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	Final report on the project		
Author:	Dr.ir. P. Hölscher	Institute:	GeoDelft
Author:	Dr.ir. P.H. Waarts	Institute:	TNO Bouw
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Abstract

The reliability of method for prediction of environmental vibrations is evaluated. An overview of methods for reducing environmental vibrations is presented.

The reliability of the following prediction methods for vibration levels from human sources is evaluated: expert knowledge, simplified calculation models, special advanced models and finite element models. The vibrations are caused by pile driving, vibratory sheet pile driving, and passing busses, lorries and trains. The total reliability is evaluated from the comparison from calculation-results with measurement-results.

For one special case the reliability of finite element methods is studied extensively. Division of uncertainty from parameter estimation, modelling and model are evaluated.

The reliability of simplified models has a good reliability of reliability in proportion to the effort to do a calculation. The reliability of expert knowledge is somewhat lower, the reliability of finite element method is a little bit higher, but the gain in accuracy is disappointing. There are no clear sources of uncertainty discovered, so, improving the reliability of such models is not easy. It is suggested to add more empirical knowledge in the advanced modelling methods.

PROJECT NAME:	Reliability of vibration predictions and reducing measures	PROJECT CODE:	01.05.02
BASEPROJECT NAME:	Environmental impact of underground structures	BASEPROJECT CODE:	01.05
THEME NAME:	Soil and Structures	THEME CODE:	01

Executive Summary

Introduction

Vibrations due to building activities or exploitation of infrastructure might lead to severe hindrance in nearby buildings. To prevent this and to avoid expensive reduction measures during or after completion of the works, vibration levels are estimated beforehand. Several methods are available. To make a good evaluation of the risk of vibration problems and the need of reducing measures, a good knowledge of the available methods is required. If this knowledge is not available, there is a high risk of making wrong decisions during the design: e.g. expensive measures will be applied which turn out to be unnecessary afterwards, or measures will be omitted, which turns out to be necessary afterwards and also much more expensive. Another option to reduce the costs of reducing measures is an accurate knowledge of the efficiency of available measures. This aspect is also studied in the project.

Reliability of predictions

In this project the accuracy of many practical and available methods is compared by comparing the predictions with the results of vibration measurements. This is carried out for practically relevant vibration sources: pile driving, vibratory sheet pile driving, and passing busses, lorries and trains. For each method the reliability is evaluated.

For one case the influence of all components on the reliability of the predictions is evaluated systematically. The influence of the model, the parameter choice and the modelling are distinguished for the application of advanced finite element models. It is concluded that all steps of the modelling are reasonable and all have a more or less similar contribution to uncertainty. Therefore, it is not easy to improve accuracy by conventional means.

For reducing uncertainty, it is concluded that it is needed to include more empirical data into the advanced modelling. This can be done by a more strict validation of the models, or by introducing the results of relevant measurements (e.g. transmission measurements) into the calculations.

Efficiency of reducing measures

Once it is decided that the measured or predicted vibration levels are too high, reducing measures are needed. Based on expert knowledge and literature an overview of commercially available and might be possible measures are worked out. All possibilities are evaluated on (proven or expected) efficiency against costs.

PROJECT NAAM:	Reliability of vibration predictions and reducing measures	PROJECT CODE:	01.05.02
BASISPROJECT NAAM:	Environmental impact of underground structures	BASEPROJECT CODE:	01.05
THEMA NAAM:	Soil and Structures	THEMA CODE:	01

Applicability for the sector

This research is useful for everybody who is involved in vibration problems in building activities and/or exploitation of infrastructure. It shows that reliability of the predictions is limited and suggests that the results don't have absolute value. This is essential information for decision on reducing measures.

Reducing measures can be selected from the overview reports, giving a good start for optimisation of the chosen reducing measures.

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Societal Relevance of the research

Uncertainty is one of the main issues for engineering. This research shows one unknown aspect of uncertainty in vibration engineering: the uncertainty in predictions. This aspect is essential in the decision for applying vibration reducing in construction activities or newly build infrastructure. It offers a good possibility to carry out a complete risk-analysis of the cases in which vibration problems might cause problems in near future, taking into account the uncertainty in our knowledge.

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1 Introduction and overview

1.1 Background of the project

Vibrations generated by various sources might lead to discomfort for people in buildings nearby, malfunctioning of vibration sensitive instruments in buildings nearby or even structural damage of buildings. Pile driving, sheet pile driving, heavy road traffic, railway traffic and industrial processes are the most well known sources of vibrations.

Nowadays, public concern about these so-called environmental vibrations leads to severe restrictions on building activities and development of infrastructure in urban regions. The vibration level in nearby buildings must meet the guidelines (e.g. SBR-guidelines on vibrations). For construction activities or newly build infrastructure this means that the vibration level must be predicted before construction activities can start. If the predicted level is above the allowed level additional measures to reduce the vibration level are needed. These vibration reducing measures are expensive.

