often are lighter. Figure 2.4 below shows two typical time-spectra for pass byes of a freight and a passenger train, measured in the ground and on the foundation of the same building respectively.

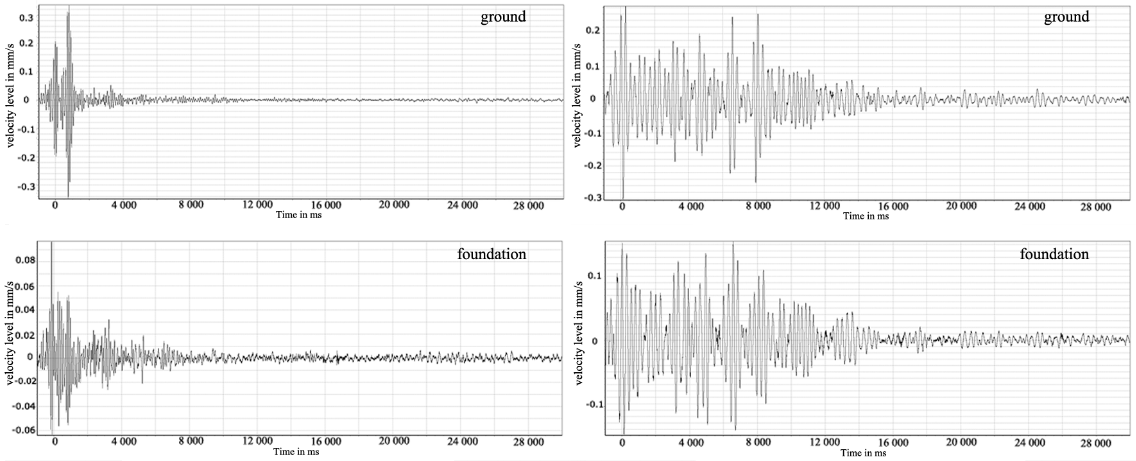


Figure 2.4: *Graphs showing the vibrational velocity as a function of time, to the left for a passenger train and to the right for a freight train. The top graphs shows the velocity to time in the ground and the bottom graphs shows the same result in the foundation for each train respectively.*

When including trains in a model they can be modelled either as a point source (at far distance), as a line source if the point for measurement is close to the railway or as a combination of both, with many point sources in a line (Jonsson, 2000). For point sources the waves are propagating as a half-sphere and for a line source as a half-cylinder. In any case, ground-borne vibrations are damped in ground both from the expanding propagation area of the half-space or half-cylinder as well as from the inner damping of the soil material (Lindberg, 1992). P- and s-waves are attenuated to normal vibration levels close to the vibrating source, while Rayleigh waves, that carry most of the vibrating energy, have a longer propagation distance. According to Lindberg (1992) the p- and s-waves only affect buildings close to the railway (about 20 m or closer), while Rayleigh waves can affect buildings at a distance of 200 m or more. Rayleigh waves are stronger close to the surface and gets more and more attenuated with depth. What makes vibrations from trains even more complicated to modell is that the ground-borne vibrations can start to propagate far ahead of the actual pass-by of a point and the ground can continue to vibrate for a long time after the pass-by, depending on the ground properties.

According to Örström et al. (2011), there is a clear relation between the vibration level in ground and the distance from the railway. Jonsson (2000) also states that there is a difference in wave propagation in two and three dimensions respectively.

Ground-borne vibrations propagate both further and with higher velocity levels the softer the soil is (Hall &Wersäll, 2013). In soft soils, like clay, the through that a vehicle causes becomes deeper which gives rise to larger forces in the ground. Soft soil types also have less inner damping than stiffer soil types.

2.2 Transmission of vibrations from ground and into a building

There are many factors that affect the vibration level caused by a train pass-by; the distance between the building and the railway, the building structure of the building, ground conditions under the railway as well as between and under the building (Lindberg, 1992). Also the weight, weight distribution and velocity of the train, as well as the train geometry and imperfections of the wheel affect the vibration level and frequency spectra of these vibrations (Jonsson, 2000). There are examples in Sweden where the vibration levels have decreased after track maintenance like tamping (Pilman, 2014).

In soft soil types vibrations occur at a frequency of 3.5-6 Hz in Sweden and in stiff soils like till, the frequency of the ground-borne vibrations are higher than 15 Hz, often around 25-30 Hz (Banverket & Naturvårdsverket, 2006).

Vibrations are strong in the foundation of a building during the time of the train pass-by according to Jonsson (2000), but strong vibrations remain in the structure attached to the foundation long after the pass-by as well. Jonsson (2000) also found during a full scale experiment, that only low frequency vibrations are effectively transmitted into the building from the ground.

Ground-borne vibrations can be divided into two types depending on how they are experienced; whole-body vibrations and structure-borne noise (Thompson, 2009). The first type of vibration is felt as the ground or building is swaying or rocking. It is sensible for vibrations between 2 and 80 Hz. The second vibration type is structure-borne noise. The noise is generated by vibrations transmitted in to the structure of a building, causing the walls, floor and ceiling to vibrate. These vibrations then radiate noise indoors. Structure-borne noise is caused by ground-borne vibrations in the frequency range 30-250 Hz. Structure-borne noise sometimes occur in buildings standing on rock or till very close to the railway (Banverket & Naturvårdsverket, 2006). Though, the noise is most common in buildings standing on rock with a passing tunnel underneath.

Also noise caused by train pass-byes can be divided into two kinds; direct noise from the train, like squeals, turbulent air flow, wheel and rail contact or the engine and secondary noise which is the above mentioned structure-borne noise (Thompson, 2009). The different kinds of noise and vibrations are shown in Figure 2.5.

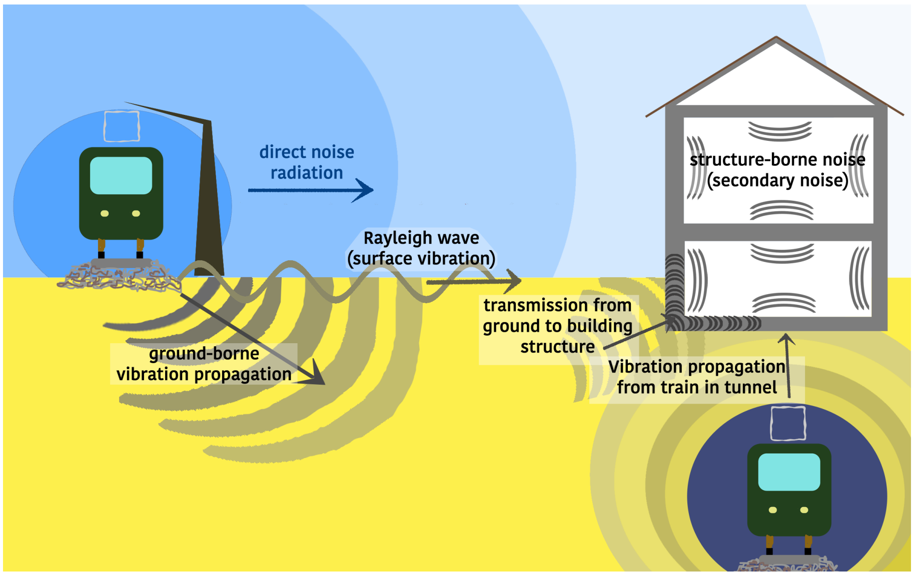


Figure 2.5: *The different types of vibration propagation affecting a building and the noise that can affect the indoor environment of the building.*

2.2.1 Transfer factors in literature for transmission between ground and foundation

In literature different transfer factors can be found for how much the vibration level is reduced or increased when transferred from ground to building. Westerberg (1995) states that for low frequencies the transfer function is close to 1. With increased frequency the amount of vibrational energy transmitted will decrease and around 40 Hz the transfer factor between ground and foundation can be as low as 0.1. The results in Westerbergs studies are not drawn from train pass-byes, but from excitation of the ground by a falling weight.

According to Remington et al. (1987) a building with a slab-on-grade-foundation will get a transfer function of about 1 between ground and foundation, since the area of the slab that is in connection with the ground is large. The same holds for most basement floors. Remington et al. (1987) states the reduction for transmission from ground to foundation will be 4-14 dB in the frequency range 4-63 Hz for 2-to 4-storey masonry buildings on spread footings and 4-7 dB for single family dwellings. The later is though in the frequency range 16-63 Hz and the reduction or amplification is not stated for frequencies below 16 Hz. Also the reference point and quantity is not clearly given and the values may not directly compare to the transfer factors as defined in this thesis. A substantial reduction is though stated.

Remington et al. (1987) also means the transmissions can be amplified in the frequency region 10-30 Hz with 5-15 dB when transfered from the foundation to the walls, floors and ceilings of the building. The amplification is especially pronounced in wood-frame buildings. Also for these numbers the dB-values are foundation levels compared to levels in ground and with no specifications for the reference points in ground.

In many reports from investigations of the situation for ground-borne vibrations in Sweden there are transmission factors given for different foundation types and structural systems. These factors can be seen in Table 2.1.

Table 2.1: *Vibration levels given in reports for transmission of vibration from ground to foundation and to the structural system of the building.*

Transmission ground to foundation with	Amplification factor
pile foundation	0.3
basement constructed as a slab on grade	0.4
slab on grade	0.6
Floor structure	
concrete, short spans	1
concrete, wide spans	3
stiff wooden floor structure	3
weak wooden floor structure	6

2.2.2 Why not a model?

For noise related problems the easiest and most reliable way to get the noise level at a site is through calculations, since the properties of the propagation medium air is relatively the same at all times (Banverket & Naturvårdsverket, 2006). Ground-borne vibrations, on the other hand, are hard to model, since as mentioned above, many things affect the propagation of ground-borne vibrations. The resulting vibration spectra is site-individual and the vibration level can differ significantly, even with small distances between two measured points. The vibration level should therefore be measured at each site to get true levels and no general spectra can be used (Banverket & Naturvårdsverket, 2006, Thompson, 2009). Remington et al. (1987) means that some of the problems with predicting velocity levels through calculations are the variety of the layers with depth for soil and rock layers depending on the point of measurement. Also, even if the structure of the layers are known, there are no information about the viscoelastic properties of the soil at the same spot. The above information holds for calculation of vibration levels for specific buildings, not for making a general model for a large amount of buildings.

2.3 Health and ground-borne vibrations

Ground-borne vibrations are shown to affect the health of people exposed. In this section results from investigations on ground-borne vibrations and health are described.

2.3.1 Ground-borne vibration characteristics and its affection on the sensibility

Guidelines for ground-borne vibrations are in the frequency-span 1-80 Hz (Banverket & Naturvårdsverket, 2006). In Sweden, vibration levels with a frequency below 10 Hz are seen as low frequencies and everything above 10 Hz can be seen as high frequencies [1]. An average for when vibrations can be felt by people is at rms-weighted velocity levels between 0,1-0,3 mm/s for vibrations in the frequency range 10-100 Hz (Banverket & Naturvårdsverket, 2006). According to Banverket and Naturvårdsverket (2006) vibration levels above 0,5 mm/s (rms-weighted) are experienced as clearly distinguishable and levels at 1,2-1,5 mm/s (rms-weighted) are strongly distinguishable. The time period for the vibration episode is important for the experience of the annoyance. Resent studies at Gothenburg University shows that healthy people without sleeping disorders get changed cardiovascular activity during sleep at the velocity level 0,3 mm/s (rms-weighted) and at the velocity level 0,4 mm/s (rms-weighted) the sleep structure starts to change and the sleep gets fragmented (Smith et al., 2015).

2.3.2 Impact on people exposed by ground-borne vibrations

From investigations in the TVANE project in Sweden, results show that noise from road traffic make people more annoyed than noise from railway traffic in areas without exposure of vibrations (Öhrström, E., et al, 2011). In areas with vibration exposure, noise from railway traffic and road traffic make people equally annoyed when present noise levels are up to $L_{A,eq,24h}$=55 dB. Field studies in the project, show that people affected by high ground-borne vibrations gets more annoyed by noise during their sleep than people living in areas without or with low ground-borne vibration levels.

People living in areas with vibration problems get clear negative effects on their sleep from vibration events during nighttime (Öhrström, et al., 2011). It is also shown that, when vibrations are present, people get more aware of noise from the emitting source. When train traffic give rise to emissions as both noise and vibrations the noise has to be 5-7 dB lower to get the same annoyance rate as if the emission just consisted of high noise levels and no vibrations were present. The increased annoyance levels from noise impact when present together with vibrations appear both when people are awake and during their sleep.

2.4 Data, database and statistics

In this section the database and soil maps used for the model is described as well as the statistics used in the model.

---

[1] Alf Ekblad, during conversation, 2015-10-21.

2.4.1 The Swedish standard used to measure ground-borne vibration response in buildings

The standard used in Sweden for measurements of ground-borne vibrations is *SS 460 48 61 - Vibrations and shock - Measurement and guidelines for the evaluation of comfort in buildings* (1992). It is based on the international standard *ISO 2631-2, Human exposure to whole-body vibration - Continuous and shock induced vibration in buildings (1 to 80 Hz)* (Swedish Standards Institute, 2011), which specifies measurements of weighted acceleration and velocity levels. According to *SS 460 48 61*, measurements should be performed in the room where the vibration levels are highest and where the vibration problems seems most annoying. The measurement, called a *comfort measurement*, should be performed in three directions; vertical, along the track and normal to the track. The comfort values are frequency weighted to root mean square (rms) values for evaluation. When measuring ground-borne vibrations caused by traffic the measurement should be performed for an extended time period and the weight used to measure comfort vibrations should have a weight distribution against the floor equal to the weight distribution of a person standing on the floor. A geophone mounted on the foundation of the building is often used to trigger the comfort measurement geophone. The foundation geophone only need to measure in one direction and is used as a reference for the vibration events.

2.4.2 The old and new guidelines in Sweden for ground-borne vibrations from railways and road traffic

There have been a guideline for ground-borne vibrations in Sweden since 1997, that got an updated title in 2006 (Banverket & Naturvårdsverket, 2006). Most measurements that are registered in the database Projektnavet, as well as the measurements performed for this thesis work, have been done according to that guideline, called *Buller och vibrationer från spårburen linjetrafik - Riktlinjer och tillämpning* (*en.* Noise and vibrations from railway traffic - Guidelines and applications). Since January 1, 2016 there is a new guideline in use in Sweden, *Buller och vibrationer från trafik på väg och järnväg* (Blidberg, 2015). To make this report easier to read *Buller och vibrationer från trafik på väg och järnväg* will be called *the new guideline* from now on and the guidelines from 2006 will be called *the old guideline.*

According to Trafikverkets old guideline, the noise and vibration levels to strive for should be planned according to what is technically, economically and environmentally motivated (Banverket & Naturvårdsverket, 2006). At comfort vibration levels above 0.5 mm/s the vibration level could amplify the experienced noise disturbance. The vibration level to strive for, as a comfort level, according to the old guideline is 0.4 mm/s as a long time goal for permanent dwellings, secondary residences and nursing homes. The areas in those buildings where the levels are valid are those where people continuously reside, like rooms for rest and sleep.

In the guidelines the highest acceptable vibration level measured as a comfort value is different depending on if the railway is new, if the railway has been essentially re-constructed or if the building is situated next to a part of the already existing railway (*sv. befintlig miljö*). According to *the new guideline*, for all three cases the long time goal to strive for is 0.4 mm/s, as mentioned above. For a new or essentially re-constructed railway the highest acceptable vibration level is 0.7 mm/s. Those two values are the highest acceptable vibration level and the vibration level to strive for in *the old guideline* for new housing estates. In the old guideline, for an essentially re-constructed railway, the highest acceptable vibration level is 1.0 mm/s. For a building close to an already existing railway the highest acceptable vibration level according to *the old guideline* is 2.5 mm/s and considerations should be made for actions if the vibration level exceed 1.0 mm/s. The exceeding of values in the old guideline is not depending on the number of exceeding events or the time of the day when this vibration event takes place, whereas the new guideline is only valid for nighttime events and the amount of events where the guideline vibration levels are exceeded.

2.4.3 The soil class map of Geological Survey of Sweden compared to the soil class in reality

Geological Survey of Sweden (Sveriges geologiska undersökning, *SGU*) has a map covering most parts of Swedens surface, showing the type of soil and ground properties at sites (Sveriges geologiska undersökning, 2015). Except for soil types, the map show where there are boulders or visible rock on the ground surface. There are also results shown for where boreholes have been made. The maps are made to help out with analyses were the soil type or ground property matters. It shows the topcoat, as well as other shallow soil layers, if the top layer is shallow or scattered. The ground properties are divided according to formation and grain size.

The quality of the soil type map differ, since the method of the mapping differ from area to area, with four main methods for evaluating the soil type (Sveriges geologiska undersökning, 2014). In some areas there have been physical mapping done, in some areas the geology and topography have been analysed with aerial photo. The ocular evaluation of soil type is most common when mapping is performed and observation is almost always done for half a meters depth. The quality also depends on the geological data that the map is based on. This material does not always agree with reality and the soil type or geological formation can sometimes differ with 50-70 m. In general, the maps agree well with reality. The maps are more precise in southern Sweden and close to densely developed areas.

2.4.4 Residents per household in Sweden

The authority Statistics Sweden collects data and compile statistics about Sweden to, among other things, use as a base for research. According to Statistics Sweden living in a freestanding small house (*sv. friliggande småhus*) is the most common way of living in Sweden (Statistiska centralbyrån, 2014a). In those dwellings the average number of residents were 2.7 people in 2013. In average for all households there were 2.2 residents per household in 2013 (Statistiska centralbyrån, 2014b).

2.4.5 Projektnavet

`Projektnavet` is a database provided by the consultant company *COWI* and used by Trafikverket to store all vibration measurements done on their behalf. The database is also used to follow specific projects, such as changing windows in a neighborhood. For each building registered there is also a map showing measurements or achievements on buildings in the area nearby. This feature can help the user to get an understanding of the noise or vibration situation in the area near a building. Documents connected to a building can be uploaded to the database and related to other buildings if the document is of concern for many buildings. The buildings and the information about them are connected to a property-individual key-number and not to the person living in or owning a property, making the information available if the owner of a property is changed.

