**Title:** Reliability of vibration predictions  
**Synthesis of predictions and measurements**

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Abstract

In this report the reliability of vibration predictions in civil engineering is quantified. Emphasis is laid on the vibration predictions for road- and rail traffic and vibrations from building activities such as (sheet)pile driving.

Several kinds of prediction techniques were used: expert opinion, very simple empirical models, dedicated models, and FEM. The prediction techniques were applied by four different institutes which are leading in the Dutch practice in vibration prediction: TNO, GeoDelft, Delft University and Holland Railconsult. Predictions were generated for a variety of characteristic situations. The predictions were compared with measurements. Besides the total uncertainty, which can be derived from the difference between prediction and measurement, a break-down of the uncertainty sources was made.
Executive Summary

In civil infrastructure where vibrations can arise either during the construction or the exploitation phase it is usual to determine firstly what vibration levels can be expected using a model and then to compare these levels with those supplied in standards or directives. The reliability of these models is presently unknown. Even the question whether a sophisticated model produces more reliable answers than an empirical model cannot be answered.

To increase confidence in vibration predictions and to stimulate their use as a basis in decision making processes, it is important that these issues are resolved. Within the framework of Delft Cluster, the project 01.05.02 “reliability vibration predictions and reducing measures” has been set up for this purpose. One of the main goals of this project is to quantify the uncertainty in the vibration levels, which are calculated using mathematical models. The study must also provide insight into which elements of such models contribute dominantly to this uncertainty. With this knowledge it should then be possible to look for means to reduce the uncertainty in the results.

The central question in this study concerns the reliability of vibration predictions, using this models. To answer this question, the uncertainty in the predictions has to be analyzed. This uncertainty may result from essentially four sources:
1. incomplete information about the specification of the system;
2. incomplete information about the input and the boundary conditions;
3. simplifications and approximations in the physical modeling;
4. discretizations and approximations in the numerical modeling.

Several types of predictions have been analysed:
- expert opinion
- very simple empirical models (D11)
- dedicated models (GeoDelft pile-driving)
- Finite Element model (FEM) (modular)
- 3D Finite Element model

For each type of prediction we aimed to assess the total uncertainty, i.e. the uncertainty in predictions:
- for the whole system including source, soil and building subsystem.
- based on a level of information as commonly available in practice

For predictions on the basis of FEM (mainly first principles based modeling approach), an attempt was made to break down the total uncertainty into:
- contributions from the various subsystems
- contributions from the various sources of uncertainty (model versus parameter uncertainty)

In order to be able to answer these questions a number of studies have been performed in which vibration predictions have been compared to measured vibration levels in different situations.

It can be concluded that the uncertainty in vibration predictions in civil engineering applications is quite large, typically 1 order of magnitude. The bias in the predictions is relatively small. The uncertainty in vibration predictions reduces from a factor 20 to a factor 5-10 when in stead of expert judgment, sophisticated computational FEM-models are used. Although this is a significant reduction, the residual uncertainty remains large. A partial explanation is that the modeling choices that have to be made are decisive for the uncertainty in the predictions. These choices are, in the end, based on expert judgment.

<table>
<thead>
<tr>
<th>PROJECT NAAM:</th>
<th>Reliability of vibration prognosis and reducing measures</th>
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<tbody>
<tr>
<td>BASISPROJECT NAAM:</td>
<td>Environmental impact of underground construction</td>
</tr>
<tr>
<td>THEMA NAAM:</td>
<td>Soil and Structures</td>
</tr>
<tr>
<td>PROJECT CODE:</td>
<td>01.05.02</td>
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<tr>
<td>BASISPROJECT CODE:</td>
<td>01.05</td>
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<tr>
<td>THEMA CODE:</td>
<td>01</td>
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</tbody>
</table>
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1 Introduction

In civil infrastructure where vibrations can arise either during the construction or the exploitation phase it is usual to determine firstly what vibration levels can be expected using a model and then to compare these levels with those supplied in standards or directives. The reliability of these models is presently unknown. Even the question whether a sophisticated model produces more reliable answers than an empirical model cannot be answered.

To increase confidence in vibration predictions and to stimulate their use as a basis in decision making processes, it is important that these issues are resolved. Within the framework of Delft Cluster the project 01.05.02 “reliability vibration predictions and reducing measures” has been set up for this purpose. One of the main goals of this project is to quantify the uncertainty in the vibration levels, which are calculated using mathematical models. The study must also provide insight into which elements of such models contribute dominantly to this uncertainty. With this knowledge it should then be possible to look for means to reduce the uncertainty in the results.

In order to be able to answer these questions a number of studies have been performed in which vibration predictions have been compared to measured vibration levels in different situations. For an overview see Hölscher & Waarts (2003). In this report the results of all these studies are brought together, analysed and compared.

In the next chapter an introduction on the prediction of vibration levels is presented. Chapter 3 addresses discusses the uncertainty in vibration predictions. Various sources of uncertainty are addressed, the representation of uncertainty is touched upon and it is explained how the uncertainty in the predictions has been quantified in the project. Chapter 4 subsequently describes the set-up of the study and briefly discusses the various prediction tools and methods that have been applied. Chapter 5 presents the results of the study, i.e. an analysis of the uncertainty in vibration predictions. Chapter 6 finally, closes the report with conclusions and recommendations.

2 Prediction of vibration levels

Just like sound, vibrations are a short disturbance of balance. Sound can be seen as a vibration of air. It is characterized by a power level in dB, and a pitch or a frequency. The frequency reproduces the number of vibrations per second. This is expressed in Hertz (Hz). As for sound the vibration of solid objects (soil, buildings) are characterized with a vibration level and vibration frequency in Hertz. Mostly the highest value of the vibration velocity ($v_{\text{max}}$) is used for the assessment of damage to buildings due to vibrations. The effective value of the vibration velocity ($v_{\text{eff}}$) is mostly used for the assessment of nuisance for people in buildings due to vibrations (Waarts & Ostendorf, 2002).

To predict these vibration levels, various techniques can be used. Table 2-1 shows the techniques that have been considered in this study.
Table 2-1 Classification of prediction techniques according to level of sophistication.