In order to be sure that such expensive measures are really needed, knowledge on the reliability of the vibration predictions is required. In order to be sure that such measures are really effective, knowledge on the efficiency of such measures is required. This knowledge is not available. Therefore, this Delft Cluster project “Reliability of vibration predictions and reducing measures” points at the development of this missing knowledge.

1.2 Outline of the research

The research is globally divided in three parts:

- a general study on the total reliability of some prediction models used in engineering practice in the Netherlands
- an exhaustive study to the reliability of finite element predictions and to the background of the unreliability
- a study on the possibilities of reducing measures for vibrations

These three parts are discussed in the chapters 2, 3 and 4 respectively. This report ends with general conclusions and recommendations.

This final report is based on the study reports written during the research. These reports are summarized at the end of the report.

1.3 Partners in the project

The research described in this report is carried out by TNO, GeoDelft, Holland Railconsult and TUDelft. It is supported by Delft Cluster and Project Organization High Speed Railway Link South. A close cooperation exists with the Center for Underground Structures COB the Netherlands.

2 The reliability of prediction models

2.1 Introduction

What is the total reliability of vibration prediction models used in engineering practice? Almost no literature is available on this question related to vibrations. This means that the engineer must make a realistic but conservative estimate of the reliability, normally based on experience. This leads that many (most expensive) reducing measures have to be built, and that many of them may be unnecessarily.

Therefore, this chapter aims at a general well founded idea of the total reliability of generally applied vibration-prediction models and the comparison of the reliability of some typical models. The total uncertainty in the prediction from a specific method captures all types of uncertainty in predictions:

- it includes both model and parameter uncertainty
- it considers the whole system (source, soil and building if present)
- it is worked out for practically relevant cases
- it is based on a level of information available in practice
- it assumes a user with generally accepted experience in applying of the model

The total uncertainty reflects, loosely stated, the prediction uncertainty of a given prediction method.



Figure 1 People living in the neighborhood of railway lines are afraid for vibrations by freight trains

2.2 Methodology

The basic method for gathering information is relatively simple:

- one makes predictions with several models for some many cases,
- and compares the results of these predictions with the results of measurements.

Several methods to determine information on reliability of vibration prediction models are evaluated [de Wit, 2001]. Four sources of unreliability must be taken into account:

1. incomplete information on the physical system
2. incomplete information on the data
3. simplification of the physical modeling of the system
4. discretisation and approximation in numerical solutions

For models which require not much calculation time and have not many parameters, many methods are available, to study the influence of incomplete information on the data (2). However, for time consuming models with many parameters, most methods are not practically applicable.

Moreover, these methods give no information on the other three sources of unreliability (1, 3 and 4). In general it is assumed that the influence of the other sources is relatively small. At the moment this assumption must be studied also in this research, since no information on this aspect is available. This can be done by comparing the results of calculations with the results of measurements. In this research we started with this last part of the method by gathering information on the total unreliability of the available models and then try to find a distribution of the unreliability over the possible sources.

In this research four types of models are considered:

- the expert, just asking an engineer who is believed to have good knowledge of the problem.
Eight experts gave their best estimates for 24 vibration velocities each. For each of the 24 velocities, a measured value was available.
- the simple general prediction model, with a simple description of the physical phenomena.
The CUR-D11 model was chosen [CUR, 1995].
- advanced models which are dedicated to one specific type of problem (so-called specials)
- several finite element models (fem), which are believed to obtain a high reliability

These models are applied to several cases:

- Rotterdam Rochussenstraat; vibrations in a building generated by an underground metro are considered
- Abcoude Thalys; the free field vibrations generated by a high speed train (Thalys) are considered
- Traffic jump Den Haag; the vibrations in a building generated by a heavy lorry on a traffic jumbo are considered
- Traffic jump Wester-Koggenland; the vibrations in a building generated by a heavy lorry and a bus on a traffic jump are considered
- Rotterdam test pit; sheet pile vibrations, the free field vibrations generated by vibratory sheet pile driving are considered

- Overijssel, middle; the free field vibrations generated by a passenger train and a freight-train are considered
- Overijssel, east; the free field vibrations generated by a passenger train and a freight-train are considered
- Delft, van Mourik Broekmanweg; the vibrations in a building generated by vibratory sheet pile driving are considered

Most of the cases are described in [de Wit, Molenaar, 2002] and [Esposito, 2001]. The case Rotterdam test pit is described in [Koopman, 2002], the case “Rochussenstraat” is described by [Gardien, Stuit, 2003] and the case Second Heinenoord Tunnel is described in [Kok, 2002a].