When a vibration measurement have been performed and a report have been written, the result and the report is added to the database. The values added for a vibration measurement are:

- **Name of project** (*Processnamn*) - the type of investigation or action that have been made, for instance a vibration measurement.
- **The order of the measurement** (*Nummer*)
- **Reference number** - from the company that made the measurement and report.
- **Tags** - what the main investigated source for ground-borne vibrations is, road or railway traffic.
- **Date** (*Datum*) - when the report was finished.
- **Signature** - of the person adding the information in the database.
- **Performer** (*Utförare*) - the company that performed the measurement.
- **Foundation** (*Grundmur mm/s*) - the highest vibration level (peak) in the foundation measured in mm/s.
- **Comfort value** (*Komfort mm/s*) - the highest vibration level in any direction measured as an rms-weighted value in mm/s.
- **Remark vibrations** (*Anm. vibration*) - the amount of days for measuring the ground-borne vibrations at the site.
- **Description of the intervention** (*Beskrivning av åtgärden*) - free script about anything that can be worth knowing about the specific measurement, e.g. if there were a night time value, if there were something special that happened during the measurement or something worth knowing about the measurement site.
- **Status** - with the options 1. Planned, 2. Not considered for action, 3. Done, 10. Not given any status.

2.5 Statistics

In this section the statistic approaches used as method later in this report is presented.

2.5.1 Standard deviation

A standard deviation is the average deviation from the mean value in a set of data (Mattecentrum, 2015a). The smaller the standard deviation, the closer to each other the values in the set of data are. The standard deviation can be calculated with Equation 2.4.

$$\sigma = \sqrt{\frac{\sum \left(x - m\right)^2}{q}} \tag{2.4}$$

where σ is the standard deviation, x is a value in the vector $\overrightarrow{x}$, m is the mean value of the vector $\overrightarrow{x}$ and q is the quantity of values in the same vector.

2.5.2 Normal distribution

For many sets of observed data, in nature and society, the values follow a certain distribution around the mean or median value of the set of data (Mattecentrum, 2015b). The distribution has a hill-like shape with many values close to the mean or median value and fewer values further from the mean or median. The distribution is also symmetric around the mean or median. This distribution is called a normal distribution.

The normal distribution depend on the standard deviation in such way that a low standard deviation gives the normal distribution a high peak and a low standard deviation results in a more spread out distribution of the data around the mean or median. Within one standard deviation on each side of the mean value 68 % of all the observed data will fall and within two standard deviations 95 % of the observed data will appear.

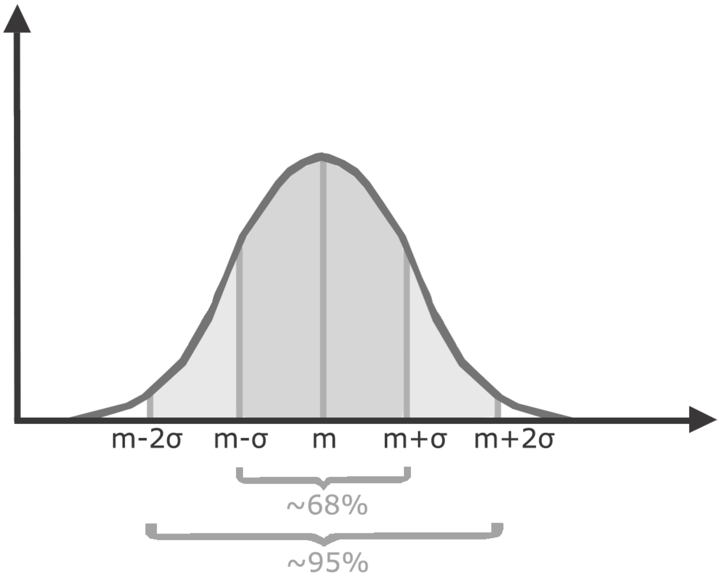


Figure 2.6: *A normal distribution with mean value, m, and standard deviations, σ, to each side of the mean value.*

2.5.3 Outliers in a set of data

An outlier is a kind of extrem value or a sample value that stands out from the mass of data. An outlier can be a correct value but should, according to Ripley (2004), be checked out to verify if there are any possible errors made. Examination of symmetry can be made of graphed data and outliers can also be detected by a box plot or a histogram. According to Nist/Sematech (2003) outliers are often bad data.

3

Methods

In this chapter the methods for vibration measurement are explained as well as how the data is used in the analyses for the two main tasks of the report. The chapter is divided into two parts; analyses of the transfer factor for vibrational energy between ground and foundation and assumptions of the amount of people in Sweden that are affected by ground-borne vibration levels above certain values.

3.1 Transfer factor for ground-borne vibrations from ground to foundation

This part of the reports is about how ground-borne vibrations are transmitted from the ground close to the building and into its foundation. The report contains measurement results from 51 dwellings. Of these, 34 measurements have been performed as part of an inventory of the vibration situation along Västra stambanan in *Region Västra Götaland*, Sweden, which is an on-going project during the time period for this thesis work. The other 17 measurements were performed before the start of this thesis work and were carried out for other projects.

3.1.1 Measurement procedure

All the measurements have been performed according to the guideline *Buller och vibrationer från spårburen linjetrafik - Riktlinjer och tillämpning.*, since the new guideline was set in action on January 1st, 2016.

For the inventory along *Västra stambanan* the company Metron Miljökonsult have made the selection of buildings for measurements as follows:

- All buildings within 100 meters from the railway have been considered possible for measurements.
- The ground conditions for all buildings within 100 meters have been analysed according to SGU:s soil type maps. For buildings standing on rock, no buildings have been measured, buildings standing on clay have been measured if situated within 100 m. For till, all buildings within 50 m have been measured.
- Were the foundation measurement on a building have exceeded 0.6 mm/s for one train pass-by, a combined comfort and ground measurement have been carried out. The selection of buildings to measure have also been based on previous measurements.

- For the foundation measurement the geophone was set to measure for 2-7 days, while ground- and comfort measurement data were collected for 7 days.

For measurements of ground-borne vibrations in ground there is no standard. The measurements of vibration levels in the ground for the inventory of Västra stambanan have been performed in two different ways, seen as equally reliable. The first approach has been to dig a 30-50 cm deep hole in the ground close to the building, place the geophone in the hole and refill the hole with soil, with the geophone leveled horizontal. This procedure is shown to the left and in the middle of Figure 3.1. The other approach has been to attach a geophone to a 10 kg steel plate (size 30 × 30 × 1.5 cm) and place the plate with the geophone leveled on ground, as can be seen to the right in Figure 3.1.

Figure 3.1: *Left: Trigger geophone at foundation and hole for ground geophone. Middle: Leveling the geophone (top), partly covered geophone (middle) and refilled whole with dug down geophone (bottom). Right: Leveled geophone on steel plate placed on lawn and trigging geophone on foundation in the background of the picture.*

For both the dug down ground meter and the steel plate approach, the ground geophone was placed parallel to the railway, about five meters from the corner where the foundation geophone was mounted as in Figure 3.2. For a few measurements the distance was between 1 m and 5 m.

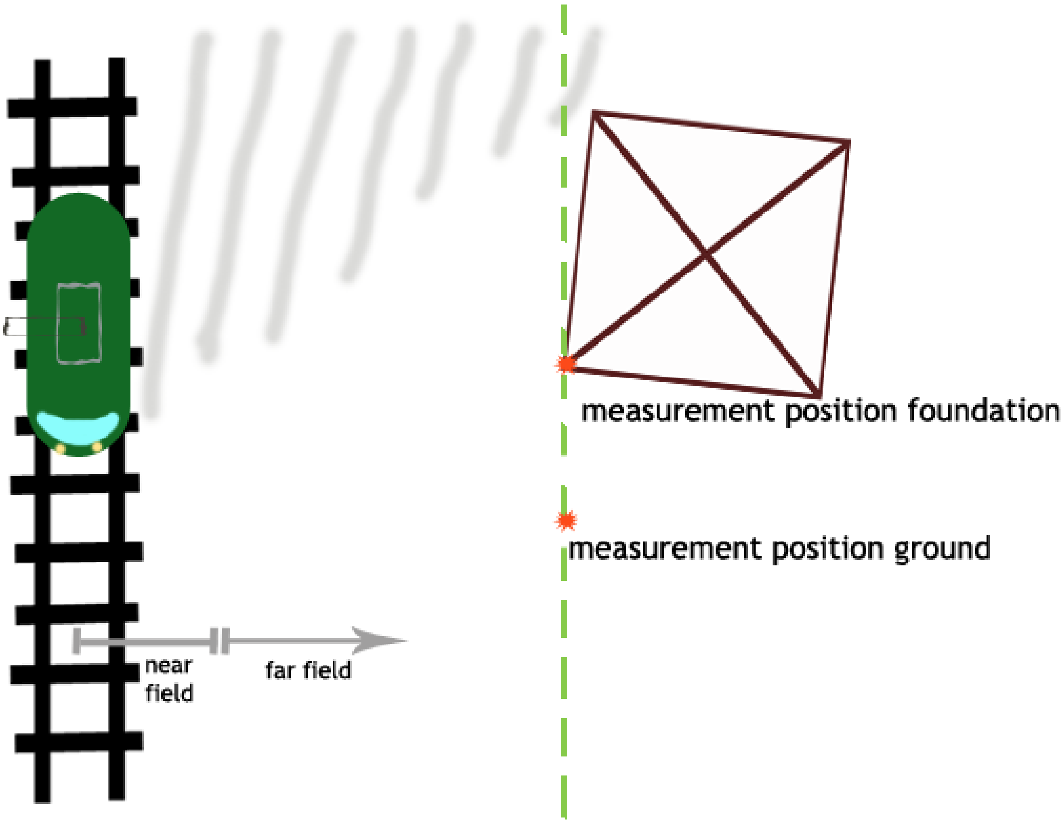


Figure 3.2: *Measurement position for ground geophone as well as foundation geophone.*

The measurements carried out by Metron Miljökonsult, that has not been made as a part of the inventory along Västra Stambanan, have been performed with the geophone dug down in the ground, as is described above. The meter have in these cases been placed in front of or next to the building, within 1-2 m from the foundation. This area is shown as a pink checked line in Figure 3.3 below. Those measurements have often been made to investigate the transfer factors and vibration levels in the specific area, often as a part of an adjacent project.

For the ground measurements in Building 45 and 46, the geophones have been placed on a picket between the building and the road running parallel to the railway (Pilman, 2014). The picket was placed 5 meters from the building towards the railway and 5 meters from the building parallel to the railway as can be seen in Figure 3.3.[1]

---

[1] Carl Pilman (consultant, ÅF Ljud & Vibrationer ÅF Infrastructure) in phone call with report author, February 15, 2016.

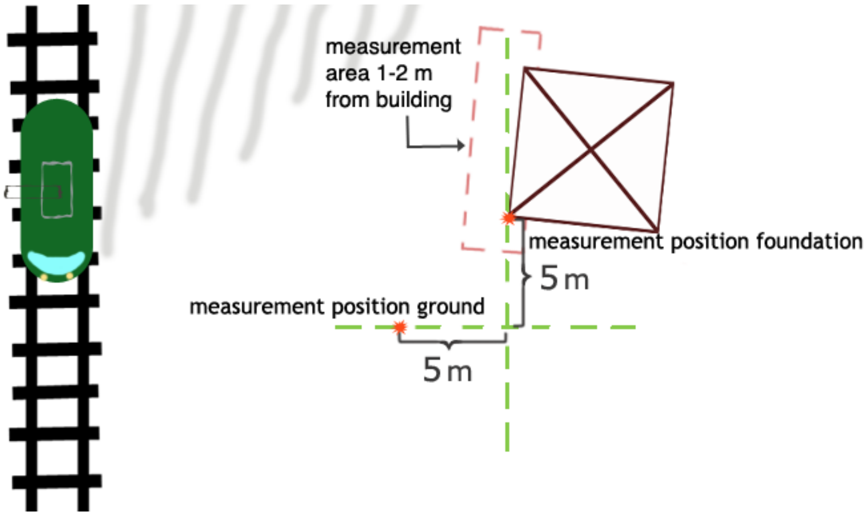


Figure 3.3: *Measurement position for ground meter as well as foundation meter for Building no.45 and Building no.46 shown by the green lines and for the measurement area for previously performed measurements made by Metron Miljökonsult AB shown by the pink area.*

For all measurements, either the system *Sigicom Infra* or the system *Fred* have been used to measure and store the vibration levels at each measurement position. *Sigicom Infra* measures up to five channels and in the frequency range 2-315 Hz, while *Fred 04* measures up to four channels in the range 1-1000 Hz.

The soil type (according to SGU) below each building, the foundation type and structural system of the building as well as if the building is a one- or multi- dwelling building was noticed for all the buildings analysed. The different parameters were observed to make analyses possible from different perspective.

For the collected data only train pass-byes within the frequency span 1-40 Hz have been analysed, in order to sort out results that most likely is affected by measurement noise. This frequency span was chosen since the frequency level for the voltage in the power mains in Sweden is 50 Hz and more measurement noise therefore can be expected around this frequency. Two exceptions from this choice of frequency span have been made, since the most common frequencies for the data for those buildings, dwelling 16 and 17, are above 50 Hz. They are both situated on till, which is why higher frequencies can be expected for the vibration events for these buildings.

There has been a trigger level for most measurements at 0.2 mm/s, both to reduce incoming data from other sources than train pass-byes and to reduce data interference and measurement noise. All values below 0.2 mm/s have therefore been erased for the analyses. The analysed data only contains triggered values and each triggered time period have been 30 seconds for all measurements. For the previously performed measurements there have been Fast Fourier transform analyses (FFT-analyses) made on the data and the train pass-byes have been matched to actual train data provided by Banverket or Trafikverket. For the data collected during the inventory of Västra stambanan there have not been any FFT-analyses performed, but some data where the results have been judged as influenced by measurement noise have been erased.

Out of the 51 buildings where measurements have been performed, one is not included in the analyses. The values for the measurement did not seem accurate for the conditions of the building, which is why FFT-analyses was made on the measurement result. The FFT-analyses showed that there seems to be measurement noise around the frequency span 40-50 Hz for all the triggered results.

3.1.2 Dealing with measurement data

All collected data for each building have been stored in an Excel-file. The files were then imported to and processed in the matrix-based analysis program MATLAB.

For each train pass-by the transfer factor has been calculated as the part of the vibration level that is transfered from the ground and into the foundation, as in Equation 3.1.

$$transfer\ factor = \frac{vibration\ level\ at\ foundation}{vibration\ level\ in\ ground} \tag{3.1}$$

The mean value and standard deviation for each building have been calculated from all the separate train pass-byes. A histogram for all the transfer factors as well as two graphs with transfer factor as a function of frequency, both the main frequency registered in the ground and in the foundation, are plotted for each building. The plots are described in Section 4.1 and can be seen for all buildings in Appendix A.

The total mean transfer factor was calculated as a mean value of the mean transfer factors for each building. Total mean values are also calculated for buildings with basements and buildings with suspended foundation, as well as for one- and multi-dwelling buildings.

Outliers have been detected in the plots for transfer factor over frequency, shown as an example in Figure 3.4 for building no. 37. The outliers have also been studied closer in the database of Metron Miljökonsult, to see if there were any measurement noise in the recordings or if the triggered recording was not caused by a train pass-by etc. Most outliers have been erased since they often turned out as not representative values, containing many errors or measurement noise.

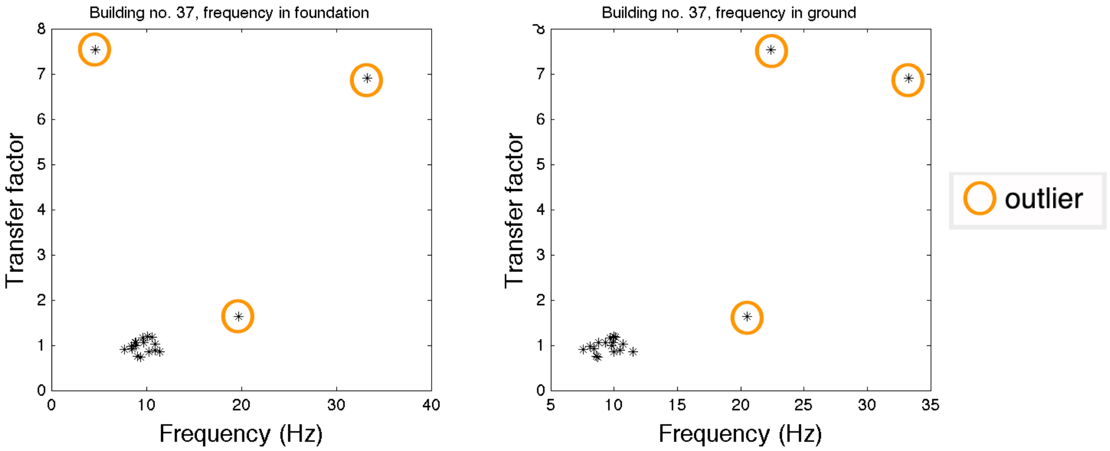


Figure 3.4: *Transfer factor for Building 37, plotted as a function of frequencies, with outliers still present.*

Two of the buildings included in the analyses (Building no. 1 and no. 2) did not contain any information for the registered result about the frequency spectra of the vibration event. The only information about frequencies for these results are that it peaked around 5 Hz for all train pass-byes. No frequency analysis has therefore been made on these buildings, but the results for the measurements have been analysed in the frequency domain (FFT-analysed) by Metron Miljökonsult AB.

3.2 Estimation of the amount of people affected by ground-borne vibrations above the levels recommended by the guidelines in Sweden

In this subsection the processing of the data used to make up a model to estimate the amount of people affected by ground-borne vibrations above certain levels is described. The mathematics of the functions that the model is based on is also described.

3.2.1 Processing of data

To be able to make estimations of how many people that are affected by high ground-borne vibrations, two types of data have been used. To collect information about all buildings situated closer than 200 m to the railway system in Sweden, and through this be able to apply an attenuation model regarding vibrational energy for the whole country, data have been compiled by the company COWI through a geographical information system, GIS. This collection of data will through the rest of this report be called *the nationwide data.*

To make a model over how the vibrational energy is damped as a function of distance, the measurement values in the database *Projektnavet* have been used. The data compiled from *Projektnavet* have been exported as an Excel-file by COWI, and the set of data used for the analyses are all data added to the database before november 23rd, 2015. The data compiled from *Projektnavet* are all data were the distance between the building and the railway is less than 500 m. The information in the file includes the ground property below the building and below the railway, the shortest distance between the railway and the closest point on the building as well as the type of building according to *Lantmäteriet*, which is the Swedish mapping, cadastral and land registration authority. The highest vibration level registered in the foundation of the building as well as a comfort value registered indoors was included for each building. So was the tag for the measurement if that information had been registered.

All buildings with the tag *väg* (meaning *road*) have been erased since these are specified as investigations of vibrations caused by road traffic. The distance used is the distance from the building to the main railway track, hence the railway track in GIS that is designated as the main track. The distance can therefore be longer or shorter for a certain train pass-by for some buildings depending on which track the train was passing on.