<table>
<thead>
<tr>
<th>prediction technique in this study</th>
<th>level of sophistication</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 expert judgment</td>
<td>without explicit models</td>
</tr>
<tr>
<td>2 D11-model</td>
<td>empirical models</td>
</tr>
<tr>
<td>dedicated models</td>
<td></td>
</tr>
<tr>
<td>CUR/COB vibration model</td>
<td></td>
</tr>
<tr>
<td>3 FEM-models</td>
<td>first principles models</td>
</tr>
<tr>
<td>- modular</td>
<td></td>
</tr>
<tr>
<td>- full</td>
<td></td>
</tr>
</tbody>
</table>

As the tables indicates, prediction of vibration levels can be done at various levels of sophistication. Here we distinguish three levels:
- without explicit models (‘expert judgment’) [Level 1]
- with an empirical model [Level 2]
- with a model derived from first principles [Level 3]

The first level concerns predictions, which are made on the basis of experience without the help of explicit models. Predictions at this level are often elicited from specialists in cases where a quick and cheap assessment has to be made, e.g. to determine whether a problem may potentially occur or not. We will refer to this type of predictions as ‘expert judgments’. Empirical models are primarily constructed from experimentally obtained input/output data, with only limited or approximate recourse to laws concerning the fundamental nature and properties of the system under study. With this type of models predictions can be produced on the basis of concise and often coarse-grained input about the system.

At the highest level of sophistication are the predictions based on models, which are derived from first principles. Among this type of models are the Finite Element Models (FEM) and the multi-body models, which are regularly used in vibration modeling. These models require detailed input and are generally expensive to build and to run. They are typically applied in alleged problem situations and/or to evaluate mitigating measures.

At sophistication levels 2 and 3 in Table 2-1, explicit models are used to obtain predictions of vibration levels. These models commonly consist of three sub-models, which are connected as shown in Figure 2.1.

![Figure 2.1 Subsystems in a model for the prediction of vibrations, and their connections.](source)

The figure expresses that vibrations are generated by a source in one place, propagate through the soil by some mechanism and subsequently result in vibrations in a construction or building at another location. It is common practice to model the three subsystems separately, and to connect them afterwards to make predictions.
The prediction techniques at level 2 mentioned in Table 2-1 indeed provide models or modelling approaches for source, soil and building subsystems. However, the FEM-technique mentioned at level 3 in this table is in fact a very general numerical technique, which can be applied to a variety of problems, including vibration prediction. Moreover, in predictions involving the FEM-approach, the source subsystem is commonly not modelled with FEM. Therefore, to avoid misapprehensions, we define the prediction technique ‘FEM’ in the context of this study as multibody dynamic systems. The models are built out of systems of many masses coupled with springs and dampers.

3 Uncertainty

The central question in this study concerns the reliability of vibration predictions. To answer this question, the uncertainty in the predictions has to be analyzed. This uncertainty may result from essentially four sources:
1. incomplete information about the specification of the (sub)system under study.
2. incomplete information about the input and the boundary conditions of the (sub)system.
3. simplifications and approximations in the physical modeling of the (sub)system.
4. discretizations and approximations in the numerical modeling of the (sub)system.

As an example we consider the soil subsystem. When modeling the behavior of the soil, uncertainty from the first source is always present. Indeed, only limited information about the soil structure and properties is available in practical contexts. The second source also contributes to the uncertainty. First, there is the uncertainty in the input data from the vibration source model. Second, the source model may not provide all required input/boundary conditions. Uncertainty from the third source is directly related to the modeling level discussed in the previous section. For practical situations, uncertainty from this source in case of a FEM modeling approach is expected to be small compared to an empirical modeling approach. Theoretically, the translation of the physical soil-model into a numerical model may introduce extra uncertainty in the FEM-approach, but we will assume here that this is a negligible contribution.

In the remainder of this report we will refer to uncertainties from the first two sources as ‘parameter’ uncertainty. Loosely stated, this is the uncertainty that arises from our limited knowledge about the state of the world: which system are we modeling and what exactly is driving it? Uncertainty from the third and fourth sources is addressed as ‘model’ uncertainty. This uncertainty may be associated with our lack of knowledge about how the system works: given that we know the structure of the system, its properties and the forces driving it, what is the system’s response? In practice, the distinction between parameter and model uncertainty is not always clear, especially as the models become more empirical. A more elaborate discussion can be found in Wit (2001).

In practice, uncertainty is not explicitly accounted for. Vibration predictions are point-estimates (‘best guesses’ or ‘conservative’ estimates), which have an unknown deviation from the actual values. We write:

\[ v_{\text{obs}} = g \times v_{\text{point}} \] (1)

where:
- \( v_{\text{obs}} \) observed or actual vibration level
- \( v_{\text{point}} \) point estimate of vibration level
- \( g \) prediction factor

and consider \( g \) a random variable. If we assign \( g \) a probability distribution, which, on the long run, matches the frequency distribution of \( v_{\text{obs}}/v_{\text{point}} \), we may consider this probability distribution a measure of the (average) uncertainty in vibration predictions. Hence the approach in this report will be to assess frequency distributions on the basis of recorded values for both \( v_{\text{point}} \) and \( v_{\text{obs}} \) in a large
number of cases. Note that we assume here that the observed value $v_{obs}$ equals the actual value without observation error.

By using this approach we implicitly choose to represent uncertainty in terms of probability. This representation is adequate for the applications of concern in this work and it has been studied, challenged and refined in all its aspects (see also Wit, 2001).

4 Approach

4.1 Introduction

As mentioned in the previous paragraph, we estimated the prediction uncertainty on the basis of a statistical analysis of values for $v_{obs}/v_{point}$, recorded in a large number of cases. In this process we distinguished between the 5 prediction techniques mentioned in section 3. For each technique we aimed to assess the total uncertainty, i.e. the uncertainty in predictions:

- for the whole system including source, soil and building subsystem.
- based on a level of information as commonly available in practice

For predictions on the basis of FEM (mainly first principles based modeling approach), an attempt was made to break down the total uncertainty into:

- contributions from the various subsystems
- contributions from the various sources of uncertainty (model versus parameter uncertainty)

In this report only a partial breakdown is investigated as shown by Table 4-1.