There are many types of sources in the cases. It is impossible to consider all cases with all models. Table 1 shows which models are applied for each case. In chapter 3, the cases calculated with finite element method are studied in more detail, to get information on the influence of parameter-choice on the reliability.¹

location	source	Model			
		expert	D11	special	FEM
Rotterdam Rochussenstraat	metro	1	1		
Abcoude	Thalys	1	1		
Den Haag	lorry on traffic jump	1	1	3	
Wester- Koggenland	bus and lorry on traffic jump	1	1	1	
Rotterdam test pit	vibratory sheet pile driving	1	1		3
Rotterdam test pit	pile driving			1	3
Rotterdam test pit	lorry on traffic jump			1	2
Rotterdam test pit	falling weight				3
Overijssel, middle	passenger & freight train	1	1		1
Overijssel, east	passenger & freight train	1	1		1
Delft, van Mourik Broekmanweg	vibratory sheet pile driving	1	1		

Table 1 Overview of all predictions for total reliability of models

¹ The cases in the Rotterdam test pit are also simulated with the L400 model, which is under development [Kok, 2002b]. It turned out that improvements were required. These improvements are made, but the calculations were too late available to be included in this research.

2.3 Results of the research

2.3.1 Analysis on probability distributions

The results are interpreted by [de Wit, Galanti, 2003]. In all cases the predicted values are compared with the measured values.

The total uncertainty in the vibration velocity v is described by a stochastic factor g and the model estimate value v_{model}

$$v = g v_{\text{model}}$$

The distribution of probability is estimated from the realized values for g , defined by

$$g = \frac{v_{\text{measured}}}{v_{\text{model}}}$$

where v_{measured} is the measured vibration velocity. It is assumed that the error in the measurements can be neglected. From the observed values for g , it is concluded that the distribution of g is lognormal, showing that the uncertainty of the models is considered as being a factor.

Figure 2 gives the frequency distributions for the expert predictions. The frequency distribution is plotted on normal probability paper, so the distribution is assumed to be log-normal. The horizontal axis shows the measured value divided by the predicted value, the vertical axis shows the probability of exceeding. Also a line is fitted on the data. Since this line almost crosses the point (0,0.5), the median is predicted reasonably well.

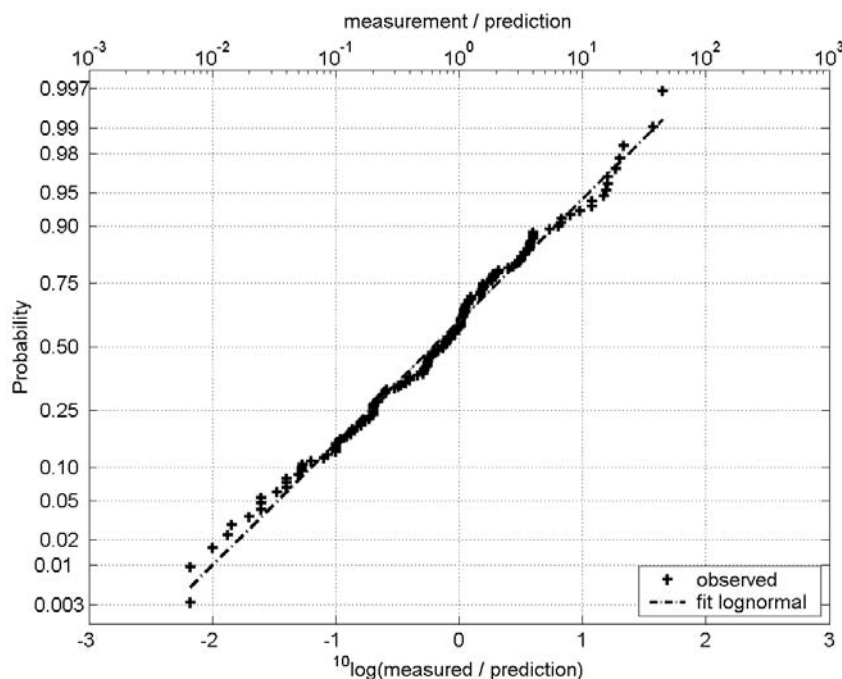


Figure 2 Frequency distribution of $10 \log$ of the ratio of measured values and the experts' best guesses.

Figure 3 shows the frequency distribution for the D11 (simple model) predictions. The Figure can be compared with Figure 2. The fitted line crosses now at (0,0.75). This means that the model overestimates the vibrations, which means a safe approximation. The inclination of the line is almost similar as in Figure 2, so the reliability is more or less the same.

The total uncertainty is expressed by a mean value (the mean under estimation) and a standard deviation. These two values facilitate the estimation of a characteristic value (which will not be exceeded with a given probability). Table 2 shows the results for all models applied in this study. The frequency distributions for finite element calculations are discussed in chapter 3.

Model	Mean value $^{10}\log g$	standard deviation $^{10}\log g$	median (50% limit) g	90% upper limit g
Expert	-0.2	0.77	0.63	10
D11	-0.6	0.8	0.25	11
FEM total	+0.1	0.6	1.25	6

Table 2 Estimates of the mean and standard deviation of $^{10}\log g$ and median and 90% upper limit of g for total uncertainty of models considered in this project

Column 2 and 3 of Table 2 shows the mean value and standard deviation of the log-normal distribution of the model mentioned in column 1. Column 4 shows the coefficient which must be applied to the results to obtain unbiased predictions. A value less than one indicates a tendency to over predict the vibration levels (conservative). Column 5 shows the factor which must be used on the calculated result to obtain a 90% upper limit (the value which will be exceeded in only 10% of the cases).