All buildings categorized as *unspecified* by *Lantmäteriet* have been investigated to learn if they are or could be a dwelling. Buildings situated on the soil classes *water* and *till alternating with sorted sediments* have been researched in documents and on Google maps. The soil class has then been changed to a more probable type.

The different soil types or bedrock types that are stated for the buildings in *Projektnavet* or *the nationwide data*, have been sorted into a total of ten groups with similar ground properties within each group. These can be seen in Table 3.1. The soil types written in italics are the types that are only present in the collection of *nationwide data*. Soil types containing two or more soils have been sorted after the component considered to have the poorest properties for this study. For instance a soil type that includes some kind of clay, as *Clay till, clay content >25%* have been sorted as clay.

Table 3.1: *Soil types grouped together to simplify the measurement model. The soil types in italics are only present in the nationwide data and not represented among the buildings in Projektnavet.*

Clay	**Silt**
Glacial clay, clay content >25%	Postglacial coarse silt to fine sand
Glacial clay, clay content 15-25%	Glacial silt
Glacial clay	Postglacial coarse silt
Gyttja clay (or clay gyttja)	Postglacial silt
Clay	Silt
Clay-silt	Fluvial sediment, coarse silt to fine sand
Clay till, clay content >25%	*Young fluvial sediment, coarse silt to fine sand*
Postglacial clay, clay content >25%	*Young fluvial sediment*
Postglacial clay	*Fluvial sediment*
Young fluvial sediment, clay to silt	
Fluvial sediment, clay to silt	
Postglacial clay, clay content 15-25%	
Gyttja	
Water	
Sand	**Till**
Glaciofluvial sand	Till
Postglacial fine sand	Sandy till
Postglacial sand	Silty to fine sandy till
Sand to gravel	*Gravelly till*
Young fluvial sediment, sand	*Fluvial sediment, cobbles to boulders*
Fluvial sediment, sand	
Aeolian sand	
Glaciofluvial sediment	**Artificial fill**
Glaciofluvial sediment	Artificial fill
Clay till	**Rock**
Till, clay content 5-15%	Rock
Clay till, clay content 15-25%	Sedimentary rock
Clay till or clayey till	Crystalline rock
Clay till	*Cobbles to boulders*
Gravel	**Peat**
Glaciofluvial gravel	Fen peat
Wave-washed gravel	Peat
Fluvial sediment, gravel	*Bog peat*

There are some soil classes present in the nationwide collection of data that are not included in any of the ten groups, since they have been hard to sort in a reliable way. These soil classes are presented in Table 3.2. There is not a large amount of buildings situated on these soil classes. In the excluded group, buildings without soil types presented by SGU (unspecified) are included. One large area where the soil classes were missing during the time of research for this project was around Falköping in *Region Västra Götaland*.

Table 3.2: *Soiltypes that are not included in the model.*

Excluded soil classes
Shingle
Till alternating with sorted sediments
Unclassified unit
Unclassified unit, partly under water
Talus (scree)
Water
Saprolite

After the soil classes were grouped together, the data in the large Excel-file was redistribute into the different soil class groups. Since the information about soil classes was provided for the building and for the nearest spot on the railway for each building, the redistribution was made both according to the soil class under the railway as well as the soil class below the building. The vibration level at the foundation was then plotted as a function of distance between the railway and the building. Such plots are shown for the clay group in Figure 3.5, sorted according to soil class below the railway and below the building respectively.

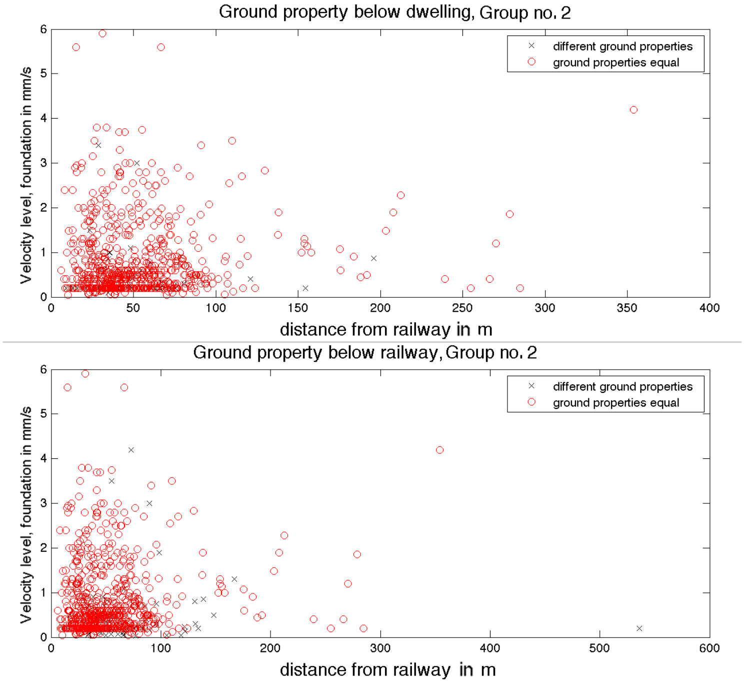


Figure 3.5: *Velocity level in foundation plotted as a function of distance between railway and building. The top graph shows results were the ground property under the buildings is clay and for the bottom graph there is clay under the railway.*

All plots have been analysed for outliers and most values that could be an extreme value have been investigated. For many outliers the ground property have been assumed as set wrong by SGU due to the resolution of the map. If that has been the case the ground property was changed into one more probable. Other errors have been a removed railway or that the wrong building is assigned to a certain set of values. For these cases the distance have been changed. For some outliers the investigation have been for road traffic and in a few cases the investigations have not been made correct, resulting in overestimated results. For the last two cases all the results have been erased for the specific building. The outliers have been checked up in reports regarding the performed measurements, in google maps, and in `Projektnavet`. The new distance have been measured in Trafikverkets map system `Stigfinnaren`.

3.2.2 Modelling a curve

In this subsection the construction of the model for the estimations of the amount of people affected by high ground-borne vibrations are described. One assumption has been that the vibration level decrease when the distance between the vibration source and the building is increased. Another assumption has been that only surface waves, i.e. Rayleigh waves, are causing ground-borne vibrations that affect buildings. As stated in Chapter 2, the attenuation of Rayleigh waves in ground can be described by the simplified relation

$$\frac{1}{r^n}. \tag{3.2}$$

where r is the radius of the circle or the distance to the point of the force and n is an attenuation constant (Auersch, 1994). For the theoretical case of a point source on an infinite half-space n will be 0.5 far from the source for Rayleigh waves. If any damping is introduced n will be higher than 0.5. When the velocity level v_0 at the distance d=0 is v_0=m, the velocity level v at a certain distance can be presumed to be

$$v = m \cdot \frac{1}{d^n}. \tag{3.3}$$

With energy losses included the constant n is increased to the constant k and the velocity level v at the distance d can be calculated by Equation 3.4

$$v = \frac{m}{d^k}. \tag{3.4}$$

For this thesis work the distance and velocity level for a large amount of buildings are known and sorted according to ground property. By using linear regression the constants k and m can be found as a mean of all the input data. The relation with the velocity level depending on the distance to the vibrating source can also be written as:

$$log_{10}(v) = log_{10}(m) - k \cdot log_{10}(d). \tag{3.5}$$

By exchanging $log_{10}(m)$ by a, k by b, $log_{10}(m)$ by y and $-log_{10}(d)$ by x, the equation will be transformed to a straight line on the form:

$$y = a + b \cdot x. \tag{3.6}$$

Using the command `polyfit` in MATLAB gives the result for linear regressions for a straight line on the form

$$[b, a] \tag{3.7}$$

Since the constant a can be calculated as in Equation 3.8, the constant m can be written as

$$a = log(m) \Leftrightarrow m = 10^a. \tag{3.8}$$

The results from the linear regression will be given as the two coefficients

$$[k, 10^a]. \tag{3.9}$$

with descending powers for a polynomial. The mean velocity v_m at a certain distance d can then be calculated using Equation 3.10

$$v_m = 10^{log_{10}(m) - k \cdot log_{10}(d)}. \tag{3.10}$$

To be able to use the model for as much data as possible the standard deviation was calculated for the input velocity levels. To calculate the standard deviation Equation 3.11 was used;

$$\sigma = \sqrt{\frac{\sum \Big(v(d) - v_m(d)\Big)^2}{q}} \tag{3.11}$$

where σ is the standard deviation and q is the quantity of velocity values. Multiplying the mean velocity function with two standard deviations, as in Equation 3.12 will result in a function which 95% of all probable results will end up below.

$$v_\sigma = 2 \cdot \sigma \cdot v_m \tag{3.12}$$

Figure 3.6 shows the input velocity values, the mean velocity function and the mean velocity function multiplied with two standard deviations for the soil class group Clay.

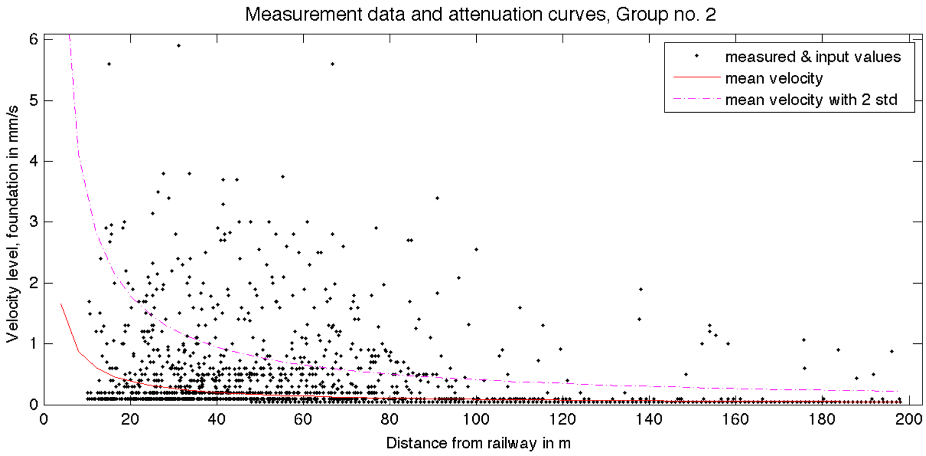


Figure 3.6: *The input velocity values for the soil class group clay, shown as dots, the mean velocity function (the full line) and the mean velocity function with two standard deviations included (crosshatched line) for the same soil class group.*

3.2.3 Inserting input values to the model

When analysing the nationwide data for buildings close to the railway, they are in general spread out with the same density at all distances from the railway. For the model and for the functions for each soil class group it can therefore be presumed that there will be many buildings without any or with low vibration problems. All buildings with a registered foundation vibration level in the range 0-0.2 mm/s are set to the vibration level 0.1 mm/s. The levels in the range 0-0.2 mm/s are hard to measure in a reliable way because there is often a big influence of background noise and noise within the instruments etc that influence the registrations. However, since the a vibration measurement have been performed it indicates that there have been problems with ground borne vibrations in the particular estate.

To make up for the loss of buildings exposed to low vibrations that are not even present in *Projektnavet*, input values have been made up and inserted into the model. The area where vibrations are investigated are divided into five equally wide spans. The amount of buildings with a registered vibration level in the foundation, that is situated within the span closest to the railway, is assumed to be the total amount of buildings that could be situated in a span, $n_{span,1}$. In $n_{span,1}$ all the foundation values with velocity level 0.1 mm/s are included.

The other spans will consist of the quantity of buildings with a registered value in the span as well as an amount of input values. The amount of input values will be the difference between $n_{span,1}$ and the amount of registered values in the specific span, $n_{span,X}$. An illustration of this approach is shown in Figure 3.7.

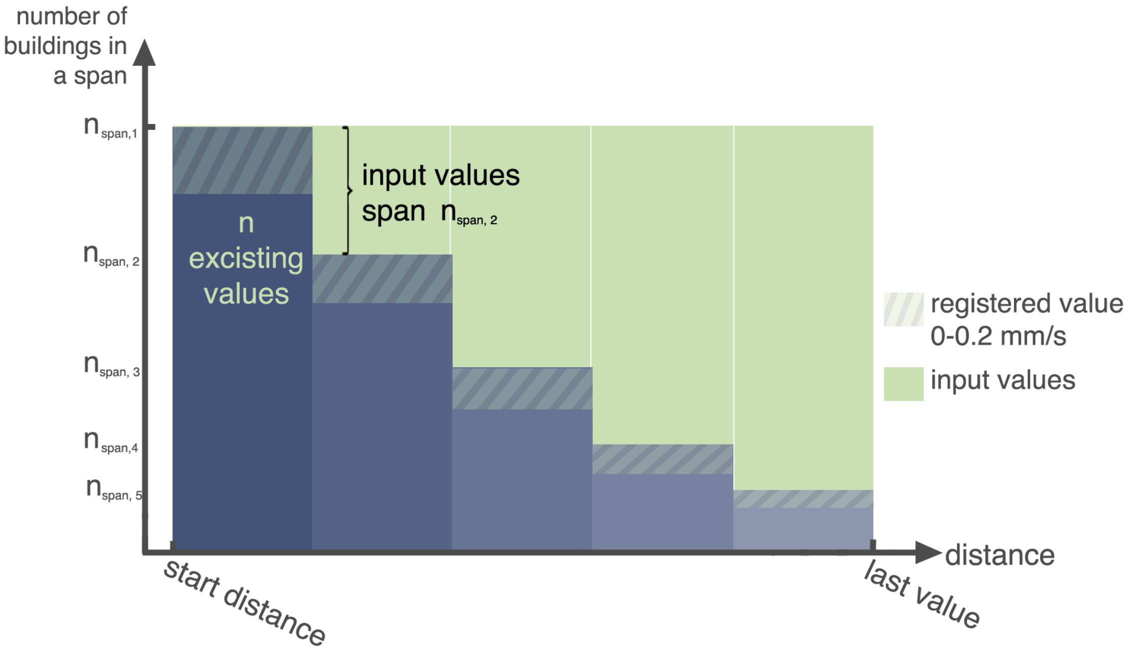


Figure 3.7: *An illustration of how the input values are made up.*

All the input values are set to a vibration level of 0.05 mm/s and the distances for all the input values within a span are set to a random distance within the specific span by using the command `rand` in MATLAB.

3.2.4 Transfer factor for transmission from foundation to comfort value

The transfer factor for transmission from foundation to comfort value is calculated from the vibration level measured in the foundation compared to the vibration level given as an rms-weighted comfort value, measured on the floor, inside the same building. Since the value of the foundation level is an unweighted value and the comfort value is frequency weighted and root-mean-squared, the transfer factor will not be a correct statistic value, but is seen as a hint of the relationship between the two values. The transfer factor for the transmission between the foundation and the comfort value for a single building is calculated as

$$TF_{fc} = \frac{v_{rms,comfort}}{v_{foundation}}, \tag{3.13}$$

where TF_{fc} is the transfer factor for the transmission of vibrations from the foundation of the building and into a bedroom of the building, $v_{foundation}$ is the vibration level in the foundation of the building and $v_{rms,comfort}$ is the rms-weighted comfort value. The transfer factor have been calculated as a mean value for all buildings regardless of soil class group, where both a foundation level and an rms-weighted comfort value is registered and where both values are larger than or equal to 0.2 mm/s. The transfer factor has been presumed to be independent of soil class as well as other factors, like structural system or building size etc. The transfer factor between foundation and rms-weighted comfort value for all buildings is therefore a general transfer factor.

3.2.5 Applying the model for estimation of high ground-borne vibrations on the nationwide data

The base for applying the model for estimation of high ground-borne vibrations is the collection of nationwide data, mentioned in subsection 3.2.1. The data is found in a file compiled by COWI, containing data about all buildings in Sweden closer than 200 m to any kind of track for transportation. Except for the nationwide railway lines, the tracks in the file includes tram tracks, museum- or historic railways as well as abandoned tracks. For the estimations described in this thesis only buildings close to railways administered by Trafikverket is included. The other buildings in the file has therefore been excluded from the large file.

The model is applicable for the area further from the railway than 10 m. The area closer to the tracks have been seen as situated in the near field for vibration propagation, where other phenomenons than surface waves can be assumed to affect the velocity level. Very few buildings are located in the area 0-10 m from the railway, why an assumption was made that the quantity of buildings in the area 10-200 m is the same as in the area 0-200 m.

The area 10-200 m have been divided into 19 different 10 m-wide spans. Since the density of buildings in the analysed area is equally distributed at all distances, the quantity of buildings for each soil class group was divided into equally many groups, hence the total amount of buildings divided by 19. The maximum expected velocity level $v_{\sigma,spanX}$ in the foundation of a building was extracted from Equation 3.12 for the shortest distance (railway to building) in each span. Figure 3.8 below illustrates how the spans are made up and how $v_{\sigma,spanX}$ is found.

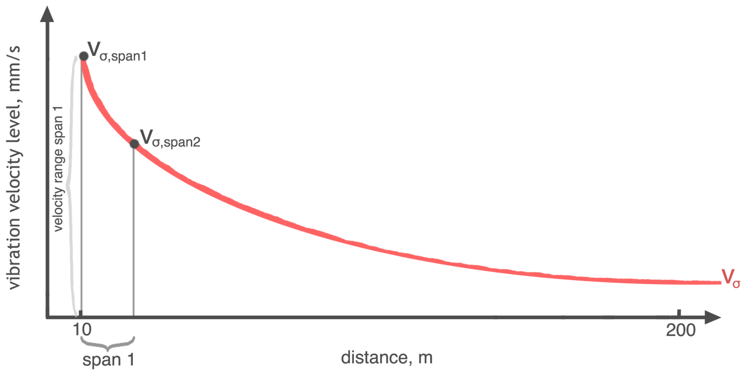


Figure 3.8: *How the spans are made up and $v_{\sigma,spanX}$ is found. All in all there are 19 in each model.*

All buildings in each span is assumed to be evenly disseminated between 0 and $v_{\sigma,spanX}$, why a vector was created with vibration levels in the velocity range of the span, $[0, ..., v_{\sigma,spanX}]$. The velocity levels in the vectors are modelled vibration levels in the foundations of the modelled buildings. To transform the foundation levels into comfort levels all vibration levels have been multiplied with the mean transfer factor from the foundation of the building to the indoors comfort value, TF_{fc} in Equation 3.13.

The 19 vectors, one for each span, has been created for all the ten soil class groups respectively and the vectors for each span make up a large matrix for each soil class group. The quantity of values in each matrix above the recommended vibration levels, as stated in the two guidelines for noise and vibration from road and railway traffic in Sweden, was found for the vibration velocity levels stated in Table 3.3 below.