Table 4-1 Breakdown of the uncertainty in vibration predictions into prediction technique, subsystem and type of uncertainty ('par': parameter, 'mod': model, 'tot': total). The crosses indicate which items are addressed in this report.

<table>
<thead>
<tr>
<th>technique \ subsystem</th>
<th>source</th>
<th>soil</th>
<th>building</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>par</td>
<td>mod</td>
<td>tot</td>
<td></td>
</tr>
<tr>
<td>expert</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>D11</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>CUR/COB (L400)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dedicated</td>
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<td></td>
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<tr>
<td>FEM modular</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>FEM full</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

All uncertainty assessments are based on statistical analyses of the ratio between measurements and predictions. Hence, predictions were collected for cases or situations, where reliable measurements were or could be made available. In all cases it was seen to that the predictions were done without any prior knowledge of the measured values.

The table shows, that although CUR/COB model L400 has been considered in the set-up of the study, unfortunately no predictions with this model have been included in the analysis.

The next sections describe the experimental set-up for the various prediction techniques separately.
4.2 Expert

As shown in Table 4-1 only the total uncertainty was estimated at this level. As experts do not use explicit models, decomposition of the uncertainty was not possible.

Eight experts were selected as a representative sample of professional consultants active in the building and construction industry in the field of vibration modeling and/or measurement. The experts had to make 24 predictions of vibration levels in 7 different cases. These cases were selected from a large number of historical cases to form a representative set. All three subsystems (vibration source, soil and building) were involved. The cases were described at a level of detail that is customary in practical situations. For a description of cases and measurements see Hölscher & Waarts (2003), Wit & Molenaar (2002).

To prepare themselves, the experts were given global, qualitative information about the cases 2 days prior to the elicitation session. The experts’ assessments were obtained through an Electronic Board-room-session. The experts were located in the same room, each seated behind a separate computer connected to a network. All experts received the same information and explanation, and made their assessments solely on the basis of their experience and background literature they brought along. They simultaneously and independently entered their assessments into their computer, without discussion with the other experts. The time available for each assessment was approximately 10 minutes on average.

The assessments consisted of values for $v_{\text{eff}, \text{max}}$ or $v_{\text{max}}$ (see section 2). For each variable, two predictions were required, i.e. a median value or ‘best guess’, and a value which in their opinion would not be exceeded with 95% probability.

The prediction uncertainty was calculated from comparisons between the predictions and the measurements (see section 3). A preliminary analysis was carried out immediately after the elicitation session. The results were presented to the experts in the same session as immediate feedback. For more information see Wit & Molenaar (2002).

An analysis of the results can be found in section 5.2.2.

4.3 D11

At this level, one single prediction tool was used, called D11 (CUR 1995). This tool is based on empirical models. The model consists of three main modules:

a source module, in which the source of the vibration is characterized;
a ground module, which describes the spreading of vibrations through the soil
a building module, in which the transfer of vibrations to the building and the response of the building are described

The source model is based on simple mathematical models that are tuned to measurement results. Relevant parameters are derived for three standard sources: road traffic, rail traffic and piling activity. The relevant parameters that determine the vibration transfer via the soil are described for three characteristic types of stratified Dutch soil profiles. The vibration transfer is modeled using FEM. The outcome of FEM models is translated into simple models.

In the building module the transfer of the free field vibration at the base of the foundations to a specific point in the building is described with the aid of empirical amplifications factors

As the user has hardly any influence on the results (limited number of choices to make in doing the predictions, choices are quite obvious) all predictions were done by one single person, a TNO employee, behind his own desk. This person had no specific expertise in the field of vibration modeling and/or prediction.

Vibration predictions were made for the same cases and variables that were used in the expert judgment study (see previous section). The predictions were point estimates, i.e. the values produced by the prediction tool\footnote{In fact, the person who made the D11-predictions also gave his 95-percentile estimates. However, as he was not supported by the tool in making these estimates nor could he be considered an expert in the field of vibration predictions, these 95-percentile assessments we were not used in the analysis.}. 

In fact, the person who made the D11-predictions also gave his 95-percentile estimates. However, as he was not supported by the tool in making these estimates nor could he be considered an expert in the field of vibration predictions, these 95-percentile assessments we were not used in the analysis.
Again the uncertainty was calculated from a statistical analysis of the ratio between predictions and measured values. Only the total uncertainty was assessed as the program does not give intermediate results. For more information about the predictions see Esposito (2002). An analysis of the results can be found in section 5.2.3.

4.4 Dedicated

At the ‘dedicated’ prediction level predictions were carried out with the GeoDelft pile-driving special, a tool dedicated to the predictions of pile-driving induced vibrations. The pile driving-special developed by GeoDelft can be used to predict the main characteristics of vibrations arising from a single source, i.e. pile driving.

The driving force is estimated by a non-linear single degree of freedom system. The hammer impact and the reaction of the pile-soil system are calculated, leading to a force from the pile toe on the soil. (Pruiksma e.a., 2003a).

The wave propagation through the soil is described by the analytical solution of the full space homogeneous elastic soil. The model is developed by De Hoop (1977). This model describes the wave propagation according the elastic-dynamic theory under a harmonic point force. Both compression wave and shear waves are taken into account. The soil parameters are estimated from the mean value between the pile toe and the immission point. No layer separations are taken into account, also the soil surface is neglected.

The vibration predictions were separately carried out at GeoDelft. The predictions concerned a selection of the cases and variables that were also used for the evaluation of the uncertainty in the FEM-predictions (see Section 4.5). This selection contained only the cases in which the source was pile-driving, according to the area of application of the prediction tool. The predictions consisted of time traces, which were post-processed to obtain vmax-values for use in the analysis. Post-processing method and result are found in Wit (2003).

Again the uncertainty was calculated from a statistical analysis of the ratio between predictions and measured values, in terms of vmax. An analysis of the results is presented in section 5.2.4.