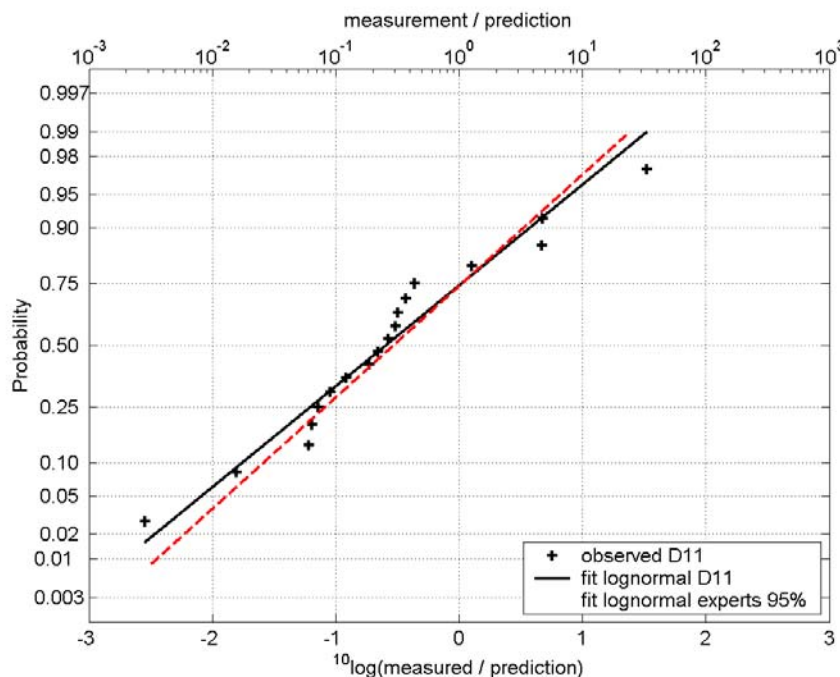


Figure 3 Frequency distribution of the $^{10}\log$ arithm of the ratio of measured values and the D11 predictions. For reference the distribution fitted to the experts' 95-percentiles is also shown (dashed line)

2.3.2 Analysis of expert session based on fuzzy logic

In the previous analysis an expert prognosis is treated similarly as a prediction by a numerical model. However, an expert will not claim knowledge of the vibration level as a numerical value. An expert claims that he can tell you whether a problem will arise or not. Therefore, the treatment by numerical values might be unrealistic for expert prognosis. [Hölscher, 2003] studies an alternative approach, based on fuzzy logic. This approach is useful and has two advantages:

- the real way of thinking of an expert: a vibration level is above, around or below the limiting value of the guideline, is included
- the guidelines are included automatically.

The conclusions are however, more or less similar as the results from the previous analysis. Many times experts give good advice, but many times large errors are observed.

2.4 Conclusions

The total uncertainty of prediction models is calculated. The models expert, D11 and finite element method have a relatively low bias (gmean close to 1). The standard deviation of finite element method is about half the standard deviation of expert. The model D11 has a somewhat higher standard deviation. However, the gain in accuracy from expert to D11 and from D11 to finite element method is rather limited.

3 The uncertainty in advanced prediction models

3.1 Introduction

In general the reliability of a prognosis is influenced by the choice of the model and the choice of the parameters for this model. The main purpose of the research described in this chapter is to distinguish the influence of these two factors.

3.2 Methodology

3.2.1 General description

The basic idea of this work is the following ideal method:

1. several parties predict the vibration level based on the available information
2. the model influence is calculated by comparing the results for several models using the same input data for all models
3. the parameter influence is calculated from the models by a standard parameter variation study
4. from these two influences the total expected uncertainty is calculated
5. the measurements are carried out
6. these measured results are compared with the results of the numerical study.

However, the complexity of the problem and the model make it impossible to follow this ideal line completely. The following work flow with five phases has been created:

1. predictions based on elaborate finite elements calculations by Holland Railconsult, GeoDelft, TNO Building and Construction Research. Each party used the models available and derived the input parameters from all data available.
2. predictions based on elaborate finite elements calculations by Holland Railconsult, GeoDelft, TNO Building and Construction Research and TU Delft. Now the input parameters were based on a common data set.
3. the uncertainty due to parameter choice can be calculated in the ‘design point’ by doing a parameter study for parameter choices around the best estimated values of the parameters.
4. the vibrations are measured.
5. in order to assess the accuracy of the predictions, the predicted vibration levels were compared to measured vibration levels for different vibration sources.

The vibration measurements were all performed at a special test-site, located in the North of Rotterdam, at the ‘van der Duijn van Maasdamweg’. The vibrations were caused by the driving of piles, the vibratory driving and pulling of sheet-piles, a truck driving over a speed ramp and a falling weight.

A series of reports describe the experimental and theoretical work related to the test site at Rotterdam. The project was subdivided into phases, according to the description above. These phases are described in the consequence sections.