Table 3.3: *The amount of buildings and people affected by ground-borne vibrations exceeding certain comfort vibration velocity levels have been found for the following comfort levels.*

Vibration velocity levels in mm/s
0.4
0.7
1.0
1.4

To get overall results, the quantity of modelled results exceeding a certain velocity level was added from each soil class. The modelled amount of buildings exceeding a certain vibration level have also been multiplied with the average amount of people living in a one-dwelling building in Sweden.

4

Results

In this chapter the results are presented from the investigation of transmission of ground-borne vibrations between ground and foundation of a building. Results are also presented for the estimation of the amount of people affected by ground-borne vibrations above the levels recommended by the guidelines in Sweden.

4.1 Transfer factor for ground-borne vibrations from ground to foundation

For each building a histogram has been created, showing the transfer factors sorted into 30 equally spaced bins along the x-axis. The amount of values in each bin is shown by the bars as *Quantity*. To make the histograms comparable, the x-axis is set from 0 to 2.0 for all histograms, making the thickness of the bars to differ. A thick bar will show a large span between the minimum and maximum value, while a thin bar means the span is short. Histograms for Building no. 9 and Building no. 10 are shown in Figure 4.1. To see all histograms for all buildings see Appendix A.

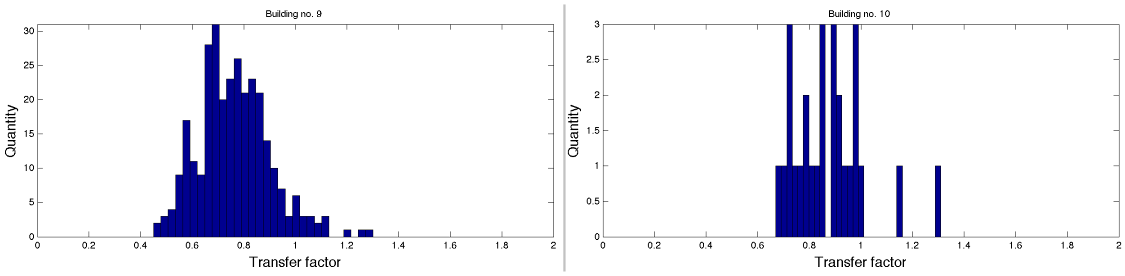


Figure 4.1: *Histogram over transfer factors for Building no. 9 (left) and Building no. 10 (right).*

For each building, the transfer factor have been plotted as a function of frequency in two plots, based on the frequency registered by the foundation mounted geophone or by the geophone placed in ground. The frequency plots for Building no. 9 and 10 can be seen in Figure 4.2 below.

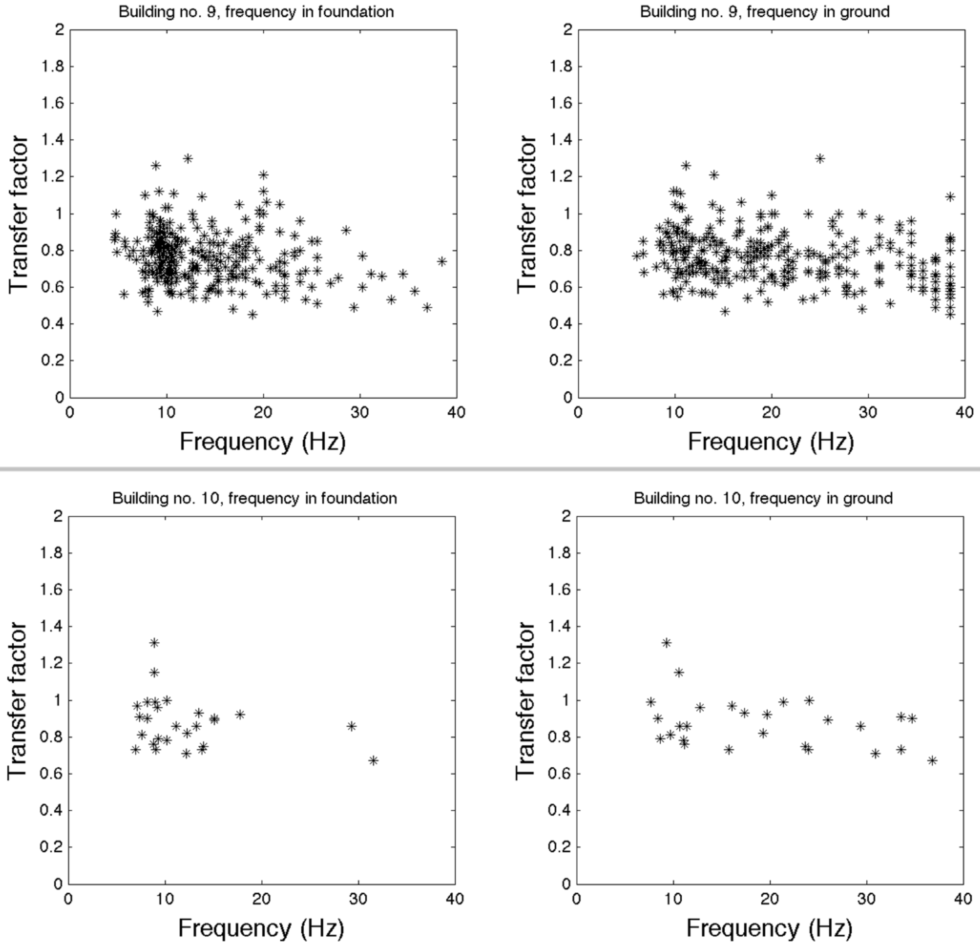


Figure 4.2: *Transfer factors plotted against frequency, registered by the foundation geophone (to the left in the figure) or by the ground geophone (to the right in the figure) for Building no. 9 (top) and Building no. 10 (bottom).*

Plots showing transfer factor as a function of frequency for all buildings can be seen in Appendix A.

In Table 4.1 below information are shown about all buildings where transfer factor analyses have been made. The information stated is the municipality where the building is situated, soil class under the building, type of building (size), foundation type and the mean transfer factor for the specific building. The building number is just a designation to keep the buildings apart with no rank.

Table 4.1: *Data for each building in the analysis. To keep the size of the table small some abbreviations have been made up. These are explained at the bottom of the table.*

Building no.	Municitipality	Foundation building*	Soil class building**	one or multi-dwelling	fft-analysed	Transfer factor
1	Partille	basement	gl. clay	one	yes	1,0
2	Partille	basement	postgl. fine sand	one	yes	1,1
3	Nyköping	basement	gl. clay	multi	yes	0,7
4	Nyköping	basement	gl. clay	multi	yes	0,8
5	Kramfors	basement	sand	one	yes	0,8
6	Alingsås	basement	clay	one	yes	1,0
7	Lerum	basement	clay	multi	yes	1,0
8	Töreboda	susp. found.	sand	one	no	0,8
9	Töreboda	susp. found.	sand	one	no	0,8
10	Töreboda	susp. found.	gl. fluv. sed.	one	no	0,9
11	Töreboda	susp. found.	gl. fluv. sed.	one	no	1,3
12	Töreboda	susp. found.	gl. fluv. sed.	one	no	1,1
13	Töreboda	susp. found.	gl. fluv. sed.	one	no	1,0
14	Töreboda	susp. found.	sand	one	no	0,9
15	Töreboda	basement	sand	one	no	0,6
16	Töreboda	basement	silt/clay	one	no	0,5
17	Töreboda	susp. found.	till	one	no	0,5
18	Ale	basement	fine sed.	one	yes	0,9
19	Ale	basement	clay	multi	yes	0,6
20	Ale	basement	clay	one	yes	0,8
21	Ale	basement	postgl. fine sand	one	yes	1,1
22	Ale	basement	postgl. fine sand	one	yes	0,9
23	Ale	basement	clay	multi	yes	1,0
24	Ale	basement	clay	one	yes	0,7
25	Ale	basement	clay	one	yes	1,3
26	Töreboda	susp. found.	gl. fluv. sed.	ones	no	0,9
27	Töreboda	basement	gl. fluv. sed.	one	no	1,0
28	Töreboda	susp. found.	gl. fluv. sed.	one/cottage	no	1,0
29	Töreboda	susp. found.	clay, silt	one	no	0,7
30	Töreboda	susp. found.	clay, silt	one	no	0,3
31	Töreboda	basement	clay	one	no	0,7
32	Töreboda	basement	gl. fluv. sed.	one	no	1,0
33	Töreboda	susp. found.	clay, silt	one	no	0,6
34	Töreboda	basement	clay, silt	multi	no	0,3
35	Skövde	slab on grade	gl. fluv. sed.	one	no	1,0
36	Skövde	susp. found.	gl. fluv. sed./clay	one	no	0,6
37	Töreboda	basement	clay, silt	one	no	0,5
38	Töreboda	basement	clay, silt	one	no	0,5
39	Töreboda	susp. found.	clay, silt	multi	no	0,3
40	Skövde	susp. found.	gl. fluv. sed.	one	no	1,1
41	Skövde	susp. found.	gl. fluv. sed.	one	no	1,2
42	Skövde	basement	gl. fluv. sed.	one	no	0,8
43	Skövde	susp. found.	gl. fluv. sed.	one	no	0,9
44	Skövde	basement	gl. fluv. sed.	one	no	1,1
45	Kristianstad	basement	postgl. sand	one	yes	0,5
46	Kristianstad	basement	postgl. sand	one	yes	0,9
47	Skövde	susp. found.	gl. fluv. sed.	one	no	1,2
48	Skövde	susp. found.	gl. fluv. sed.	one	no	1,0
49	Skövde	basement	gl. fluv. sed.	one	no	0,8
50	Skövde	basement	gl. fluv. sed.	one	no	0,6
51	Skövde	basement	gl. fluv. sed.	one	no	no value

*susp. found.=suspended foundation, **gl.=glacial, sed.=sediment, postgl.=postglacial, gl. fluv. =glaciofluvial

The mean transfer factor for each building can be seen in Figure 4.3, where the buildings are sorted according to increased order of the transfer factor, hence the number on the x-axis does not correspond to the number in Table 4.1. The mean transfer factor calculated as a mean of all the separate mean transfer factors is shown as a line in the same figure. This total mean transfer factor is 0.83.

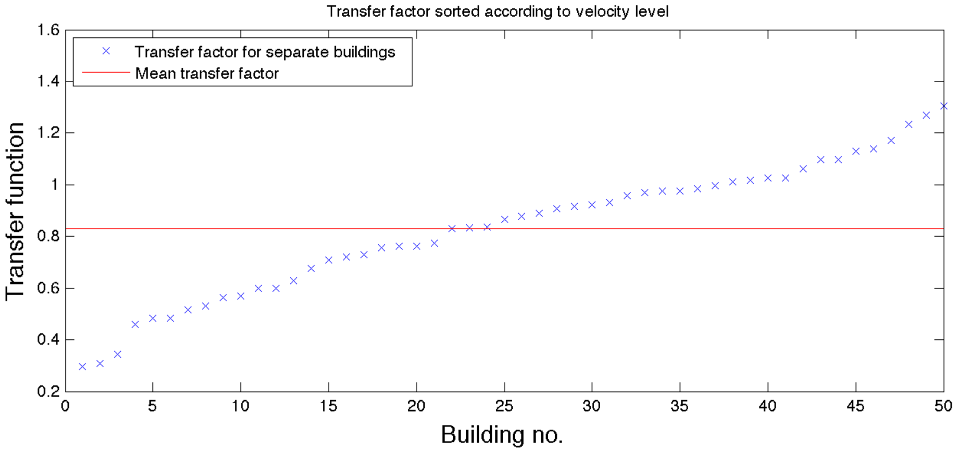


Figure 4.3: *Transfer factors for each building plotted in increasing order. The line shows the mean transfer factor 0.83.*

A histogram for all the mean transfer factors sorted into 10 bins are shown in Figure 4.4. The horizontal line at 0.83 shows the mean value of all transfer factors. In the span of transfer factors 58% of the values are between 0.8-1.1.

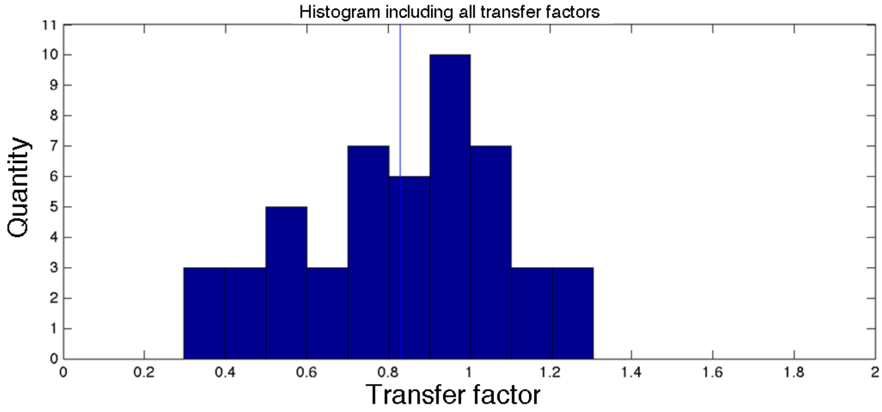


Figure 4.4: *A histogram for all the mean transfer factors sorted into 10 bins. The vertical line shows the total mean transfer factor.*

When the buildings are separated according to foundation type, two types of foundations are represented in the analysis; buildings with basement and buildings with suspended foundation. The transfer factors sorted according to these foundation types are plotted in increased order in Figure 4.5, where the horizontal lines indicates the mean transfer factor for buildings with basements and for buildings with suspended foundation respectively. The mean values for the two foundation types are 0.83 for buildings with basement and 0.83 for buildings with suspended foundation.

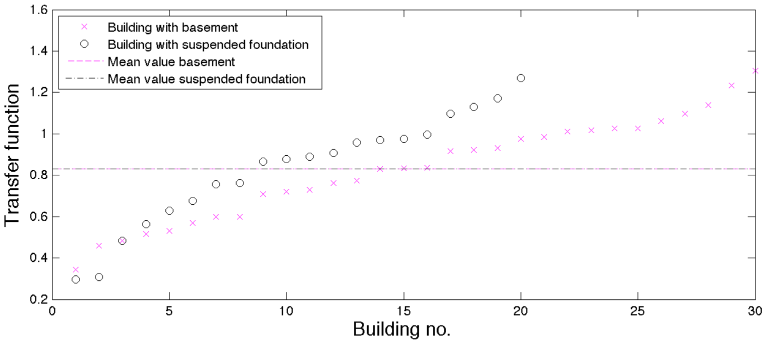


Figure 4.5: *Transfer factors for buildings with basement (pink/x) and buildings with suspended foundation plotted in increasing order (black/rings). The lines shows the mean transfer factors for both buildings with basement and buildings with suspended foundation.*

In Figure 4.6 and Figure 4.7 the transfer factors for buildings with basement and buildings with suspended foundation are shown as histograms with ten bins respectively. The horizontal line in each histogram shows the mean value of all transfer factors for the specific foundation type.

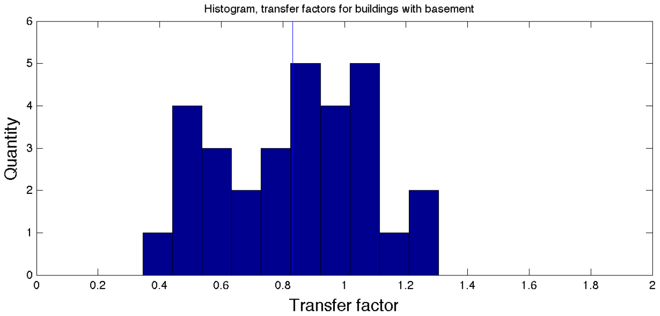


Figure 4.6: *Transfer factors for buildings with basement shown as a histogram with 10 bins. The vertical line shows the mean transfer factor for buildings with basements.*

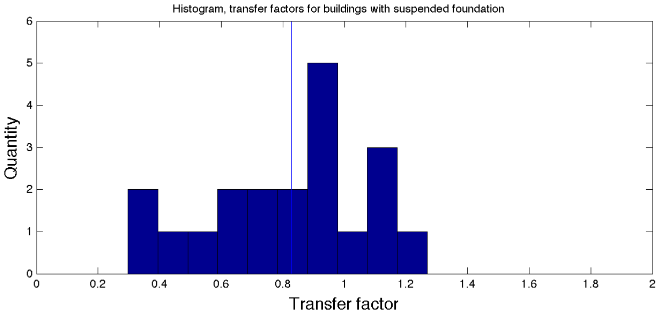


Figure 4.7: *Transfer factors for buildings with suspended foundation shown as a histogram with 10 bins. The vertical line shows the mean transfer factor for buildings with suspended foundation.*

The buildings have also been separated according to the size of the building. The two groups analysed are *one-dwelling buildings* and *two- or multi-dwelling buildings*. The transfer factors sorted according to the size of the building are plotted in increased order in Figure 4.5, where the two horizontal lines indicate the mean transfer factor for one-dwelling buildings and two- or multi-dwelling buildings respectively. The mean transfer factor is 0.86 for one-dwelling buildings and 0.68 for multi-dwelling buildings.

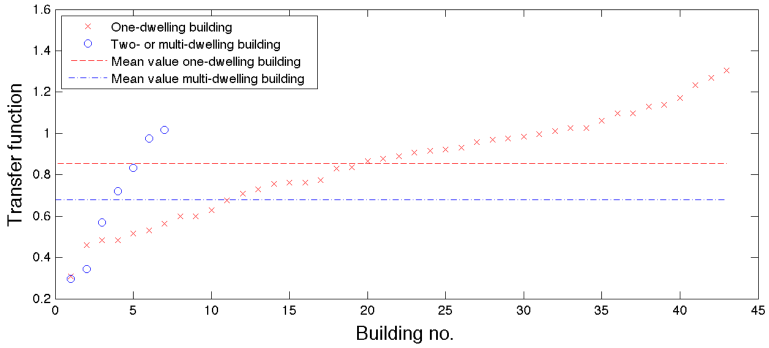


Figure 4.8: *Transfer factors for one-dwelling buildings (red/x) and multi-dwelling buildings plotted in increased order (blue/rings). The lines shows the mean transfer factor for both buildings with basement and buildings with suspended foundation.*

In Figure 4.9 and Figure 4.10 the transfer factors are shown as histograms with ten bins each for one-dwelling buildings and two- or multi-dwelling buildings respectively. The horizontal line in each histogram shows the mean value of all transfer factors for the specific building size.