4.5 Finite Element Modeling (FEM)

4.5.1 Introduction

Finite element modeling can consist of a full model including source, soil and building. In most of the cases it only consists of a FEM model of the soil, completed with separate FEM models for the building and a multi body dynamic system of the vibration source. Connection between the various submodels is based on connectivity of vibration velocity or force at a limited number of nodes.

The soil is modeled into the soil layers that can be distinguished in CPT or boring diagram. Most of the times the minimum layer thickness is approximately 0.5 m. The material properties of the soil layers is based on empirical formulas. For a description of the source models see Sections 4.3 and 4.4.

For this level of prediction sophistication another set of cases was used than for the expert judgment study and the D11 predictions. Indeed, to be able to break down the uncertainty, specific measurements were required. These measurements were done by TNO near the building pit of the ‘Tunnel Rotterdam Noordrand’ in The Netherlands. Two grids of vibration sensors were installed in the soil, one at surface level and one at a depth of 14 m below surface level. Both horizontal and vertical vibration components were measured. Various vibration sources were used: pile driving, sheet piling and a heavy vehicle over a speed ramp. For a more detailed description of the measurements see Koopman (2002b).
The raw measurement data (time traces of vibration levels) are digitally available on a DVD. The exact reference was not yet known at the moment this report was issued. The reference will be included in the final project report (Holscher and Waarts, 2003). The measured vibration data were post-processed to obtain \( v_{\text{max}} \)-values for use in this analysis. The post-processing and the resulting \( v_{\text{max}} \)-values are reported in Wit (2003).

Prior to the measurements, the vibration levels at the various sensor positions had been predicted by four different Dutch institutes, i.e. Delft University of Technology, GeoDelft, Holland Railconsult and TNO. All four institutes regularly carry out sophisticated vibration predictions in civil engineering projects. The information provided about the vibration sources and the soil was intended to mimic typical practical consultancy situations (see Pruiksma, et al., 2003a). The raw prediction data are also time-traces, which were post-processed to obtain the required \( v_{\text{max}} \)-values. The prediction time traces are digitally available. The reference will be included in the final project report (Holscher and Waarts, 2003). Both the method and the results of the post-processing are documented in Wit (2003).

4.5.2 Total uncertainty

From a comparison of all the predicted and measured vibration levels (\( v_{\text{max}} \)), regardless of the institute that carried out the prediction, the source type, the distance to source, etc., the total uncertainty has been estimated. Note that these uncertainty estimates concern a system that only consists of a source and soil subsystem, without the component ‘building’. An analysis of the results is presented in section 5.2.5.

4.5.3 Break-down of the uncertainty

To gain more insight in the prediction uncertainties, various efforts were made to break down this uncertainty. The experiments at the Rotterdam Noordrand building pit, for which the FEM-predictions were produced, were designed in such a way that various uncertainty decompositions could be analyzed.

**Uncertainty in predictions as a function of vibration source**

First, the uncertainty in the FEM-predictions was analyzed as a function of vibration source (pile-driving, sheet-piling and a heavy vehicle crossing a speed ramp). Results are presented in Section 5.3.2. This analysis was done on the basis of the same predictions and measurements as used for the analysis of the total uncertainty.

**Uncertainty in predictions as a function of distance to the source**

Second, the influence of the location relative to the source:

- as a function of depth below the surface (at surface level, at 14 m below surface level)
- as a function of the distance to the source (10 m, 20 m, 30 m and 40 m)

Results are given in Section 5.3.3. Again, this analysis was done on the basis of the same predictions and measurements as used for the analysis of the total uncertainty.

**Uncertainty contribution from soil-subsystem only**

Thirdly, it was attempted to isolate the uncertainty resulting from the soil sub-model from the total uncertainty. To do this, separate predictions and measurements were done. These predictions and measurements concerned the same subsystem ‘soil’ (same grid or sensors), but a different source: a drop weight. First of all, drop weight tests were simulated: an impulsive loading was applied at a location on the surface of the soil model and the response of the model at the location of the various sensors along the measurement grid was calculated. From the imposed loading and the response at each sensor, transfer functions (admittance spectra) were determined. In a similar fashion, transfer functions were determined from the experimental data, which included mass and deceleration on impact of the drop weight.
In order to make comparisons with the total uncertainty associated with other types of sources, the transfer functions have been determined for a number of frequency ranges. Each type of source was then associated with a specific frequency band, according to the most dominant frequency in the signal generated by the source\(^2\). Table 4-2 gives these bands:

<table>
<thead>
<tr>
<th>Source</th>
<th>Frequency Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>traffic</td>
<td>8 – 15 Hz</td>
</tr>
<tr>
<td>pile driving</td>
<td>8 – 15 Hz</td>
</tr>
<tr>
<td>sheet piling low frequencies</td>
<td>31 - 35 Hz</td>
</tr>
<tr>
<td>sheet piling high frequencies</td>
<td>36 – 40 Hz</td>
</tr>
</tbody>
</table>

The uncertainty in the transfer function for the sub-system soil has been determined for each frequency band by comparing the average admittance obtained in the prediction with the average admittance obtained from the experimental results. So, in this analysis band-averaged admittances have been used as vibration characteristics in stead of \(v_{\text{max}}\)-values. For details see Hölscher & Waarts (2003).

An analysis of the results is presented in section 5.3.4.

**Model uncertainty versus parameter uncertainty in soil subsystem**

Finally, it was investigated how extra information about the soil properties, i.e. reduced parameter uncertainty, reduces the uncertainty in the predictions. To discriminate between parameter uncertainty and model uncertainty, two sets of predictions were carried out for the subsystem ‘soil’ under the drop weight loading. These predictions were produced in two subsequent phases, phase 1 and phase 2. For the purpose of the predictions in phase 1, information about the structure and properties of the soil was provided at a level, which resembles the level of information that is available in common practical situations. This was the same information that was also used for the assessment of the total uncertainty in the predictions. This information is limited and therefore gives rise to uncertainty in the model parameters: parameter uncertainty.