Figure 4 Overview of testfield in the north of Rotterdam

3.2.2 Phase 1: Prediction of vibration levels

In the first phase, the predictions of three parties involved (TNO, Holland Railconsult and GeoDelft) were based on the information known about the measurement site and the vibration sources [Koopman, 2002]. The extent of this information was similar to the extent of the information provided in standard engineering practice. Therefore, the information had to be interpreted and converted to parameters that could be used in the models [Pruiksma, 2003a]. The goal of the first phase was to gain an insight in the reliability of vibration predictions used in common engineering practice where in general relatively little detailed information of vibration sources and subsurface is available. Comparing the predictions with measurements for this case gives insight in the overall accuracy of these types of predictions.

It is believed that the difference between predictions and measurements is caused by the uncertainty in the modelling of the subsurface and sources, and the uncertainty in the values chosen for the parameters in the models. The first phase calculations were independent predictions made by the parties involved and have both uncertainties.

3.2.3 Phase 2: Influence of the model

In the second phase, the differences between the models used by the various parties were investigated. To do this, the parameters used in the models were as much as possible brought into line, to reduce the parameter uncertainty when comparing model results with one another. New predictions were made by all parties using this collective parameter set [Pruiksma, 2003b]. The prediction results of the three parties are compared. The goal is to get an impression of the spread of the results for one particular case and compare it with the spread of the model results used in phase one. This comparison results in conclusions about the model uncertainty. If the same subsurface layering and input for source models is used, one might expect a narrow range for the

results of the models used by the various companies. However, the source models used by the various companies are quite different sometimes; hence it's not trivial to find a narrow range of results. Therefore, not only the vibrations at the receiver points are compared, also a detailed comparison of source models is made to get an idea of the cause for found differences in model results [Pruiksma, 2003b].

In phase two, the model results have not been compared with the measurements, since the main goal was to find the differences in models. The collective parameter set was determined to eliminate the differences between models as much as possible. Hence, the phase two parameter set was not intended to be the best approximation of the measurements.

At this time two more fundamental questions had to be answered:

- Are the results the finite element programs accurate
- How the damping must be treated to obtain similar results for all finite element programs

The first question occurred since two finite element programs used direct time integration, and a third calculated in the frequency domain with inverse fast Fourier transform at the end. Time integration schemes and element types differ fundamentally. One simple case: 'half space with a pulse loading' was calculated using all programs. [Gardien, *e.a.*, 2003]. At the end the results of all programs were identical, so this is not a source of uncertainty. However, the first series of calculations showed differences due to (minor) errors in the input. Sometimes results were obviously wrong, but some errors were that small (order factor 2) that they were not seen, until the results of all models were compared. Human errors can not be ignored!

The second question occurred since each finite element model and partner had its own definition of damping and it was not known whether all these definitions were in accordance. Therefore, a more fundamental report on damping is presented [Hölscher, 2002a]

3.2.4 Phase 3: Influence of the parameter choice

Phase three of the project was a more detailed investigation in the parameter uncertainty.

The research was started by gathering more precise information about the soil data, in order to define a parameter set as close as possible to the so called 'design point' [Hölscher, 2002b]. Borings were made and laboratory tests of the soil were performed to find densities and damping values. Also vertical seismic profiling tests were used to determine shear modules. Based on this information of the subsurface, the mean value and the range were determined for each parameter. If one chooses a value within that range, that value would still be considered realistic by all parties involved.

With the average parameters resulting from this study, the falling weight problem was calculated again by all parties and results are compared with the measurements. The results are expected to be closer to the measurements because of the more detailed information of the subsurface that has been available.

For the falling weight problem a sensitivity study has been made to see in what range the results can lie depending on the range of the chosen parameters. The sensitivity study was performed by one party to eliminate model uncertainty and study parameter uncertainty only.

3.2.5 Phase 4: Measurements

The measurements were carried out. This was done already after completion of phase 1, but measures were taken to be sure that no one of the researchers involved in the phases 2 and 3 had knowledge of the measurement results.

The measurements are reported in [de Wit, 2003]. The measured data are available in digital format.

3.2.6 Phase 5: Total uncertainty

Based on these results the uncertainty of advanced prediction models can be analyzed (see also table 2, in chapter 2).

3.3 Some results

3.3.1 Total uncertainty

Figure 5 shows the result of the analysis of total uncertainty. From this Figure, the total uncertainty can be derived: *e.g.* if the probability of exceeding a certain value is supposed to be 10%, the calculated value must be multiplied by a factor 8. Further study showed that for this case this number depends on partner. On average the finite element predictions are almost unbiased. Figure 5 shows also the experts' best guess. Since the line for finite element calculations is steeper, the finite element method is a bit more reliable.