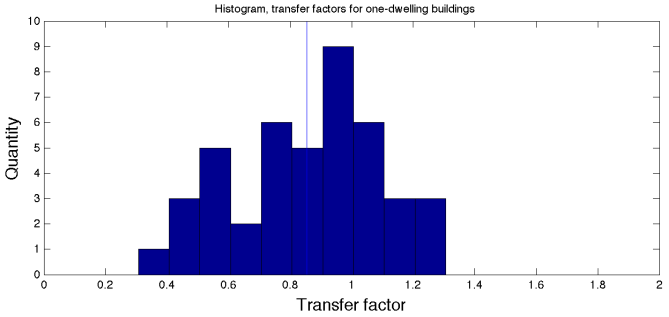


Figure 4.9: *Transfer factors for one-dwelling buildings shown as a histogram with 10 bins. The vertical line shows the mean transfer factor for one-dwelling buildings.*

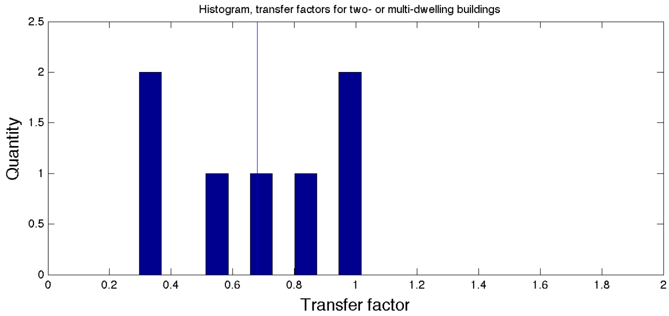


Figure 4.10: *Transfer factors for multi-dwelling buildings shown as a histogram with 10 bins. The vertical line shows the mean transfer factor for two- or multi-dwelling buildings.*

All the different mean transfer factors found in the analyses of the 51 buildings are shown in Table 4.2 according to the different properties studied.

Table 4.2: *Transfer factors for different construction types.*

Mean value	Transfer factor
Total	0.83
Buildings with basement	0.83
Buildings with suspended foundation	0.83
One-dwelling buildings	0.86
Multi-dwelling buildings	0.68

4.2 Estimation of the amount of people exposed by ground-borne vibrations above the levels recommended by the guidelines in Sweden

The mean transfer factor for transmission from foundation and in to the building as a comfort value was found to be 0.86 for all buildings with a registered vibration velocity both at the foundation of the building and as an indoor rms-weighted comfort value. The standard deviation was calculated to 0.59. The median value for the same group of buildings was found to be 0.70. The average transmission factor between the foundation of a building and the indoor comfort value is based on 575 couple of values. A histogram for these values can be seen in Figure 4.11 below. The transfer factor between foundation value and comfort value is calculated from the maximum values registered respectively during the measurement period and are often registered during different train pass-byes.

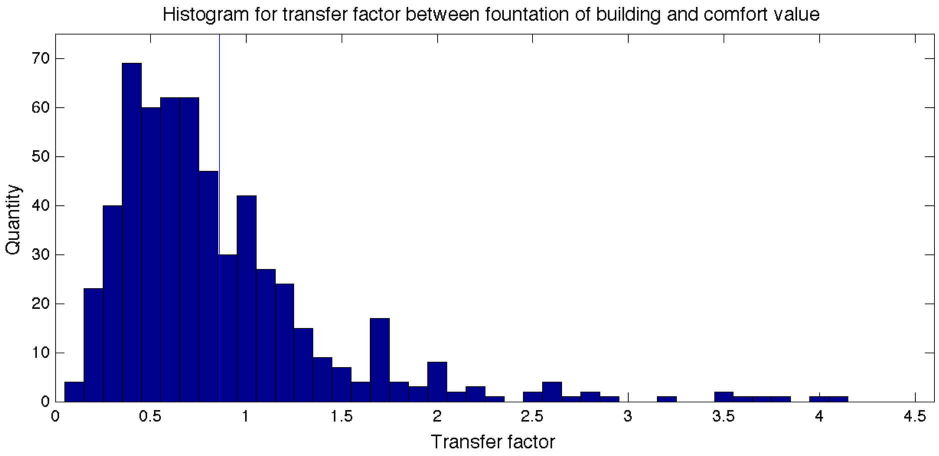


Figure 4.11: *Histogram showing the transfer factor for transmission of vibrational energy from the foundation of a building to the rms-weighted comfort value. The vertical line shows the mean transfer factor between foundation value and rms-weighted comfort value*

The m- and k-values for each soil class group described in Subsection 3.2.2, as well as the standard deviation for each soil class group is shown in Table 4.3. The values have been used to find the mean velocity function for the different soil class groups as well as the mean velocity function multiplied with two standard deviations.

Table 4.3: *Constants used to calculate mean velocity functions and mean velocity functions including two standard deviations for the different soil class groups.*

Group no.	Soil class group	k-value	m-value	std
2	Clay	0.92	5.93	2.33
3	Till	0.81	2.67	1.98
4	Sand	1.09	13.52	2.77
5	Silt	1.00	10.82	2.55
6	Glaciofluvial sediment	1.07	10.38	2.58
10	Artificial fill	0.83	3.40	2.04

The group *Rock* has been excluded from the model because the model seemed to give a false picture of the damping compared to what happens in reality. The groups *Clay til* and *Peat* have been added to the group clay, and are therefore not shown separately. The buildings and data in these groups are though still included in the model. The same has been done with the group *Gravel*, which is included in the group *Glaciofluvial sediment.*

For all soil class groups the vibration levels have been plotted as a function of the distance. In the same plot a curve with the mean function, compiled through linear regression have been plotted as well as the mean function multiplied with two standard deviations. An example of such a plot is shown in Figure B.2, where the results for clay can be seen.

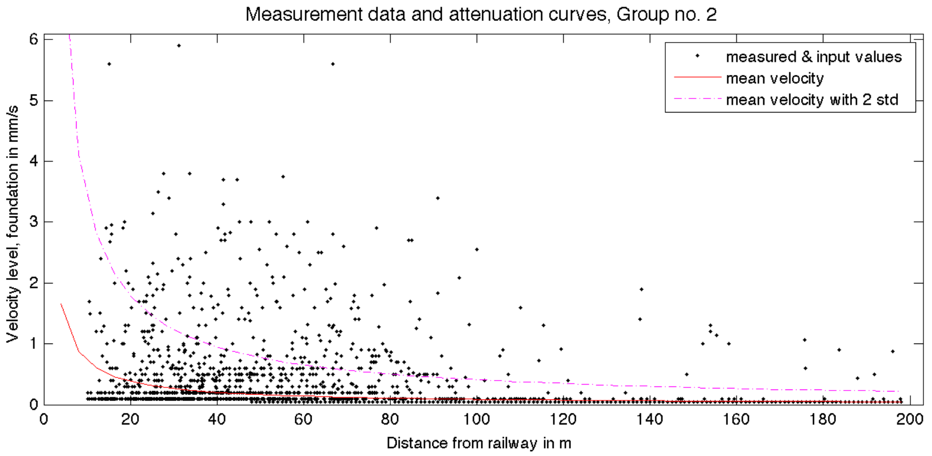


Figure 4.12: *Velocity level as a function of distance for the soil class group clay. The full line shows the mean velocity level at a certain distance and the crosshatched line shows the mean velocity including two standard deviations.*

Figure 4.13 shows all the mean velocities with two standard deviations for the six soil class groups included in the results.

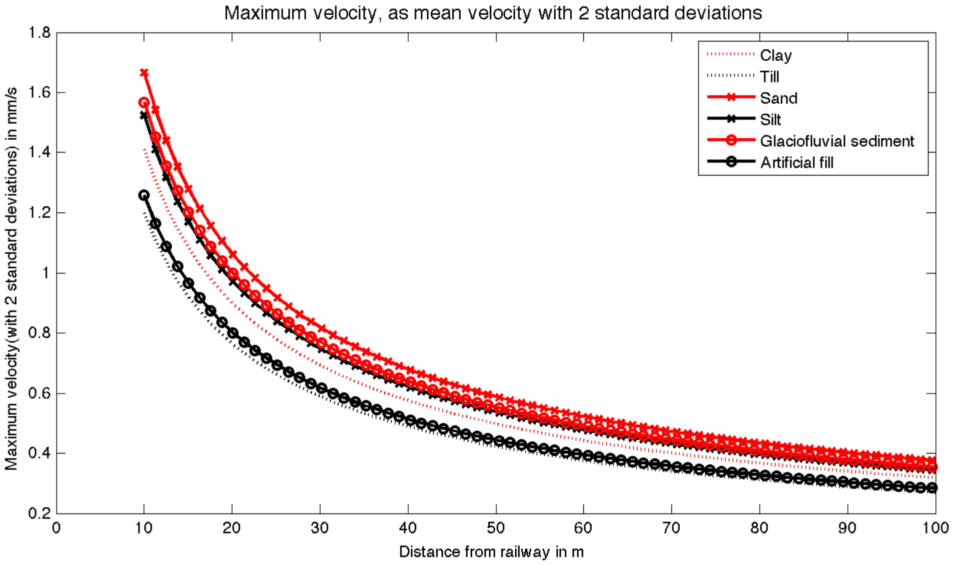


Figure 4.13: *All the mean velocity functions multiplied with two standard deviations for the six soil class groups included in the results.*

4.2.1 Applying the model for estimation of high ground-borne vibrations on the nationwide data

For the nationwide collection of data only the buildings close to a railway administered by Trafikverket is included. Some soil classes are erased as described in Subsection 3.2.1 and some soil class groups are not included in the results. The total quantity of buildings along the railways in Sweden, administered by Trafikverket, as a total as well as divided according to the six different soil class groups where plots are made are shown in Table 4.4. The amount of buildings included in the results are also shown.

Table 4.4: *The quantity of buildings included in the model for each soil class group, the total amount of buildings along tracks in Sweden and the amount of buildings that is included in the model are stated.*

Buildings along:	**Railways**	**All tracks**
Total quantity	202 997	254 626
Without building classification	9 738	
With excluded soil classes	192	
Buildings founded on		
Clay	50 127	
Til	58 155	
Sand	30 511	
Silt	13 998	
Glaciofluvial sediment	22 021	
Artificial fill	3 079	
Soil class groups not in results		
Rock	15 176	
Gravel	Incl in glaciofluvial sediment	
Peat	Included in clay	
Clay til	Included in clay	
Total quantity in model	177 891	

The amount of people and buildings exposed by ground-borne vibrations exceeding the velocity levels 0.4, 0.7, 1.0 and 1.4 mm/s are stated for each soil class group in Table 4.5 below. The total amount of buildings with values exceeding the above stated velocity levels and people living in these buildings can also be read in that table. The assumed number of residents living in any single dwelling building, used to compile the data regarding exposed people in Table 4.5 below, is set equal to 2.7 residents, which is the average amount of people living in a single family home in Sweden.

Table 4.5: *The quantity of people and buildings where guideline levels are exceeded along Swedish railways administered by Trafikverket, shown as a total as well as divided according to soil class groups and rounded to two significant figures.*

Comfort velocity level, mm/s	**0.4**	**0.7**	**1.0**	**1.4**
Buildings on:				
Clay	6 100	2 800	1 500	820
Til	3 800	1 200	450	0
Sand	4 600	2 400	1 600	890
Silt	2 400	1 200	730	430
Glaciofluvial sediment	2 600	1 400	840	500
Artificial fill	260	100	50	4
Total amount of buildings	19 800	9 100	5 100	2 600
People living in dwellings on:				
Clay	16 500	7 500	4 100	2 200
Til	10 200	3 300	1 200	0
Sand	12 400	6 500	4 200	2 400
Silt	6 500	3 300	2 000	1 200
Glaciofluvial sediment	7 100	3 600	2 271	1 300
Artificial fill	700	280	130	10
Total amount of people	53 400	24 600	13 900	7 100

5

Discussion

In this chapter the methods used for this thesis work will be discussed. So will the calculation of the transfer factor and the method for the estimation of the amount of people exposed to ground-borne vibrations above guideline levels will be discussed.

5.1 Transmission factors between ground and foundation of buildings

The transfer factors for transmission from ground to foundation for buildings, computed in this thesis work, shows there are no large difference between a building constructed with a basement or a suspended foundation. The values compiled are closer to the values given in literature than the values commonly used by the industry of ground-borne vibration work in Sweden. The values used by the industry tend to represent the lowest expected vibration levels, rather than representing the most probable outcome of an investigation. In literature it is not specified what work or results that the values are based on or if the values are valid for traffic, while the results of the research in this thesis work is based on measurement on 50 buildings exposed by ground-borne vibrations from actual traffic and specifically from trains. Even though for the transmission factor between the surrounding ground and the foundation of a building shows a spread between 0.3 and 1.2, the bulk of transmission factors is in the range 0.8-1.0 according to the histogram for the total amount of buildings. This show that a transfer factor as the mean value of 0.83 can be expected.

When sorting the buildings according to size, there is a tendency that large buildings get lower transmission factors between the ground surrounding the building and the foundation of the building than smaller buildings. There are not many two- or multi-dwelling buildings included in this thesis work, why the amount of results from this kind of buildings are also few. The statistics for these type of buildings can therefore not be seen as reliable as the results from the other separating factors. On the other hand, since the transmission factors for large or heavy buildings are small for the buildings included in this thesis work, this can show that there are in general low transmission of vibrational energy between the ground and foundation of large buildings. Therefore they do not get problems with ground-borne vibrations as often, hence they do not get measured.

The buildings included in this research are mostly situated in *Region Västra Götaland* and along Västra stambanan. That is one of the most problematic areas in

Sweden regarding high ground-borne vibrations. One benefit of measuring along Västra stambanan is the high traffic load on the railway. This gives many train pass-byes that trigger the measurement equipment, generating a large set of data to base the statistics on. The focus on just one region could mean that the transfer factors are only representative for Region Västra Götaland. On the other hans the buildings in this thesis work that is not situated in the mentioned region does not stand out. To investigate if the transmission factor would be the same for other regions, with or without problematic conditions concerning ground-borne vibrations, is an interesting topic for further investigations.

The older measurement data included in the research about transmission factors between the ground and the foundation of a building are analysed in the frequency domain (FFT-analysed) and matched with trains. For the data from the inventory along Västra stambanan this has not been done, which could influence the results. Outliers have been analysed and data with measurement interference have been erased. By only analysing data with frequencies below 40 Hz (except for Building no. 16 and Building no. 17, where the data have been looked up on) it is assumed that data containing some kind of disturbance have largely been avoided.

For further investigations within this research area more multi-dwelling buildings could be included and more investigations in other areas than the western part of southern Sweden could show if the transmission factors are accurate nationwide or if they differ, which would imply that there are region specific transfer factors. It could also be good if other foundation types were included, especially pile foundation and slab on grade-foundations. An investigation of the transmission factor between the foundation of buildings and the values inside buildings, on their top floor, could be interesting for further investigations, with comparisons between different structural systems and how the foundation type influence the transmission factor for buildings with the same structural system but different foundation type.

The linear correlation coefficient between separate values for a building have been calculated with MATLAB, with the intention to analyse if there is a correlation between the frequency and the transfer function. This has though not been analysed in this master thesis.

5.2 Modell for estimating the amount of people exposed by ground-borne vibrations exceeding the guideline levels

The model for estimating the amount of people exposed by ground-borne vibrations exceeding the guideline levels is based on a large set of data. Probably the largest set of data there is for this type of investigations. The data registered in the database `Projektnavet` can sometimes be registered in the wrong way. However, that data can though be seen as more of an exception. Most data are seen as correct and as the outcome from investigations performed in a reliable way. Furthermore, the set of data used has been analysed for outliers, so the data used to make up the model can be seen as trustworthy.

The information about soil classes for both the data in Projektnavet and the nationwide data for all buildings close to railways is based on SGUs map for soil classes. The data is based on the topcoat of the soil and the borders between two different soil classes are not extremely exact. Even though the soil classes are shown wrong in some areas, the final result should not be too affected, since the soil classes sometimes are showing a softer soil class in some areas and a more stiff soil class in other areas. Even if the soil classes are shown correct there are other things that influence them as well and even for a specific soil class the properties of the soil can vary. The soil classes can be seen as accurate as to the level of detail required for work where ground-borne vibrations is analysed. Factual errors can occur when the soil class is determined in a specific coordinate.

Clay is known to be the softest soil type and also the soil class in which the highest velocity levels appears as ground borne vibrations. According to the attenuation curves calculated in this thesis this seems not to be the case. One reason for this could be that all soil classes containing some kind of clay are gathered in the same soil class group. Some of these soil classes might be stiffer than the average clay type and should therefore be sorted into another group. If this is the case the number of people exposed to vibration velocities in dwellings exceeding the stated levels is probably underestimated, since more than 30% of the estimated number of people are living in houses founded on clay and this number will raise.

The chosen statistical method is used since the model is one of the most basic methods to use for statistical analyses. Since the model is a simple one with many assumptions included, the improvement with using a more advanced statistical model would probably be very small.

For the model, the transfer factor for transmission of vibrations from the foundation of a building to the rms-weighted comfort value have been calculated between an unweighted value and an rms-weighted value. The transfer factor used would have been a more reliable value if only unweighted values had been used. One option could have been to calculate the transfer factor between the foundation and comfort value from the 51 buildings used in the analyses for the transmission from ground to the foundation of a building, since unweighted values are available for these buildings. The disadvantage of using those values are that not all soil classes are included among them and the amount of values used to get a mean transfer factor had been less than 10% of the ones included to get the mean transfer factor between foundation and indoors comfort level currently used in the model.

Things that can improve the model is to use more exact soil class data if this could be found in some way. The model is based on the soil class under the building. The soil class below the railway could also be investigated and a combination of the two soil classes could maybe improve the model further.

By improving the database `Projektnavet` with simple modifications, like to register the unweighted comfort value and the rms-weighted value, as well as adding information about the building such as the number of floor levels of the building, foundation type for the building and the structural system of the building. Ticking boxes for type of measurement with the alternatives *train*, *road* or *train & road* would also improve the usability of the database if further scientific investigations is to be made using the data in the database.

6

Conclusion

The mean transfer factor for transmission of ground-borne vibrations from the ground next to a building and into the foundation of the building is approximately 0.8. The majority of the transmission factors are in the range 0.8-1.1, where 58% of the results appear.

The transmission factor does not seem to be dependent on if the foundation type is suspended foundation or basement.

Multi-dwelling buildings seems to have much lower transfer factor than one-dwelling buildings, but more data for Multi-dwelling buildings is needed to establish if this is statistically correct.

The estimated amount of people exposed by vibration levels exceeding 0.4, 0.7, 1.0 and 1.4 mm/s are 53 400, 24 600, 13 900 and 7 100 people respectively.