In phase 2, extra information about the soil had become available through additional sophisticated measurements (see Pruiksma et al. 2002b, Hölscher 2002). This information implied a reduction of the parameter uncertainty. The reduction of the prediction uncertainty in phase 2 compared to phase 1 gives an indication of the relative contribution of the parameter uncertainty to the overall uncertainty for the subsystem ‘soil’.

An analysis of the results is presented in section 5.3.5.

## 5 Results and discussion

### 5.1 Introduction

In the previous chapter it has been explained how this study has been designed to examine the total uncertainty in vibration predictions for various prediction tools. Moreover, it has been discussed how a break-down of the uncertainty will be established for predictions on the basis of FEM-models. As mentioned in section 3, the uncertainty in the predictions is estimated from the frequency distribution of the prediction factor \(g\), the ratio of the measured values and the predicted values. In section 5.2, the frequency distributions of this factor \(g\) will be presented displaying the overall uncertainty in predictions from the various prediction tools under study. Section 5.3 is dedicated to the analysis of various breakdowns of the total uncertainty in FEM-predictions. Finally in Section 5.4 a summary of the results is given.

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\(^2\) This approach is in fact not fully correct as some of these frequency bands are based on frequencies occur after propagation through a stretch of soil. To obtain a first impression, though, the approach seems viable.
5.2 Total uncertainty

5.2.1 Introduction
The total uncertainty in the predictions from a specific prediction method captures the uncertainty in predictions:
- for the whole system including source, soil and building subsystem.
- based on a level of information as commonly available in practice while randomizing over type of vibration source, distance to the source, depth below the soil surface, direction of the vibrations, etc. It reflects, loosely stated, the prediction uncertainty of a given prediction method or tool.
In the following sections estimates are given for the total uncertainty of the various prediction methods considered in this study.

5.2.2 Expert judgment (level 1)
For each vibration velocity, the experts gave two assessments, i.e. a best guess (median value) and a 95-percentile (a value with a 5% probability of exceedance). These assessments are subsequently discussed in the next subsections.

5.2.2.1 Best guesses
In the expert judgment study, 8 experts gave their best estimates for 24 vibration velocities each, giving a total of 192 predictions. For each of the 24 velocities, a measured value was available. Realizations of the random prediction factor \( g \) (see equation 1) were obtained by division of measured value by the corresponding prediction. A frequency distribution of the resulting ratios is shown in Figure 5.1. More details about the measurements and the predicted values can be found in Wit & Molenaar (2002).

![Figure 5.1 Frequency distribution of \( 10 \log g \), the logarithm of the ratio of measured values and the experts’ best guesses. The frequency distribution is plotted on normal probability paper.](image)

The values of \( g \) in the sample cover a range of almost 4 orders of magnitude, which is a considerable spread. This suggests that we should consider the logarithm of \( g \) rather than \( g \) itself. This choice is also supported by the apparent goodness of fit between the frequency distribution of \( 10 \log g \) and the normal distribution. We will interpret the observed frequency distribution as an estimate for the probability distribution of \( g \). The underlying assumption is that the realizations of \( g \) are (sufficiently) independent.
The frequency distribution can be characterized by the estimates of the mean and standard deviation of $10\log g$, which are given in Table 5-1. The mean value is a measure for the bias in the predictions. A mean of $10\log g$ equal to 0 ($g$ equals 1), indicates unbiased predictions ‘on average’. The standard deviation is a measure of the spread or uncertainty in the values of $10\log g$.

In Table 5-2 we also introduce an alternative characterization of the frequency distribution in terms of two factors: $g_{50}$ and $g_{95/50}$. The factor $g_{50}$ is the median value of $g$, i.e. value at an exceedance probability of 50%. If this value of $g$ would be used to correct all predictions, the corrected predictions would be unbiased. Values of $g_{50}$ less than 1 indicate a tendency to overpredict the vibration levels (conservative), whereas values of $g_{50}$ exceeding 1 indicate a tendency to underpredict. The factor $g_{95}$ is the 95-percentile value of $g$, i.e. the value at a 95% probability level (5% exceedance probability). This factor could be considered as a ‘safety factor’ to obtain values, which, on the long run, will be exceeded by the measurements in only 5% of the cases.

The factor $g_{95/50}$ is defined as the ratio of $g_{95} / g_{50}$. It is a measure of the spread in the predictions. In case the log of $g$ is well-described by a lognormal distribution, the relation between the moments (mean $m$ and standard deviation $s$) and the quantiles ($g_{50}$ and $g_{95}$) is:

$$g_{50} = 10^m$$

$$g_{95/50} = 10^{1.64s}$$

<table>
<thead>
<tr>
<th>Table 5-1 Estimates for the mean and standard deviation of $10\log g$ for best guesses of all experts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
</tr>
<tr>
<td>standard deviation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5-2 Estimates for the percentiles of $g$ for best guesses of all experts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{50}$</td>
</tr>
<tr>
<td>$g_{95/50}$</td>
</tr>
</tbody>
</table>

Both Figure 5.1 and, the mean value of $10\log g$ in Table 5-1 and the value of $g_{50}$ in Table 5-2 show that on average the experts’ estimates are hardly biased. This is consistent with the assignment to generate best guesses, so as a group the experts are well-calibrated in this respect.

The variation between the experts is not too large. If we select the best expert (median value close to 0 and smallest standard deviation) the statistics are:

<table>
<thead>
<tr>
<th>Table 5-3 Estimates for the mean and standard deviation of $10\log g$ for best guesses of the ‘best’ expert.</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
</tr>
<tr>
<td>standard deviation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5-4 Estimates for the percentiles of $g$ for best guesses of the ‘best’ expert.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{50}$</td>
</tr>
<tr>
<td>$g_{95/50}$</td>
</tr>
</tbody>
</table>

### 5.2.2.2 95% percentiles

The same procedure as described in the previous subsection can be repeated with the experts’ 95-percentiles. We will refer to the ratios between measurement and 95-percentile as $g_{\text{high}}$. If the experts would be well-calibrated in their 95-percentile assessments, the frequency distribution of $g_{\text{high}}$ would cross $g_{\text{high}} = 0$ at a probability level of 95%. Only then the measured values would exceed the predicted values in only 5% of the cases.