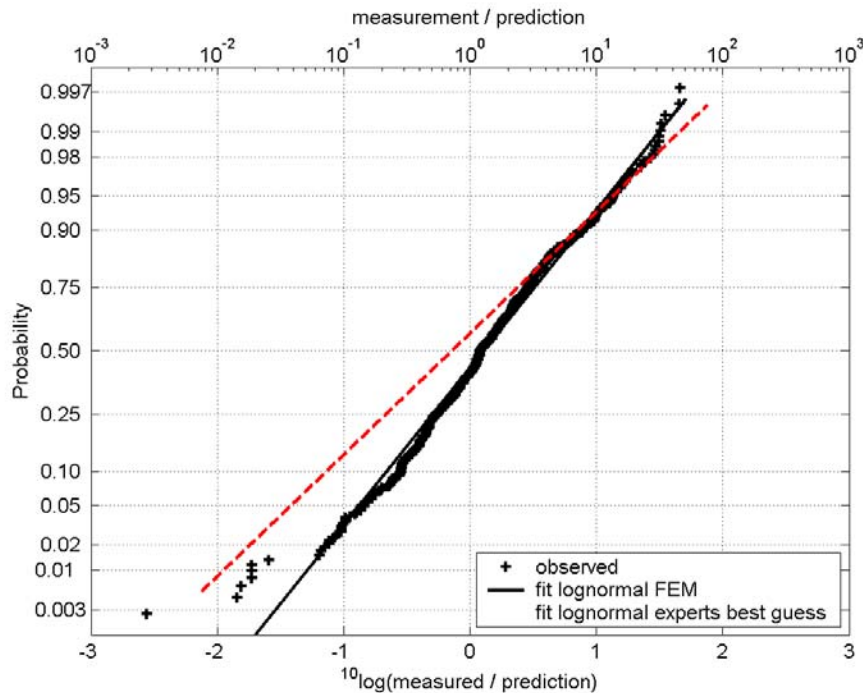


Figure 5 Frequency distribution of the $10\log$ arithm of the ratio of measured values and the FEM-predictions. For reference the distribution fitted to the experts' best guesses is also shown (dashed line)

3.3.2 Source models

[Pruiksma, *e.a.*, 2003b] compared the results of the source models for the all partners. The comparison is carried out with identical parameters for all models, so phase 2 parameters. Therefore, the differences encountered are mainly related to modeling aspects.

For pile driving only the total force exerted by the pile on the soil can be studied. The maximum load differs up to a factor 7. The time dependence of the load and the distribution of the loads over the pile toe and pile shaft differ strongly. Thus the source models for pile driving are essentially different.

For sheet pile-driving a more or less similar result has been obtained: the maximum force diverges (up to a factor 3) and the distribution over shaft and toe diverges strongly.

For the traffic-problem the time dependant behavior of all models are more or less the same, but the maximum values differs up to 50%.



Figure 6 Pile driving: a very difficult source to describe

3.3.3 Soil model

The transmission in the soil, which modeled with advanced models, is studied separately. The transfer functions from a surface load to some measurement points in the soil are calculated for a frequency ranges relevant for road-traffic, pile driving and sheet pile driving. Both phase 1 and phase 2 parameters are taken into account.

Figure 7 shows the resulting uncertainty, using phase 1 parameters. For reference the distribution fitted to the FEM-predictions for the system source+soil is also shown (dashed line). This Figure clearly shows that

- the median of the predicted values doesn't coincide with the 50% probability; for the final predictions using these results, the predicted value does coincide with the 50% probability.
- the uncertainty in the soil system is larger than in the soil-source system

It seems that the choice of the source model compensates the differences in the soil model.

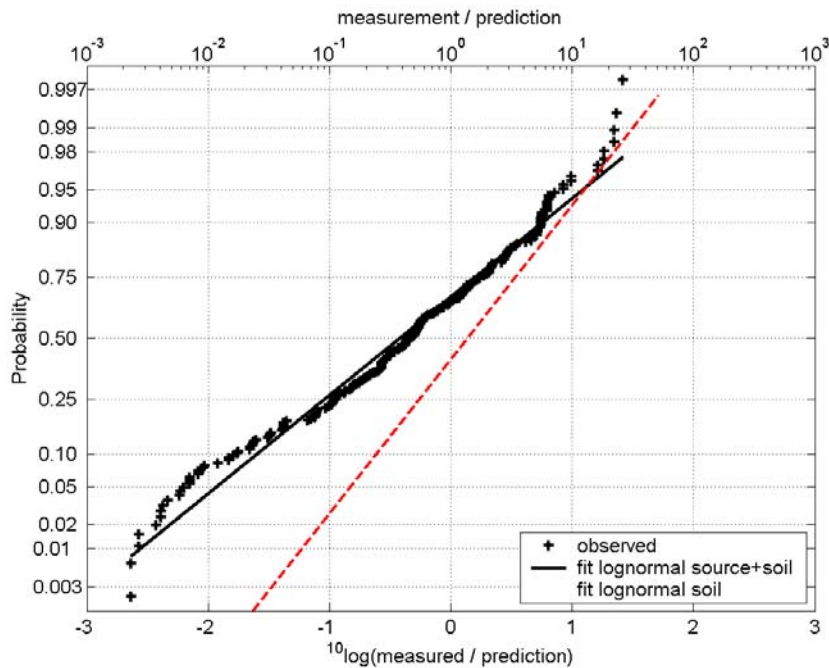


Figure 7 Frequency distribution of $10 \log$ of the ratio of measured values and the FEM-predictions for the soil only. For reference the distribution fitted to the FEM-predictions for the system source soil is also shown (dashed line)

Table 3 summarizes numerically the total uncertainty in the soil model (using phase 1 parameters) with the uncertainty in the full model of soil and source (compare Table 2).