The model for estimating the amount of buildings or people exposed by ground-borne vibrations exceeding certain levels could be improved by using more precise soil class information. Another improvement could be to base the model on the soil class under both the railway and the building in combination, as well as the ground properties in between them.

The model could be used to improve the usability of the database Projektnavet and to simplify analyses of the probability that a certain vibration level appears in a building.

Bibliography

Auersch L. (1994) Wave propagation in layered soils: Theoretical solution in wavenumber domain and experimental results of hammer and railway traffic excitation. *Journal of Sound and Vibration*, vol. 173, no. 2, p. 233-264.

Banverket, Naturvårdsverket (2006) *Buller och vibrationer från spårburen linjetrafik - Riktlinjer och tillämpning.* Stockholm och Borlänge.

Blidberg, K. (2015) *TDOK 2014:1021 Buller och vibrationer från trafik på väg och järnväg.* Borlänge: Trafikverket.

Broberg, A. (2015) *Järnvägstransporter 2015 kvartal 2.* Trafikanalys.se http://trafa.se/globalassets/statistik/bantrafik/jarnvagstransporter/jarnvagstransporter-2015-kvartal-2.pdf?. [2015-09-11].

Elias, P., Villot, M. (2011) *Review of existing standards, regulations and guidelines, as well as laboratory and field studies concerning human exposure to vibration.* Version 3. Rivas. http://www.rivas-project.eu/index.php?id=9. [2015-09-10].

Hall, L., Wersäll, C. (2013) Markvibrationer. Svenska Geotekniska Föreningen, Markvibrationskommittén. (SGF Informationsskrift 1:2012).

International Organization for Standardization (1989) *ISO 2631-2 Evaluation of human exposure to whole-body vibration - Part 2: Continous and shoch-induced vibration in buildings (1 to 80 Hz).* Switzerland.

Jonsson, O. J. (2000) *On ground and Structural Vibrations Related to Railway Traffic.* Göteborg: Chalmers University of Technology. (Department of Structural Engineering, Division of Steel and Timber Structures).

Lindberg, G. (1992) *Vågutbredning i jord – Analys och åtgärder, Vibrationer från tågtrafik.* Stockholm: Kungliga Tekniska Högskolan. (Rapport nr 93/9, Institutionen för jord- och bergmekanik).

Mattecentrum (2015a) Standardavvikelse. *Matteboken.* http://www.matteboken.se/lektioner/matte-2/statistik/standardavvikelse. [2016-02-25].

Mattecentrum (2015b) Normalfördelning. *Matteboken.* http://www.matteboken.se/lektioner/matte-2/statistik/normalfordelning. [2016-02-25].

Nist/Sematech (2003) e-Handbook of Statistical Methods. Last significant update, 2012. *Engineering Statistics Handbook - 7.1.6. What are outliers in the data?* http://www.itl.nist.gov/div898/handbook/prc/section1/prc16.htm. [2016-02-25].

Pagoldh, C., Bähler, S. (1990) *Godstågstrafikens stambanenät - Vibrationsstörningar från järnvägstrafik i Sverige.* Stockholm: Ingemansson AB.

Remington, P.J., Kurzweil, L.G., Towers, D.A. (1987) Low-Frequency Noise and Vibration from Trains. In *Transportation Noise Reference Book*, red. P.M. Nelson, chapter 16. London : Butterworths & co.

Pilman, C. (2014) *Vibrationsmätningar, Önnestad, mars 2014 - Mätning av vibrationer som riskerar skada byggnad enligt SS 02 52 11:1999 och mätning av komfortvibrationer enligt SS 460 48 61.* Malmö: ÅF Ljud & Vibrationer ÅF Infrastruktur AB.

Ripley, B.D. (2004) *M.Sc. in Applied Statistics MT2004 - Robust Statistics.*

Shift^{2}Rail (2015) Mission and Objectives. *Shift2Rail.org.* http://www.shift2rail.org/about-shift2rail/mission-and-objectives/. [2015-09-14].

Smith, M., Ögren, M., Persson Waye, K. (2015) *Physiological reaction thresholds to vibration during sleep.* Gothenburg: Gothenburg University, Unit for Occupational and Environmental Medicine in Gothenburg. Report No. 2:2015.

Smith, D.R., Leggat, P.A. (2005) *Whole Body Vibration - Health effects, measurement and minimization.* http://crawl.prod.proquest.com.s3.amazonaws.com/fpcache/76672efd61066ab66c263ac9f82d912e.pdf?AWSAccessKeyId=AKIAJF7V7KNV2KKY2NUQ&Expires=1443166763&Signature=Et2tsQ%2Bu%2FLxCjYBymMRGhY9vmNc%3D. [2015-09-25].

Standardiseringskommissionen i Sverige (1992) *Svensk Standard SS 460 48 61 - Vibration och stöt - Mätning för bedömning av komfort i byggnader.*

Statistiska centralbyrån (2014a) Villa vanligaste boendeformen. *Statistiska centralbyrån - Statistics Sweden.* Nr 2014:4. http://www.scb.se/sv_/Hitta-statistik/Artiklar/Villa-vanligaste-boendeformen/. [2015-11-27].

Statistiska centralbyrån (2014b) Antal personer och hushåll samt personer per hushåll 31 december 2013. *Statistiska centralbyrån - Statistics Sweden.* http://www.scb.se/sv_/Hitta-statistik/Statistik-efter-amne/Befolkning/Befolkningens-sammansattning/Befolkningsstatistik/25788/25795/Helarsstatistik—Kommun-lan-och-riket/367830/. [2015-11-27].

Statistiska centralbyrån (2016) Om SCB. *Statistiska centralbyrån - Statistics Sweden.* http://www.scb.se/sv_/Om-SCB/. [2016-05-01].
Sveriges geologiska undersökning (2014) *Produktbeskrivning - Produkt: Jordarter 1:25 000-1:100 000.* Uppsala: Sveriges geologiska undersökning.

Sveriges geologiska undersökning (2015) Jordarter 1:25 000-1:100 000. *Sveriges geologiska undersökning.* http://www.sgu.se/produkter/kartor/kartvisaren1/jordkartvisare/jordarter-125-000-1100-000/. [2015-11-27].

Swedish Standards Institute (2011) *Vibrationer och stöt - Riktvärden för sprängningsinducerade vibrationer i byggnader.* Third edition. Stockholm: SIS Förlag AB.

Thompson, D. (2009) *Railway Noise and Vibration - Mechanisms, Modelling and Means of Control.* Oxford: Elsevier.

Trafikverket (2015a) Sveriges järnvägsnät. *Trafikverket.se.* http://www.trafikverket.se/Privat/Vagar-och-jarnvagar/Sveriges-jarnvagsnat/. [2015-09-09].

Trafikverket (2015b) Järnvägstermer. *Trafikverket.se.* http://www.trafikverket.se/Privat/Vagar-och-jarnvagar/Sveriges-jarnvagsnat/Jarnvagstermer/. [2015-09-09].

Westerberg, B., et al. (1985) *Vibrationers transmission från undergrund till byggnad.* Stockholm: Byggforskningsrådet. (Rapport R86:1985).

Öhrström, E., et al. (2011) *Slutrapport Forskningsprogrammet TVANE – Effekter av buller och vibrationer från tåg- och vägtrafik – tågbonus, skillnader och samverkan mellan tåg- och vägtrafik.* Göteborg: Sahlgrenska akademin. (Rapport nr 1:2011. Enheten för Arbets- och miljömedicin, Avdelningen för Samhällsmedicin och Folkhälsa).

A

Appendix 1

In this appendix histogram over transfer factors for each building (no. 1-50) is presented. So are figures for the transfer factors for each building (no. 1-50) as a function of frequency.

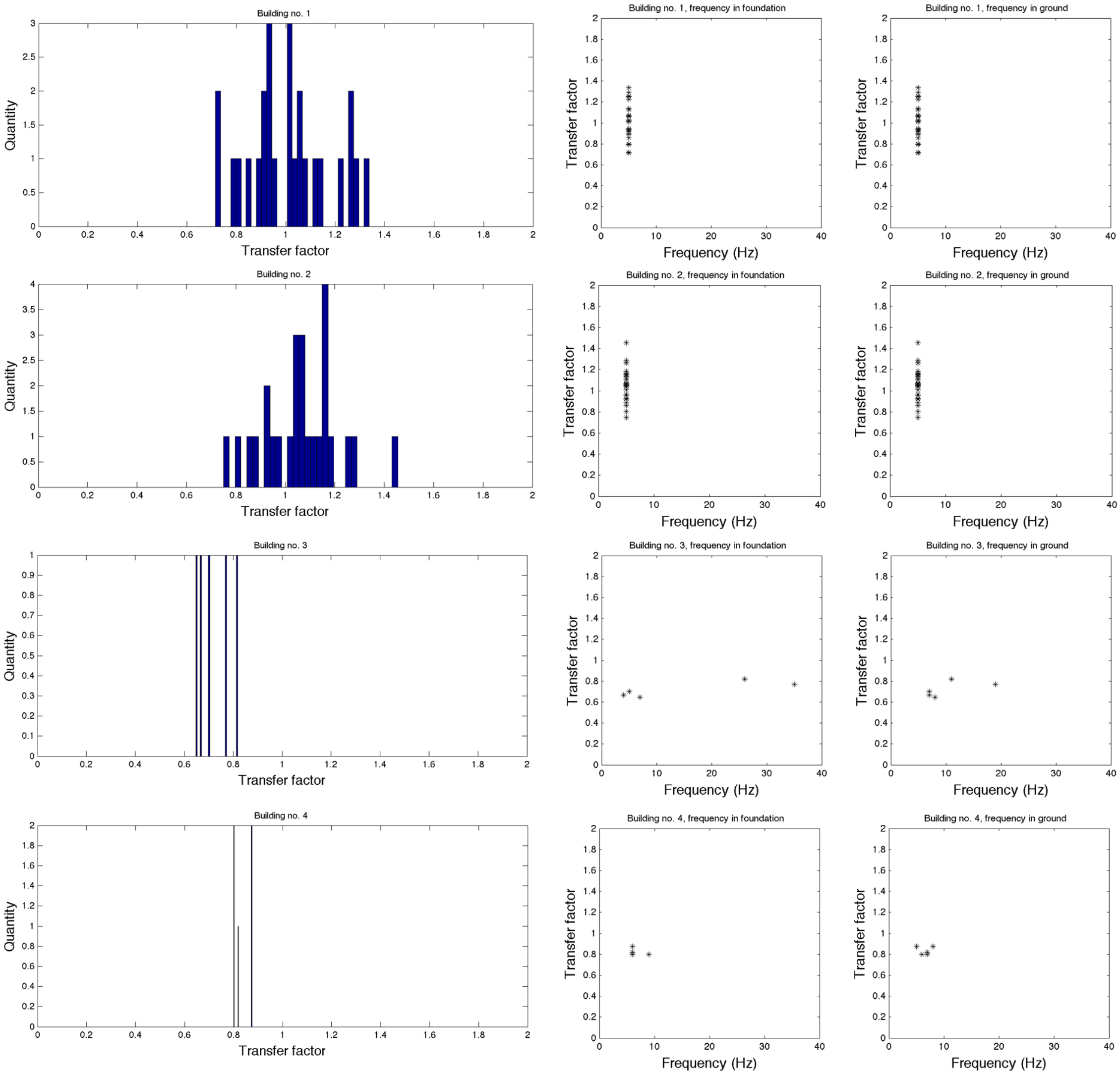


Figure A.1: *Histogram for transfer factors (left) and Transfer factors as a function of frequency in foundation (middle) and in ground (right) for Building no. 1-4.*

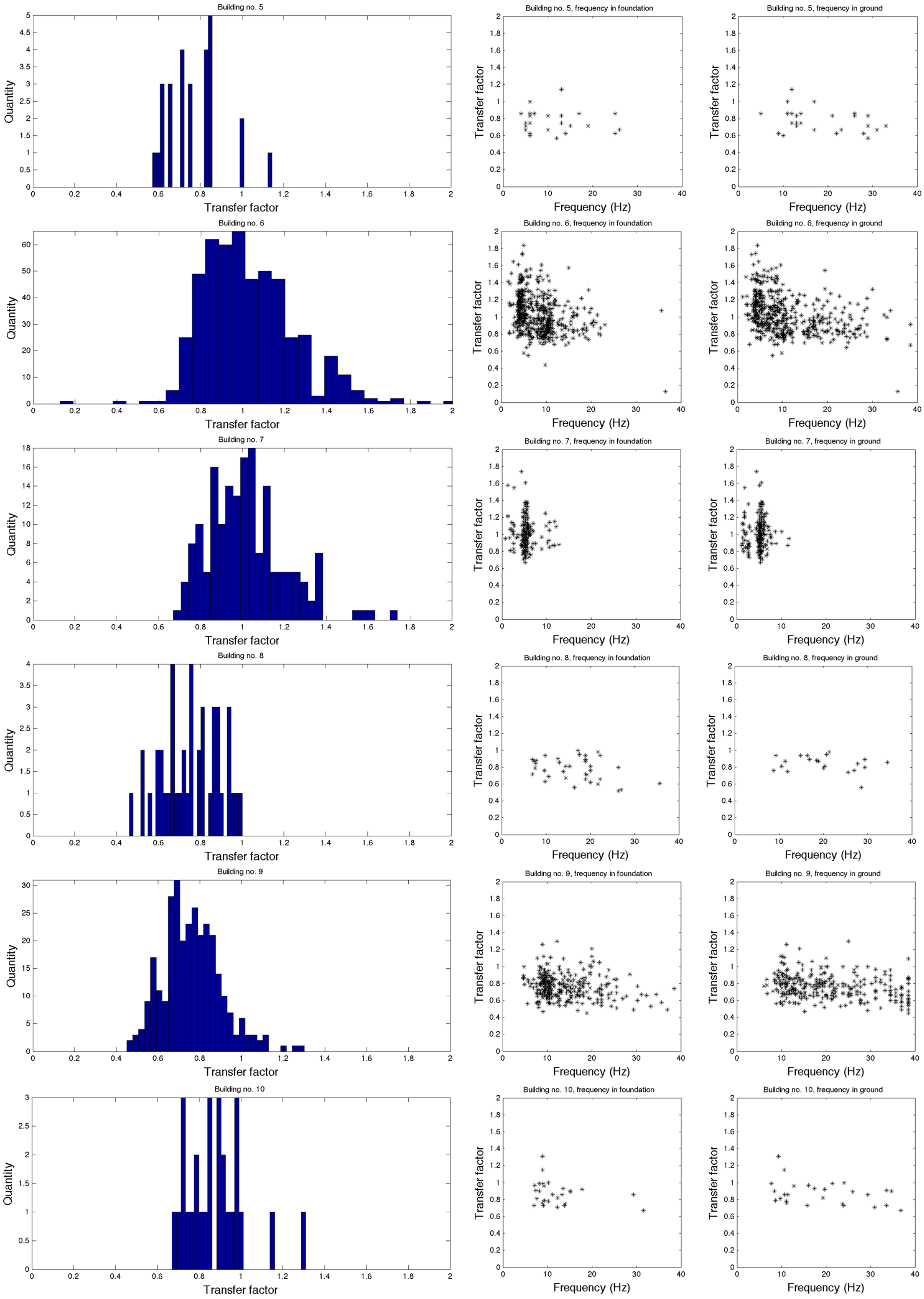


Figure A.2: *Histogram for transfer factors (left) and Transfer factors as a function of frequency in foundation (middle) and in ground (right) for Building no. 5-10.*

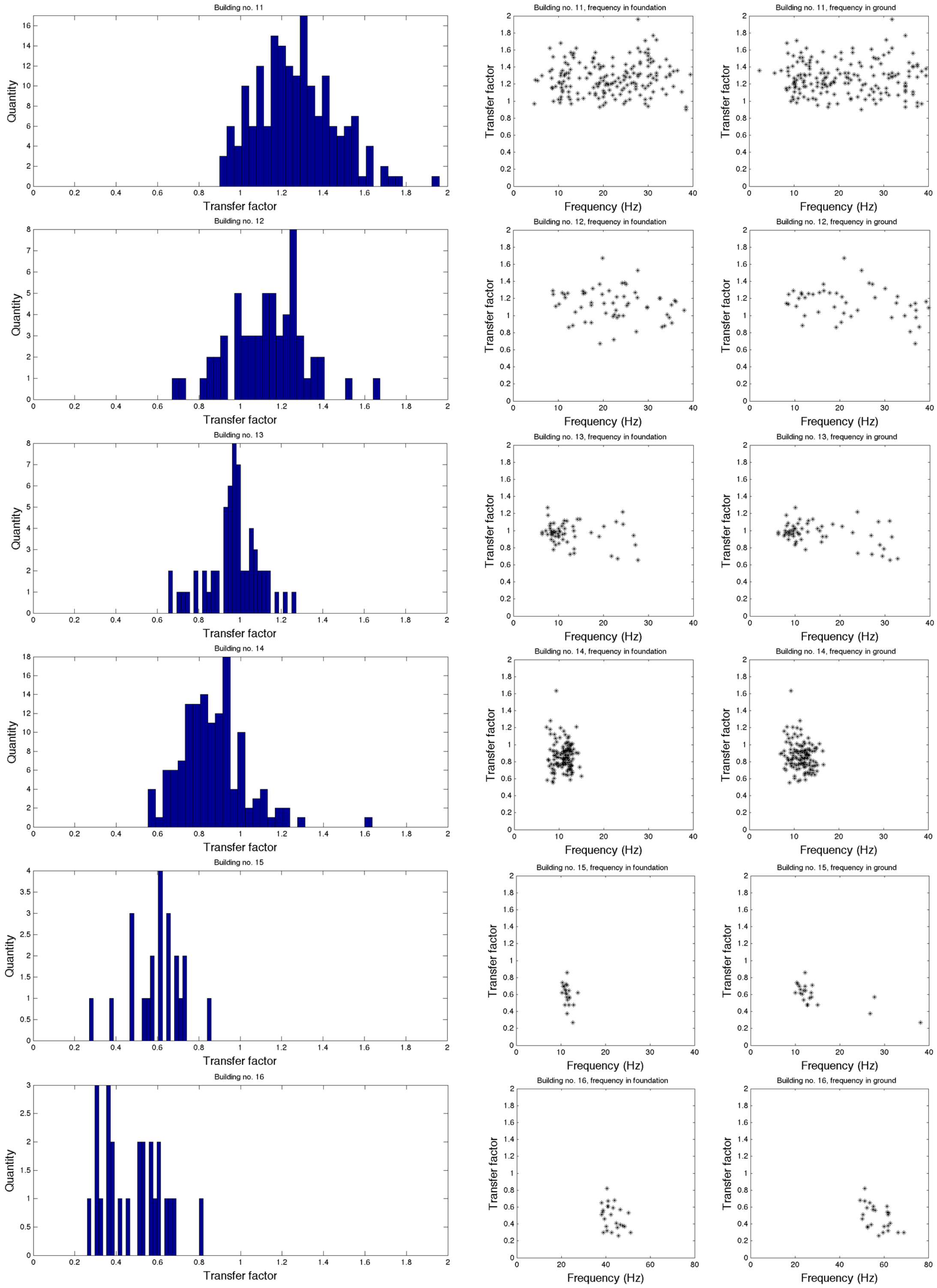


Figure A.3: *Histogram for transfer factors (left) and Transfer factors as a function of frequency in foundation (middle) and in ground (right) for Building no. 11-16.*