Figure 5.2 shows, however, that the observed frequency distribution crosses $g_{\text{high}} = 0$ at a probability level of 75%.
Figure 5.2 Frequency distribution of $10 \log g_{\text{95\text{\textendash}percentile}}$, the logarithm of the ratio of measured values and the experts’ 95-percentiles. The frequency distribution is plotted on normal probability paper.

This indicates that the experts as a group are overconfident; they choose their 95-percentile values too low, a factor 6 on average.

5.2.3 Empirical (Level 2)
The predictions were made with prediction tool ‘D11’ for the same cases as presented to the experts (see section 4). Few cases fell outside the scope of application of the tool and were skipped. A total of 18 predictions resulted. The predicted values were divided by the corresponding measured values to obtain realizations of $g$. Figure 5.3 shows the frequency distribution of $g$.

Figure 5.3 Frequency distribution of $10 \log g$, the logarithm of the ratio of measured values and the D11 predictions. The frequency distribution is plotted on normal probability paper. For reference the distribution fitted to the experts’ 95-percentiles is also shown (dashed line).

Figure 5.3 shows that the D11 predictions are somewhat conservative on average as the probability of finding a measurement exceeding the predicted value is only 25%. The figure also shows that the frequency distribution of the D11 results is very similar to the distribution of the experts’ 95-percentiles. The D11-tool is apparently successful in the sense that with this tool a non-expert can produce ‘conservative’ predictions, which are equally well (or poorly) calibrated as conservative predictions from an arbitrary expert. The degree of conservatism, although, is probably less than expected.
Table 5-5 and Table 5-6 summarize the statistics of g for the D11-results.

Table 5-5 Estimates for the mean and standard deviation of $10 \log g$ for D11 predictions.

<table>
<thead>
<tr>
<th>Mean</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard deviation</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 5-6 Estimates for the percentiles of g for D11 predictions.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{50}$</td>
<td>0.25</td>
</tr>
<tr>
<td>$g_{95/50}$</td>
<td>20</td>
</tr>
</tbody>
</table>

### 5.2.4 Modeling level ‘dedicated’

The GeoDelft pile driving-special was used to generate predictions for the pile-driving induced vibration levels at the various sensor-locations in the Rotterdam Noordrand building pit (see sections 4.4 and 4.5.1). These predictions were combined with the measured values to obtain realizations of the prediction factors g. The frequency distribution of $10 \log g$ on normal probability paper is shown in Figure 5.4. Table 5-7 and Table 5-8 summarize the main characteristics of the frequency distribution.

![Figure 5.4 Frequency distribution of $10 \log g$, the logarithm of the ratio of measured values and the GeoDelft pile-driving special predictions. The frequency distribution is plotted on normal probability paper.](image)

Table 5-7 Estimates for the mean and standard deviation of $10 \log g$ for GeoDelft pile-driving special.

<table>
<thead>
<tr>
<th>Mean</th>
<th>-0.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard deviation</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 5-8 Estimates for the percentiles of g for GeoDelft pile-driving special.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{50}$</td>
<td>0.6</td>
</tr>
<tr>
<td>$g_{95/50}$</td>
<td>3</td>
</tr>
</tbody>
</table>

A comparison with FEM-predictions for pile-driving induced vibrations is given in section 5.3.2.1.

### 5.2.5 Finite element modeling level

A total of 560 FEM-predictions were produced by three institutes, which were compared with measured values as in the previous sections. These predictions were made for vibration levels at the various sensor-locations in the Rotterdam Noordrand building pit. Predictions were made for several vibration sources, i.e. pile-driving, sheet-piling (multiple sheets and driving blocks) and a heavy
vehicle crossing a speed ramp (multiple crossing speeds). The vibrations levels were also measured (see section 4.5).
The frequency distribution of the ratio between measured and predicted values is shown in Figure 5.5.

![Lognormal distribution of 10log g](image.png)

Figure 5.5 Frequency distribution of $10\log g$, the logarithm of the ratio of measured values and the FEM-predictions. The frequency distribution is plotted on normal probability paper. For reference the distribution fitted to the experts’ best guesses is also shown (dashed line).

Again, the lognormal distribution appears to describe the frequency distribution well. The predictions are not significantly biased as the median value of $10\log g$ is close to 0. A summary of the total uncertainty statistics is given in Table 5-9 and Table 5-10.

Table 5-9 Estimates for the mean and standard deviation of $10\log g$ for all FEM-predictions.

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 5-10 Estimates for the percentiles of $g$ for all FEM-predictions.

| g50   | 1.3  |
| g95/50| 10   |

These numbers are an indication for the uncertainty in the predictions of an arbitrary institute. When we extract the results for the best performing institute in the study (median value close to 0 and smallest standard deviation) we find the statistics in Table 5-11.

Table 5-11 Estimates for the mean and standard deviation of $10\log g$ for FEM-predictions of ‘best’ performing institute.

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 5-12 Estimates for the percentiles of $g$ for FEM-predictions of ‘best’ performing institute.

| g50   | 1.3  |
| g95/50| 7    |

The limited reduction of the variance in $10\log g$ that is obtained when using FEM-based predictions in stead of instant expert judgment is striking. If we compare the predictions of all experts with the predictions of all institutes we find a factor of $(0.6)^2 / (0.8)^2 = 0.6$. Comparison of the best expert with the best institute gives a variance reduction of about 0.7. If we bear in mind that the FEM-predictions only concerned the subsystems source and soil, whereas the experts had to predict the behavior of source, soil and building in several cases, the reduction in practical cases might even be less.
5.3 Breakdown of the uncertainty

5.3.1 Introduction
The previous section describes and discusses the total prediction uncertainty for each of the considered prediction methods. In the current section an attempt is made to break down this uncertainty to gain more insight. Uncertainty break-down is only done for the FEM-predictions. Indeed, the experiments at the Rotterdam Noordrand building pit, for which the FEM-predictions were produced, were designed in such a way that various uncertainty decompositions can be analyzed. More information on the approach towards uncertainty break-down can be found in Section 4.5.3.