Model	Mean value $10 \log g$	standard deviation $10 \log g$	median (50% limit) g	90% upper limit g
FEM total	+0.4	0.9	2.5	14
FEM soil	+0.1	0.6	1.25	6

Table 3 Total uncertainty of fem model for soil only compared with soil and source

For the model uncertainty, the parameters of phase 2 must be used. Then, the median does coincide with 50% probability and the uncertainty halves compared with the total uncertainty. This last observation means that the parameter uncertainty and the model uncertainty each are of equal importance. Here it is noted that the layering is treated as a part of the parameter uncertainty.

3.4 Additional analysis of influences

In the previous Section a backward calculated estimation of model and parameter uncertainty was given. That analysis gives useful numbers, but limited knowledge of the backgrounds. In this section some aspects are evaluated.

3.4.1 Sensitivity of transmission to soil parameters

The sensitivity of the transmission to soil parameters can be estimated by a traditional parameter study. This is carried out for the case at the test pit [Koningen, 2003]. The best estimate of phase 2 was chosen as design point; the layering was based on the mean value of the vertical seismic profiling measurements [Hölscher, 2002b]. Two aspects were tested:

- Is it reasonable to add thin layers with more or less identical parameters to one layer
- Which parameters are important

This study resulted in the following answers:

- Adding thin layers to thicker layers with mean properties is not advised. This might lead to errors
- The most sensitive layers are the layers in which the source and the receivers are placed. Intermediate layers are less sensitive

The falling weight tests in the test pit, see Section 3.2.5, are used to derive the measured transfer functions in the frequency domain from a surface source to the measurement-points in the soil. These functions are also derived from the calculated results from the partners.

3.4.2 Estimation of soil parameters

In practical engineering most parameters are roughly estimated. Others are measured very carefully, but several methods are available. In order to gather knowledge of the accuracy, several methods are applied in this test pit case [Hölscher, 2002b]. The parameters used in the first and second phase are evaluated against more accurate measurements. This study showed that initial rough predictions were sometimes very wrong; but also several ‘accurate’ measurement methods give differences which are significant.

Moreover, it turned out that experts overestimate the accuracy of roughly estimated parameters: the originally indicated accuracy limits are exceeded often when a parameter is measured more accurately.

3.3.4 The assessment of parameters

In the test pit case it is assumed that all parameters are measured separately. However, a measurement of transfer functions might be more accurate. This aspect is evaluated for a special case, the vibration test carried out by [Lombaert, 2001] at a test site in the south of the Netherlands. Lombaert measured the soil properties by SASW tests and VSP tests. He simulated the problem with an advanced model.

This problem was studied in detail using the GeoDelft model for vibrations from traffic [Hölscher, Pruiksma, 2002]. The influence of the modeling and the parameters choice were studied. For the modeling the differences between axle load or wheel load and the influence of the road was studied. These turned out to be strong, up to a factor 3 for this case. For the parameter choice both parameter sets were used.

This influence was also strong. Similar results were obtained with different parameter sets with different models.

Therefore it is not uniquely possible to decouple parameter- and model uncertainty. Parameter assessment might be an essential part of a model. Or, in other words, the total reliability of a model depends on the method of parameter assessment.

3.4.3 Analytical solution wave propagation in the soil

In problems of environmental vibrations the propagation of waves in the soil plays an important role. In the Dutch case of soft soil it is expected that the dynamic deformation of the interface between a structure and the soil is small. It might be useful to possess a solution for wave propagation in the soil, taking into account the fact that the interfaces do not deform. The possibilities of such solutions using analytical methods are studied in [Kok, *e.a.*, 2003].

3.5 Conclusions

The contribution of several aspects to the reliability of advanced prediction models is studied carefully. A division of uncertainty in a contribution due to parameter choice and due to model is tested and turned out to be too limited. Influence of modeling (and the engineer who models) cannot be neglected. The aspects can not be separated completely.

However, the following aspects are worthwhile to memorize:

- finite element models have a small pure model inaccuracy, but the contribution of modeling uncertainty is large
- for source models are not generally accepted descriptions available, so large contribution of model uncertainty can be expected
- parameter uncertainty is of the same order as modeling uncertainty
- uncertainty is well spread over all components of the prediction (source, transmission, receiver)
- usage of empirical data in predictions is advised

4 The possibilities of reducing measures

Another part of the project studies the possibilities of reducing measures. Reducing measures are needed if the vibration level is (expected to be) too high. Two studies are carried out.

- Eight experts are interviewed in an electronic board room
- Two literature reviews are carried out, pointing at measures for vibrations from rail traffic.