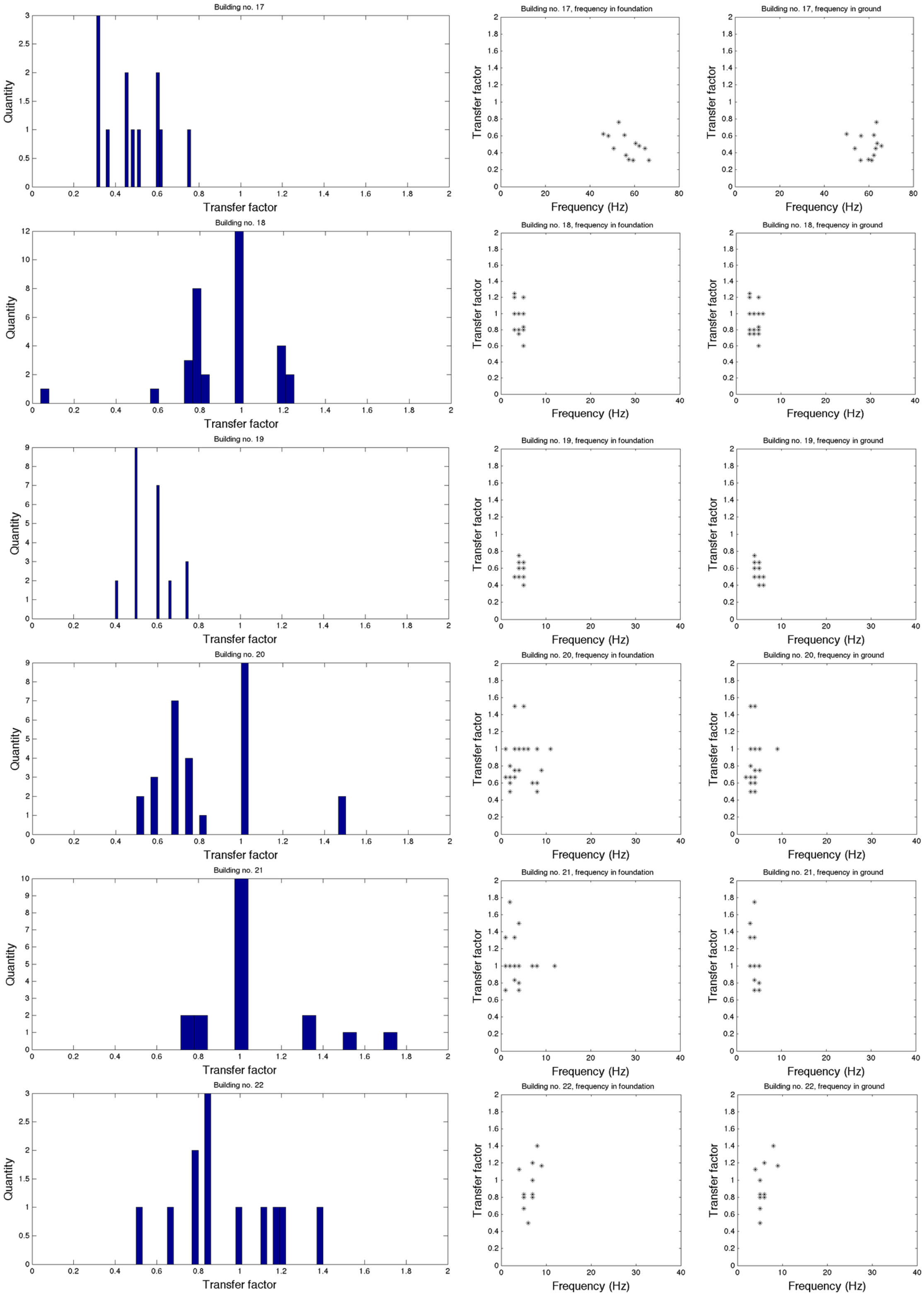


Figure A.4: *Histogram for transfer factors (left) and Transfer factors as a function of frequency in foundation (middle) and in ground (right) for Building no. 17-22.*

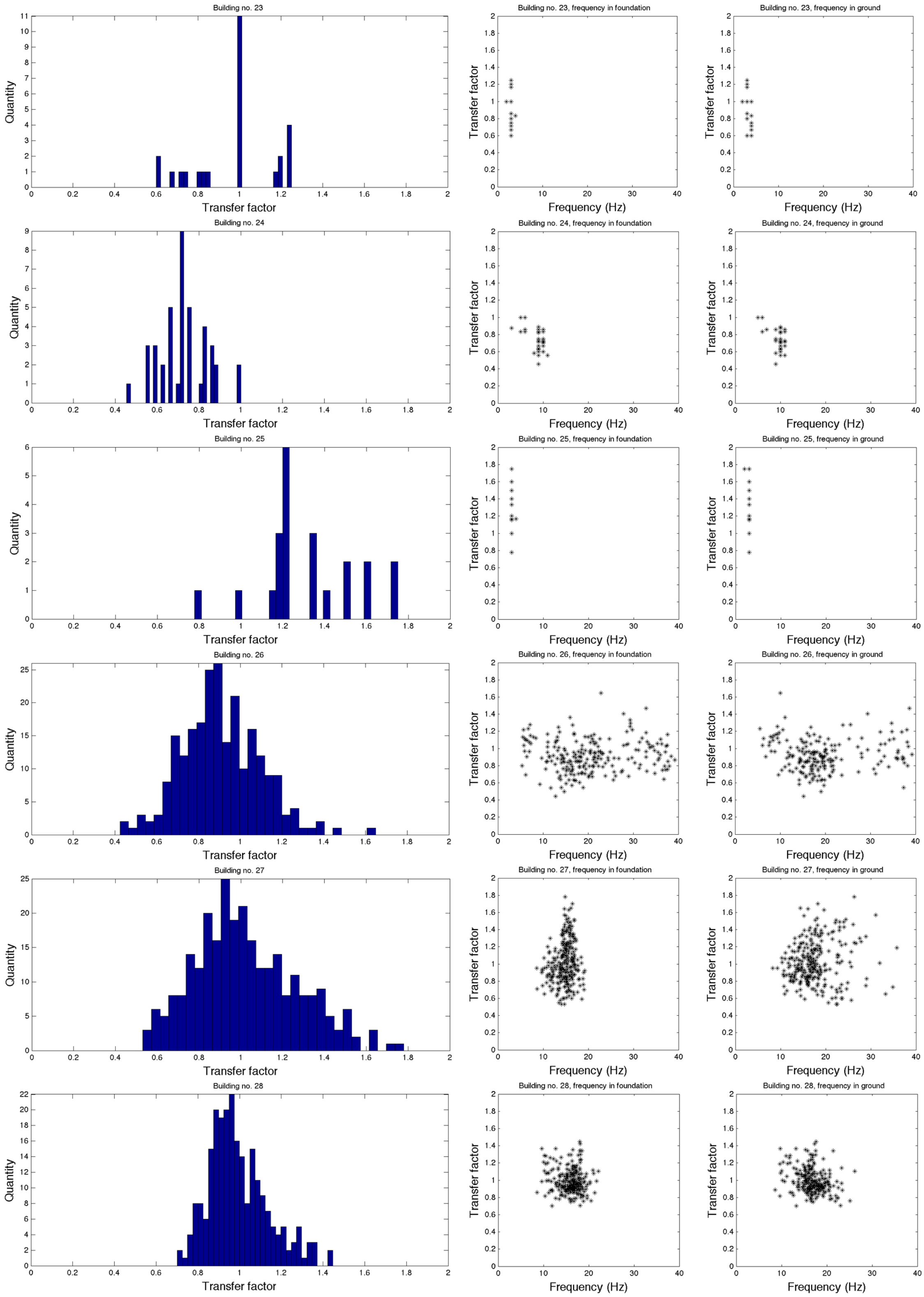


Figure A.5: *Histogram for transfer factors (left) and Transfer factors as a function of frequency in foundation (middle) and in ground (right) for Building no. 23-28.*

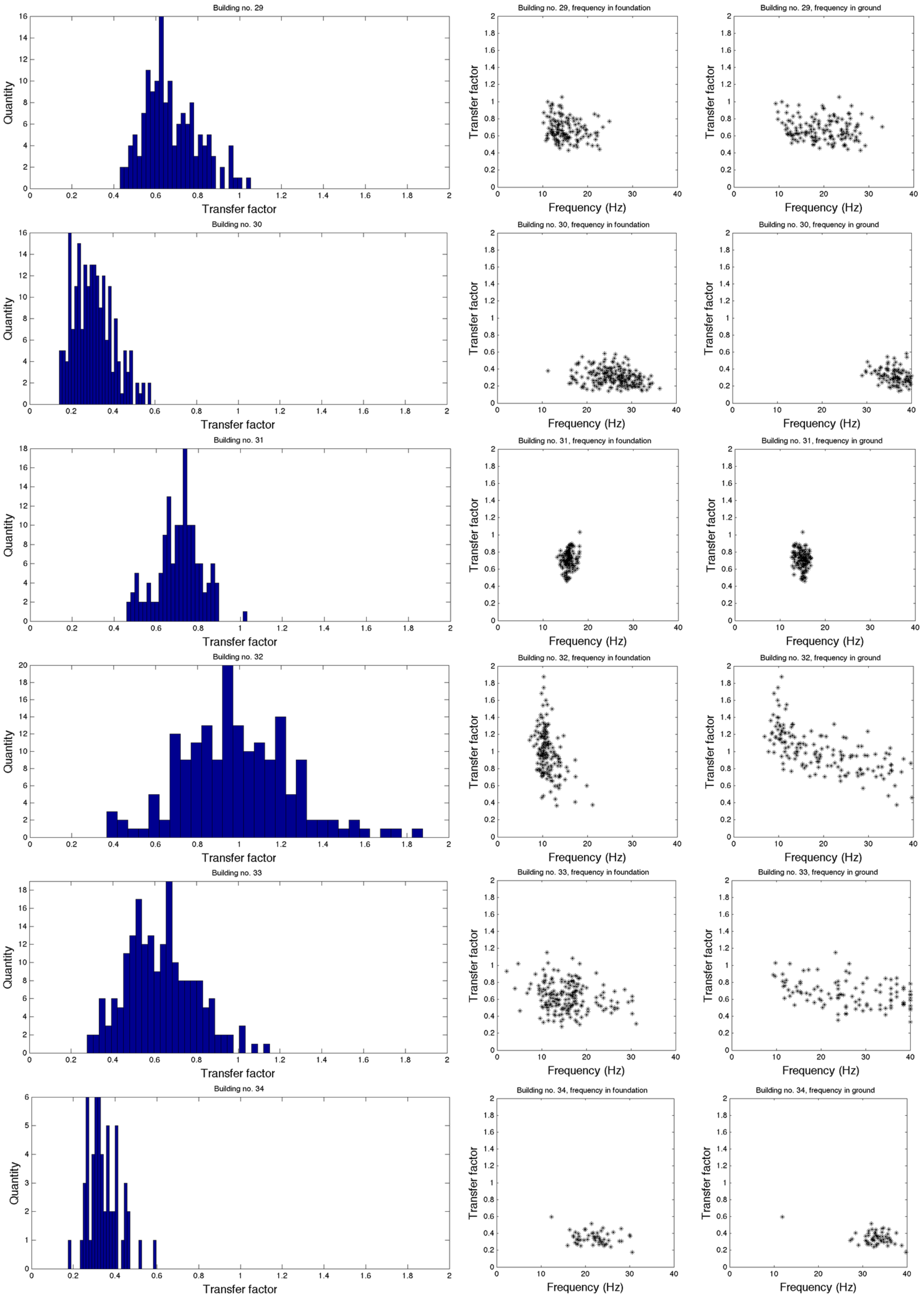


Figure A.6: *Histogram for transfer factors (left) and Transfer factors as a function of frequency in foundation (middle) and in ground (right) for Building no. 29-34.*

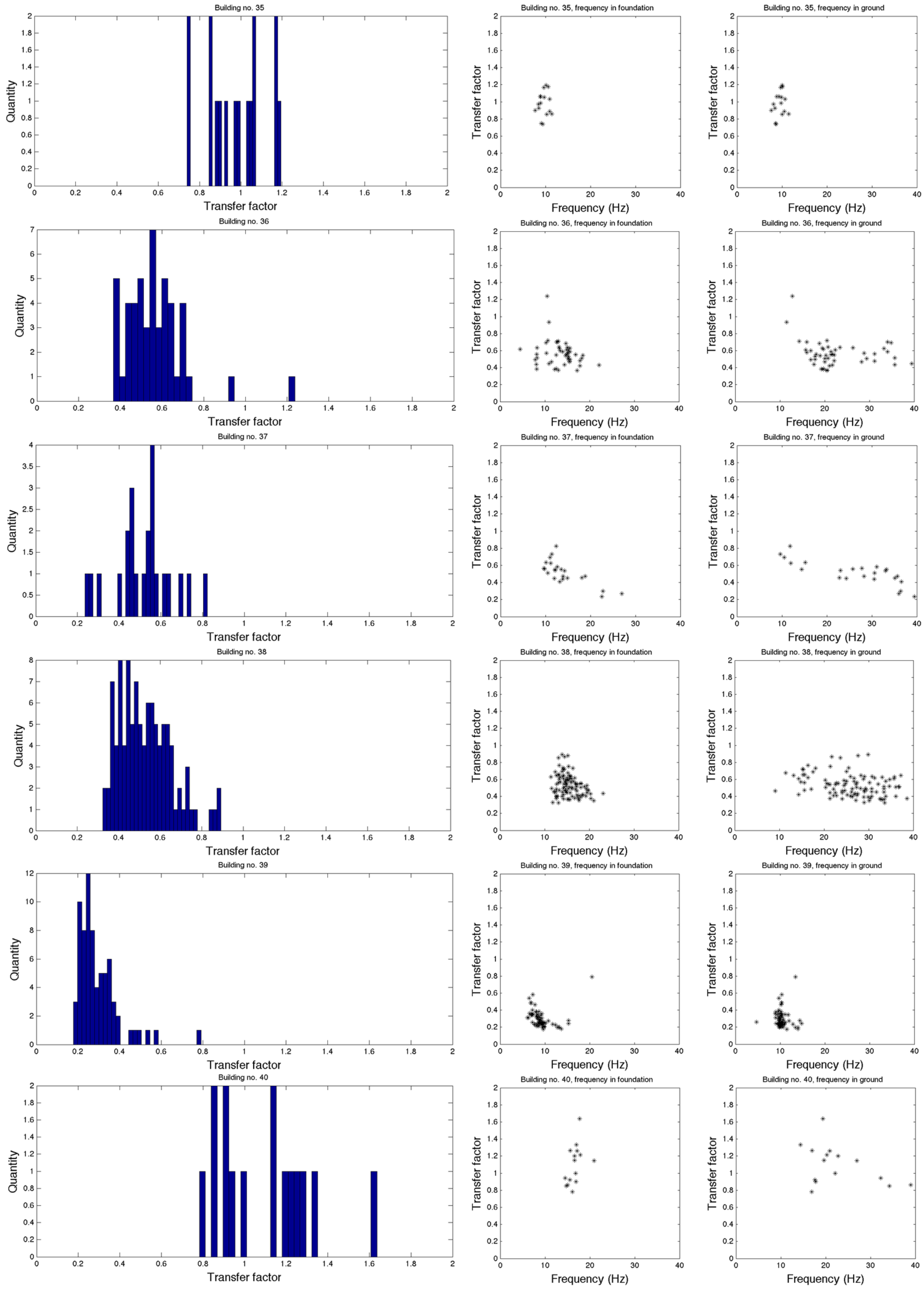


Figure A.7: *Histogram for transfer factors (left) and Transfer factors as a function of frequency in foundation (middle) and in ground (right) for Building no. 35-40.*