In the next subsection, the uncertainty in the FEM-predictions is analyzed as a function of vibration source. The influence of the location relative to the source on the vibration level is investigated in section 5.3.3, depth below the surface and distance to the source. This analysis is done on the basis of the same predictions and measurements as used in section 5.2.5. In section 5.3.4 it is attempted to isolate the uncertainty resulting from the soil sub-model. This attempt is made on the basis of additional, dedicated predictions and measurements. In section 5.3.5 it is investigated how extra information about the soil properties, i.e. reduced parameter uncertainty, reduces the uncertainty in the predictions. Additional predictions were made on the basis of this extra soil information to allow for this analysis.

5.3.2 Uncertainty in predictions for various vibration sources
As described in section 5.3.2, measurements and FEM-predictions were made for various vibration sources (pile driving, sheet piling and a heavy vehicle crossing a speed ramp). In this section, the uncertainty in the FEM-predictions is calculated per vibration source. The frequency distributions are shown and discussed in the following subsections.

5.3.2.1 Pile-driving
The frequency distribution of the prediction factor $g$ for pile-driving is shown in Figure 5.6.

![Figure 5.6 Frequency distribution of $10\log g$](image)

Figure 5.6 Frequency distribution of $10\log g$, the logarithm of the ratio of measured values and the FEM-predictions for the vibrations resulting from pile-driving. The data corresponding to the predictions of the three different institutes have been marked with different colors, i.e. institute 1 has blue markers, the markers of
institute 2 are green and the data of institute 3 are marked red. The data in the left upper corner show the mean of $10^{\log g}$ ($\mu$), the standard deviation of $10^{\log g}$ ($\sigma$), the median value $g_{50}$ (confusingly denoted by $f_{50}$) and $g_{95/50}$ (denoted by $f_{95-50}$) and the number of data in the frequency distribution.

The frequency distribution shows, that the predictions of pile-driving induced vibrations are hardly biased. The spread in the predictions around the measurements is clearly lower than the average uncertainty in vibration predictions as e.g. indicated by the factor $g_{95/50}$ which for pile-driving has a value of approximately 5, whereas the value for FEM-predictions more in general amounts to 10 (see Table 5-10). This value of 5 is somewhat higher than the $g_{95/50}$ value found for the GeoDelft pile-driving special ($g_{95/50} = 3$, see Table 5-8). This extra spread may be caused by the fact that the FEM-predictions were carried out by three different institutes, whereas the predictions with the GeoDelft pile-driving special were carried out by one institute only. Indeed, Figure 5.7 shows that the spread in the green markers is smaller than the spread in the red and blue markers. If we plot the frequency distribution of the pile-driving FEM-predictions from the best performing institute we find the following figure:

![Figure 5.7 Frequency distribution of $10^{\log g}$, the logarithm of the ratio of measured values and the FEM-predictions from the best performing institute for the vibrations resulting from pile-driving. The data in the left upper corner show the mean of $10^{\log g}$ ($\mu$), the standard deviation of $10^{\log g}$ ($\sigma$), the median value $g_{50}$ (confusingly denoted by $f_{50}$), $g_{95/50}$ and the number of data in the frequency distribution.](image)

These predictions are also almost unbiased, while the spread in the predictions around the measurements is quite small, i.e. $g_{95/50} = 1.6$, a factor 2 lower than the spread resulting from the GeoDelft pile-driving special and a factor 3 lower than the average spread in pile-driving predictions from the three institutes.

Analysis of the predictions of the worst-performing institute shows g-statistics comparable to the average scores for pile-driving.

Summarizing, the uncertainty in predictions of pile-driving induced vibration levels is a factor 2 less than the overall, total uncertainty in FEM-predictions. For the predictions of the best performing institute this is even a factor 6.
5.3.2.2 Sheet-piling

The frequency distribution of the prediction factor $g$ for pile-driving is shown in Figure 5.8.

![Figure 5.8 Frequency distribution of $10\log g$, the logarithm of the ratio of measured values and the FEM-predictions for the vibrations resulting from sheet-piling. The data corresponding to the predictions of the three different institutes have been marked with different colors, i.e. institute 1 has blue markers, the markers of institute 2 are green and the data of institute 3 are marked red. The data in the left upper corner show the mean of $10\log g$ ($\mu$), the standard deviation of $10\log g$ ($\sigma$), the median value $g_{50}$ (confusingly denoted by $f_{50}$) and $g_{95/50}$ (denoted by $f_{95-50}$) and the number of data in the frequency distribution.]

Apparently, vibrations resulting from sheet-piling are more difficult to predict than pile-driving induced vibrations. Although the bias is small, the spread in the predictions around the measured values is quite high as indicated by a factor $g_{95/50}$ of 14. The differences in performance between the various institutes is much smaller here than in the case of pile-driving.
5.3.2.3 Heavy vehicle crossing a speed ramp
The frequency distribution of the prediction factor $g$ for vibrations induced by a heavy vehicle crossing a speed ramp is shown in Figure 5.15.

![Frequency distribution of $10\log g$](image)

Figure 5.9 Frequency distribution of $10\log g$, the logarithm of the ratio of measured values and the FEM-predictions for the vibrations resulting from a heavy vehicle crossing a speed ramp. The data corresponding to the predictions of the three different institutes have been marked with different colors, i.e. institute 1 has blue markers, the markers of institute 2 are green and the data of institute 3 are marked red. The data in the left upper corner show the mean of $10\log g$ ($\mu$), the standard deviation of $10\log g$ ($\sigma$), the median value $g_{50}$ (confusingly denoted by $f_{50}$) and $g_{95/50}$ (denoted by $f_{95-50}$) and the number of data in the frequency distribution.

The bias in the predictions is almost a factor 2 (predictions somewhat underestimated). The spread is again almost a factor 2 smaller than on average: $g_{95/50} = 6$ in stead of 10 for all FEM-predictions. Differences between institutes are not striking.