4.1 Expert opinions

The expert opinions are collected in a session in the electronic board room [van Duin, 2001]. The group of experts was identical with the group referred to in chapter 2

The session was divided into three parts

1. Mention all measures you have seen or have seen suggested in your experience or mentioned in literature. Please add all ideas of your own for possible measures
2. For all measures mentioned at step 1, please specify the measure, the field of application, the known experience (calculation of measurement) and the expected efficiency. Now all suggestions are grouped in location measure (source, soil, and building) and type of source (rail- and road traffic, pile driving, vibratory sheet pile driving).
3. Finally all measures are evaluated by all experts, leading to a rating (10 very useful, 1 useless). After collecting all expert opinions an overview of most promising measures is presented.

This research leads to a report which shows a complete overview of the state of the art.

For constructions activities many measures were seen, but most of them already used in practice. For rail traffic track maintenance was chosen to be important together with structural measures (spring-systems) in the track and the building.

4.2 Literature review for rail traffic

Two aspects were evaluated: Measures at the building [Garito, Koopman, 2001] and measures at the track [Russelli, Koopman, 2002]

[Garito, Koopman, 2001] discuss the measures for buildings. This type of measures is well-known from earthquake engineering. It consists of base isolation by springs and adding artificial damping to the building. The reports show an overview of commercially available materials and components.

[Russelli, Koopman, 2002] discuss the measures for rail structures. All components are inspected thoroughly, based on commercially available components. For all possibilities expected vibration reductions are estimated, based on test and other data for each component. Also the prices are evaluated. It turns out that many reducing measures are available, but prices are high an optimized spring mass system cost up to 5000 k € per track kilometer, 10-20 times the price of conventional track on sleepers.

5 Conclusions and recommendations

5.1 Conclusions

In this report a detailed study of the reliability of vibration prediction models is summarized. All types of prediction models are compared. The reliability of finite element models is studied in more detail. Possibilities for reducing vibrations are listed.

Comparing models showed that all models give in the average predictions which are unbiased. The uncertainty in the models decreases from expert model, the simple model to advanced finite element. Thus, the advanced models give slightly higher reliability. It turns out that the reliability of the models can be improved.

For the advanced finite element models the reliability is studied in more detail. No clear reason of unreliability is found. This means that all aspects are of more or less equal importance: parameter choice, experience of the engineer, quality of the (source)-model.

With respect to reducing measures an overview of possibilities is listed and expert opinions on promising measures is gathered. These activities lead to a good overview over all possibilities, but no new methods are found.

5.2 Recommendations

With respect to vibration predictions it is recommended to include more results of measurements into the modeling effort. This holds for both simple and advanced models.

Models must be verified more thoroughly. Introduction of ‘new’ models and ‘improvement’ of existing models must be critically evaluated against relevant measurements. These results must be reported truly.

In order to improve the quality of prediction models it is recommended to create an ‘open’ database, which can be used by all who add results into the database.

The reliability of the predictions must be taken into account. The results presented in this research can be considered as a good estimate, if no better data are available.

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measurement data

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General Appendix: Delft Cluster Research Programme Information

This publication is a result of the Delft Cluster research-program 1999-2002 (ICES-KIS-II), that consists of 7 research themes:

► Soil and structures, ► Risks due to flooding, ► Coast and river , ► Urban infrastructure, ► Subsurface management, ► Integrated water resources management, ► Knowledge management.

This publication is part of:

Research Theme	:	Soil and structures		
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Project name	:	Reliability of vibration prediction and reducing measures		
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Project number	:	01.05.02		
Projectduration	:	01-03-2000	-	31-06-2003
Financial sponsor(s)	:	Delft Cluster		
		TNO Bouw		
		GeoDelft		
		Projectorganisatie HSL Zuid		
		TUDelft		
		Holland Railconsult		
Projectparticipants	:	GeoDelft		
		TNO Bouw		
		TUDelft		
		Holland Railconsult		
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Number of involved PhD-students	:	0		
Number of involved PostDocs	:	0		

Delft Cluster is an open knowledge network of five Delft-based institutes for long-term fundamental strategic research focussed on the sustainable development of densely populated delta areas.

Name	Organisation
Dr. ir. P. van den Berg	GeoDelft
prof. dr. ir. J. Rots	TNO-Bouw

Projectgroup

During the execution of the project the researchteam included:

Name	Organisation
1. Dr. ir. P.H. Waarts	TNO Bouw
2. Dr. ir. P. Hölscher	GeoDelft
3. Dr. ir. A.W.M. Kok	Delft University of Technology
4. Dr. ir. H. Stuit	Holland Railconsult

Other Involved personnel

The realisation of this report involved:

Name	Organisation
1 dr.ir. P. Hölscher	Geodelft
2 dr.ir. P. Waarts	TNO Bouw
3 dr.ir. H.G. Stuit	Holland Railconsult
4 dr.ir. M.S. de Wit	TNO Bouw
5 ir. J.P. Pruiksma	Geodelft
6 dr. ir. A.W.M. Kok	TU Delft