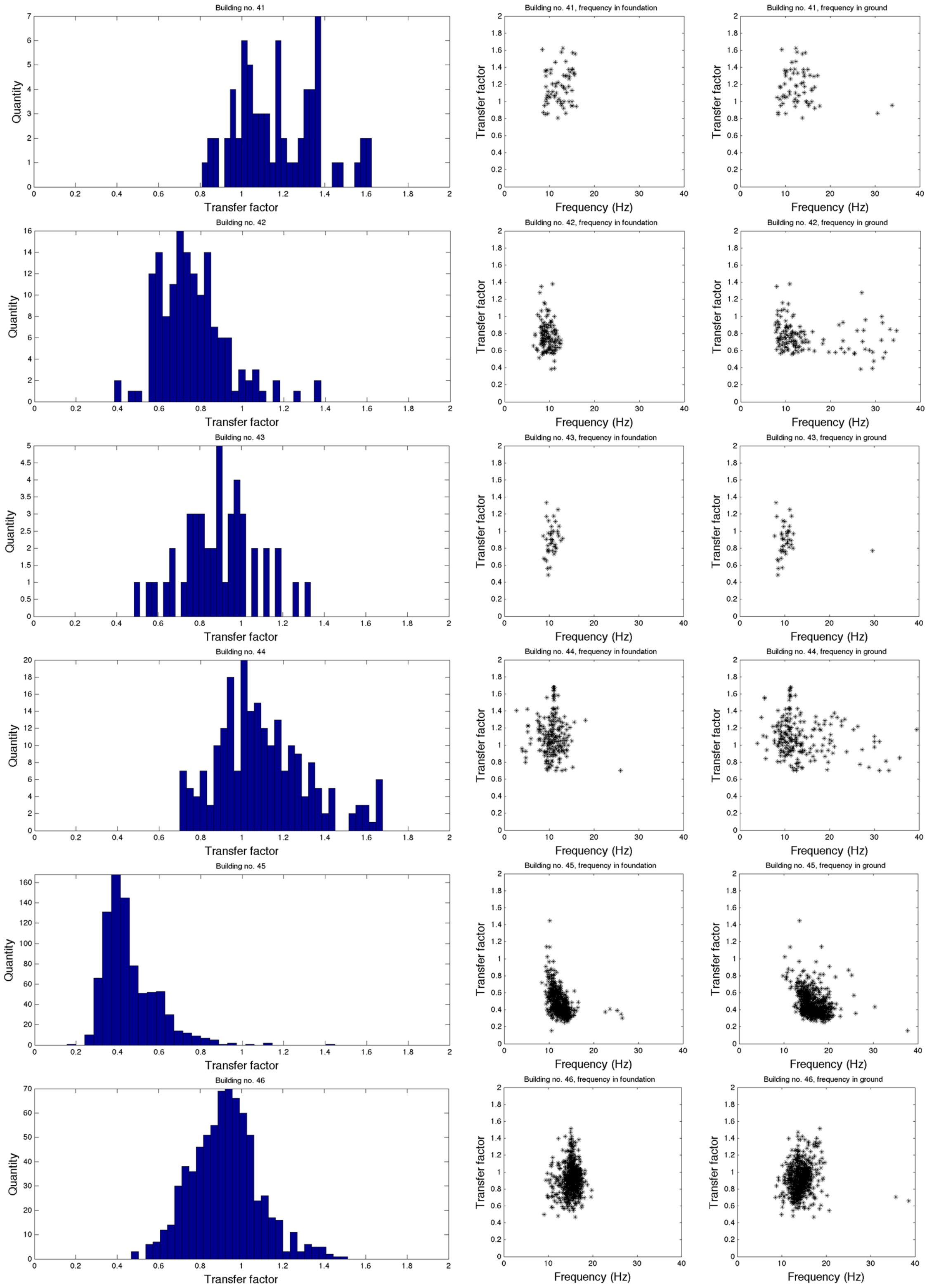


Figure A.8: *Histogram for transfer factors (left) and Transfer factors as a function of frequency in foundation (middle) and in ground (right) for Building no. 41-46.*

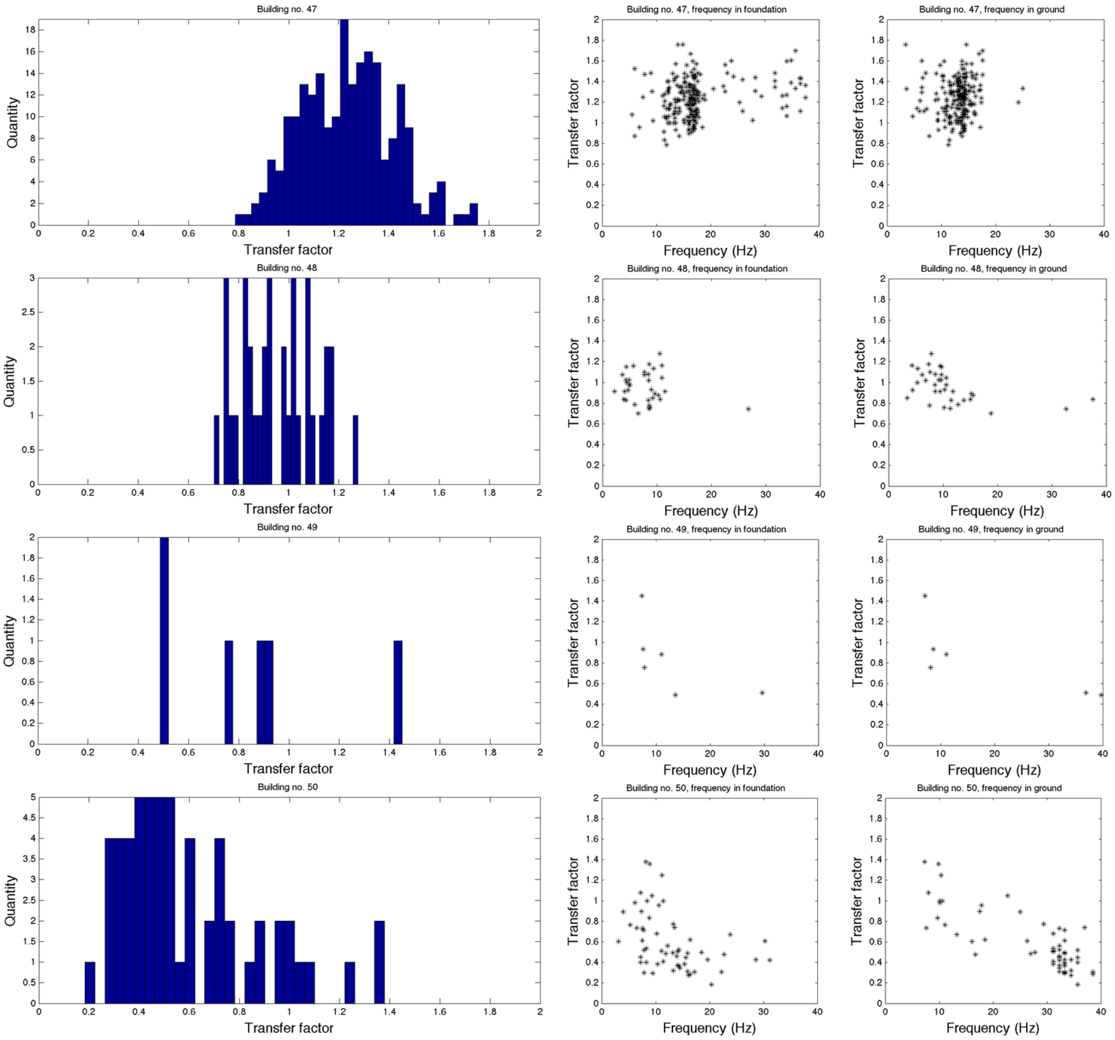


Figure A.9: *Histogram for transfer factors (left) and Transfer factors as a function of frequency in foundation (middle) and in ground (right) for Building no. 47-50.*

B

Appendix 2

In this appendix histograms with vibration levels above 0.2 mm/s are shown for all soil class groups included in the results in section 4.2. Results are also shown for vibration levels plotted as a function of distance for the same soil class groups. In all figures with attenuation curves, a curve with the mean function, compiled through linear regression, are plotted as well as the mean function multiplied with two standard deviations. In the figures the full line shows the mean velocity level at a certain distance and the crosshatched line shows the mean velocity including two standard deviations.

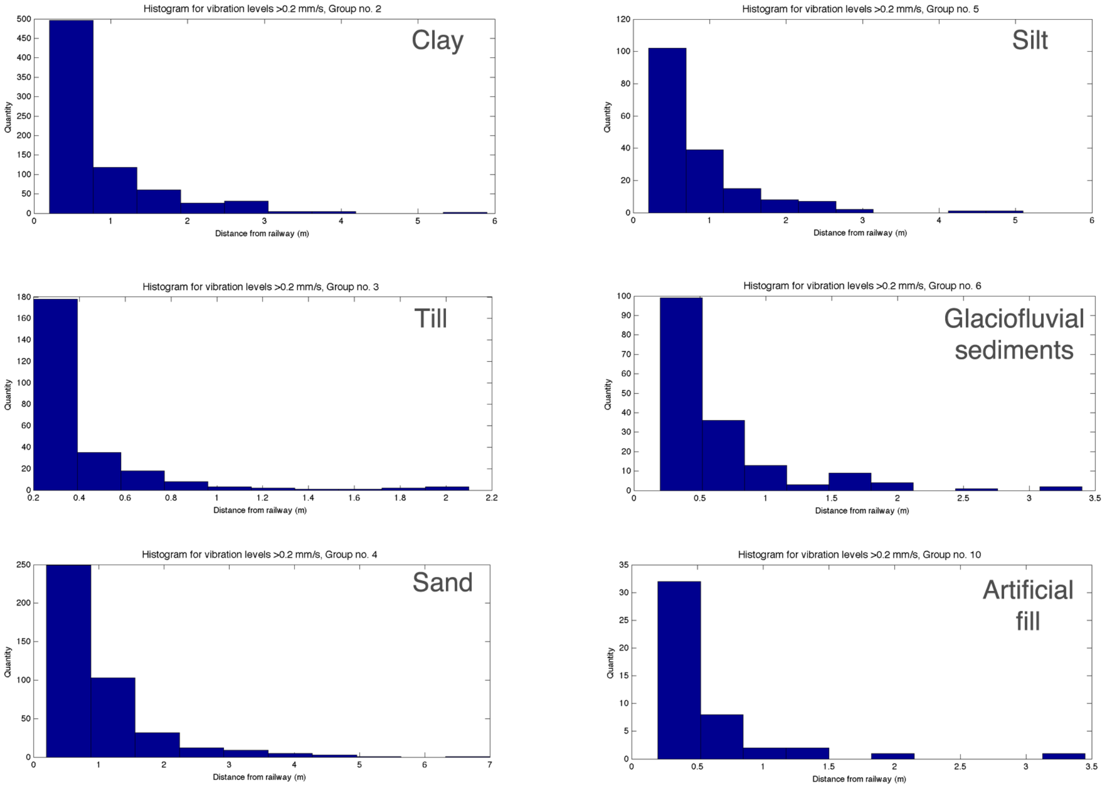


Figure B.1: *Histogram for all vibration levels above 0.2 mm/s included in the model for the soil class group Clay, Till and Sand to the left and Silt, Glaciofluvial sediments and Artificial fill to the right.*

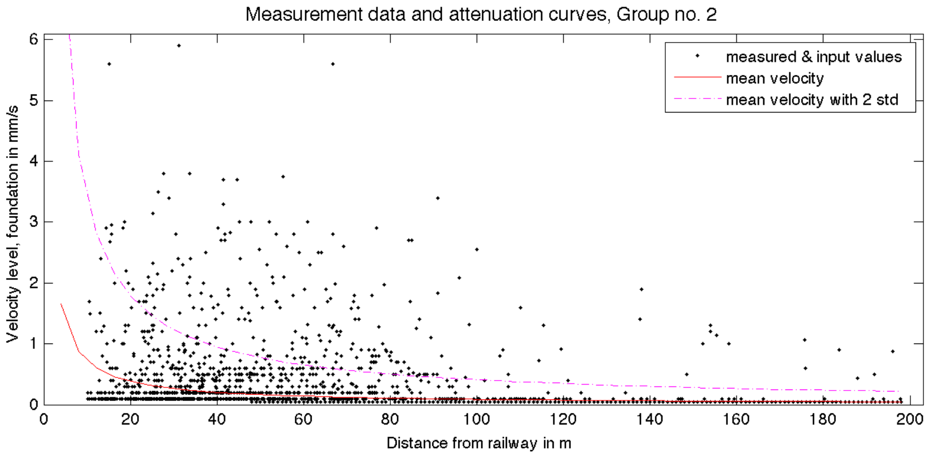


Figure B.2: *Attenuation curves as a mean and multiplied with 2 standard deviations for the soil class group Clay.*

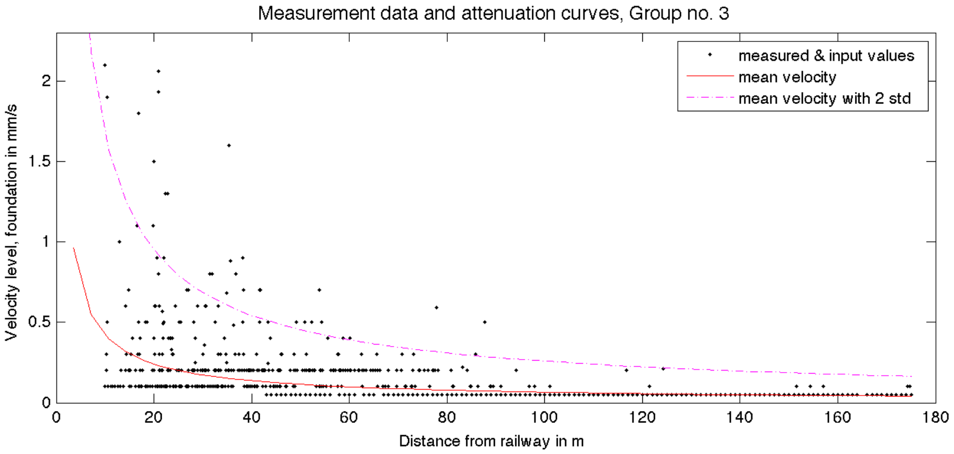


Figure B.3: *Attenuation curves as a mean and multiplied with 2 standard deviations for the soil class group Till.*

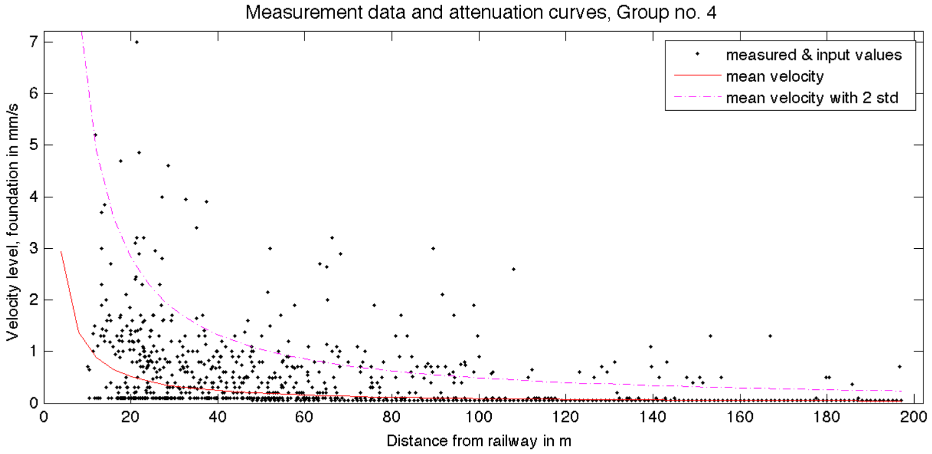


Figure B.4: *Attenuation curves as a mean and multiplied with 2 standard deviations for the soil class group Sand.*

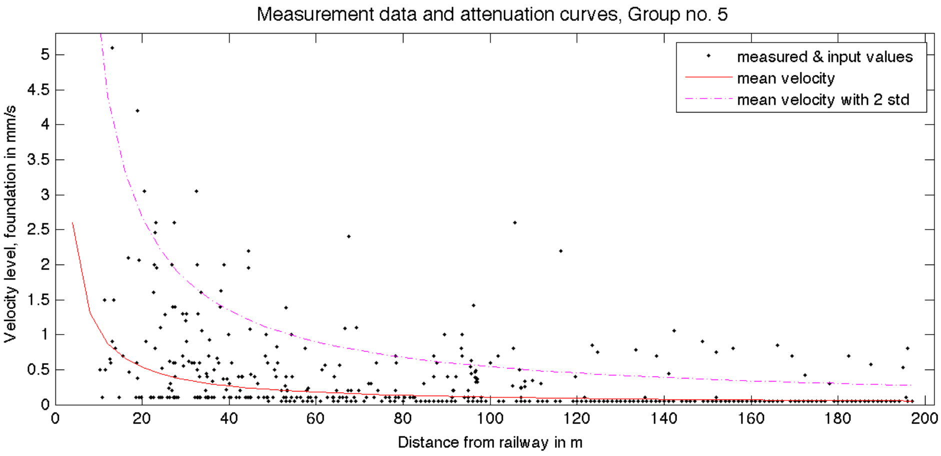


Figure B.5: *Attenuation curves as a mean and multiplied with 2 standard deviations for the soil class group Silt.*

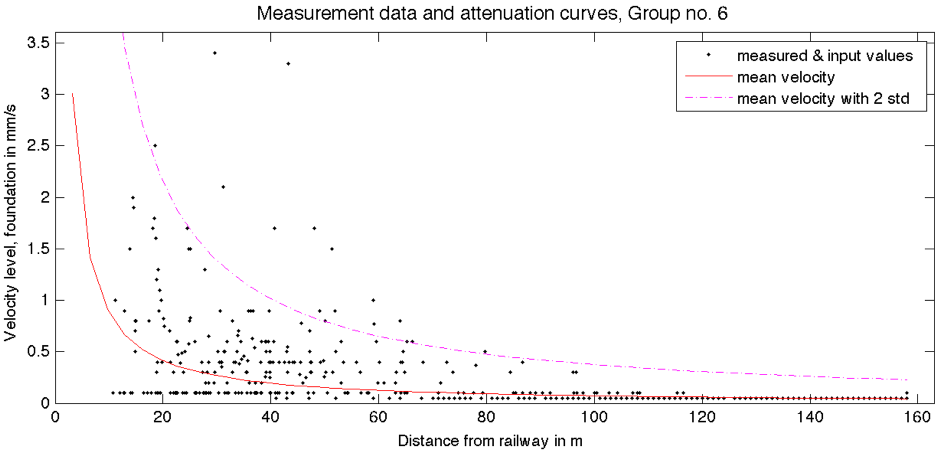


Figure B.6: *Attenuation curves as a mean and multiplied with 2 standard deviations for the soil class group Glaciofluvial sediment.*

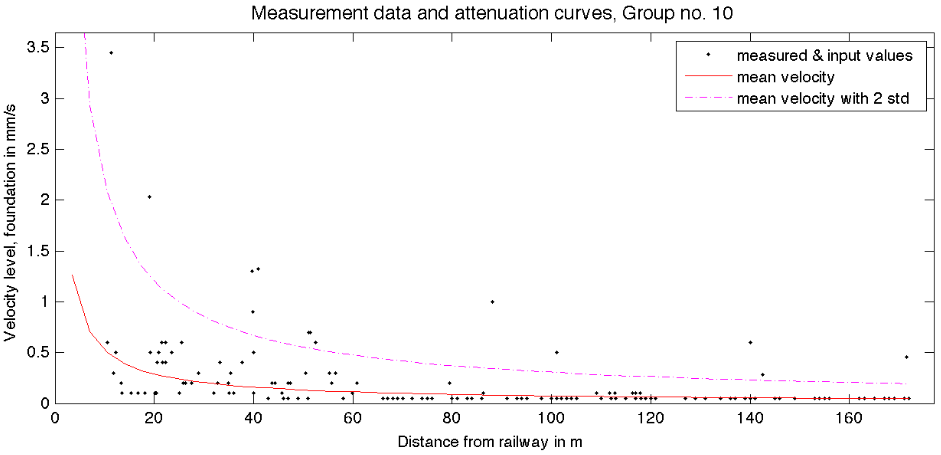


Figure B.7: *Attenuation curves as a mean and multiplied with 2 standard deviations for the soil class group Artificial fill.*