5.3.2.4 Summary
The analysis in the previous sub-sections shows, that the overall poor performance of the FEM-predictions ($g_{95/50} = 10$) mainly results from the predictions of vibration levels from sheet-piling ($g_{95/50} \approx 15$). Predictions of vibrations induced by pile-driving and heavy vehicle crossing a ramp are less uncertainty-ridden ($g_{95/50} = 5$).

5.3.3 Uncertainty in the predictions as a function of the distance to the source
As described in section 5.3.2, measurements and FEM-predictions were made at sensor locations at two levels (surface level and 14 m below the surface) and at various distances from the source (approx. 10 m, 20 m, 30 m, and 40 m from the source). In this section, the uncertainty in the FEM-predictions calculated as a function of the location relative to the source. The frequency distributions are shown and discussed in the following subsections.
5.3.3.1 Pile driving
The following figures show frequency distributions of the prediction factor $g$ for pile-driving, itemized in terms of sensor location.

Figure 5.10 Frequency distributions of $10 \log g$, the logarithm of the ratio of measured values and the FEM-predictions for the vibrations resulting from pile driving. The data corresponding to the predictions of the three different institutes have been marked with different colors, i.e. institute 1 has blue markers, the markers of institute 2 are green and the data of institute 3 are marked red. The data in the left upper corner of each graph show the mean of $10 \log g$ ($\mu$), the standard deviation of $10 \log g$ ($\sigma$), the median value $g_{50}$ (confusingly denoted by $f_{50}$) and $g_{95/50}$ (denoted by $f_{95-50}$) and the number of data in the frequency distribution.
Considering the limited number of data in each of the figures, the frequency distributions show a rather constant behavior, except for the location at surface level, 10-15 m from the source. The frequency distribution for this location shows a large spread in the predictions around the measured data. From the colors of the markers it shows that this spread is mainly due to the predictions of institute 1 (blue), which hugely overestimate the vibration levels at this point. This might indicate an error.

The figures also show, that at surface level, the vibration levels are overall somewhat overestimated. This is hardly the case for the sensors at 14 m depth. As the highest vibration levels may be expected when the pile point is almost at its intended depth and the vibrations are mainly generated at the pile-point, this could be an indication that the damping of the soil across the various soil layers may not be accurately modeled.
5.3.3.2 Sheet piling

Figure 5.11 shows frequency distributions of the prediction factor $g$ for sheet-piling, itemized in terms of sensor location.

Figure 5.11 Frequency distributions of $10\log g$, the logarithm of the ratio of measured values and the FEM-predictions for the vibrations resulting from sheet piling. The data corresponding to the predictions of the three different institutes have been marked with different colors, i.e. institute 1 has blue markers, the markers of institute 2 are green and the data of institute 3 are marked red. The data in the left upper corner of each graph show the mean of $10\log g$ ($\mu$), the standard deviation of $10\log g$ ($\sigma$), the median value $g_{50}$ (confusingly denoted by $f_{50}$) and $g_{95-50}$ (denoted by $f_{95-50}$) and the number of data in the frequency distribution.
A number of observations can be made from the figures.
First, the bias in the predictions at surface level seems to decrease with the distance from the source (from overestimation of a factor 4-5 close to the source to underestimation of a factor 2 at long distance). For the sensor-locations at 14 m depth, the predictions show a more constant underestimation of about a factor 4. The upper right picture should be disregarded in this respect due to the huge spread.
Second, the spread in the predictions around the measured values at short and mid-range from the source is clearly higher for the locations at depth than for the locations at surface level. Most striking is the huge spread in the predictions at depth, close to the source (9-14 m), where institute 2 (green) is performing well, but the predictions from the other two institutes show an enormous scatter around the measured values.
Finally, for the long-range, i.e. far from the source, the frequency distributions for the various institutes become almost completely disentangled, indicating that they seriously disagree about the vibration levels at this distance.
5.3.3.3 Heavy vehicle crossing a speed ramp

Figure 5.12 shows frequency distributions of the prediction factor $g$ for sheet-piling, itemized in terms of sensor location.

Figure 5.12 Frequency distributions of $10\log g$, the logarithm of the ratio of measured values and the FEM-predictions for the vibrations resulting from a heavy vehicle crossing a ramp. The data corresponding to the predictions of the three different institutes have been marked with different colors, i.e. institute 1 has blue markers, the markers of institute 2 are green and the data of institute 3 are marked red. The data in the left upper corner of each graph show the mean of $10\log g$ ($\mu$), the standard deviation of $10\log g$ ($\sigma$), the median value $g_{50}$ (confusingly denoted by $f_{50}$) and $g_{95-50}$ (denoted by $f_{95-50}$) and the number of data in the frequency distribution.
The first observation from the figures is that for the locations at depth, the institutes 2 and 3 tend to seriously underestimate the vibration levels, whereas institute 1 slightly overestimates, especially at shorter distances from the source.

Another observation is that the spread in the predictions around the measured data is significantly larger at depth than at surface level. The disagreement between the institutes mentioned before may be a (partial) explanation for this observation.

Finally, the bias in the predictions at depth is larger than the bias at surface level. This is especially the case for institutes 2 and 3. As the vibrations in this case are clearly generated at the surface, the relatively poor performance of the predictions at depth may indicate that the modeling of the soil is not entirely adequate.

5.3.4 Uncertainty contribution from soil subsystem only

The previous sections concerned predictions with models describing both the source and the soil subsystem. To find out which uncertainty is generated by the soil-model only, predictions and measurements were carried out for a completely specified vibration source: a drop weight (virtually no uncertainty in source subsystem). The set-up of the experiment is described in 4.5.3.

The predictions and measurements were compared and statistically analyzed. The predictions were carried out on the basis of the same soil data that were used for the analysis of the total uncertainty (section 4.5.2). The frequency distribution of the ratio between measured and predicted values is shown in Figure 5.13.

Figure 5.13 Frequency distribution of $10\log g$, the logarithm of the ratio of measured values and the FEM-predictions for the soil only. The frequency distribution is plotted on normal probability paper. For reference the distribution fitted to the FEM-predictions for the system source+soil is also shown (dashed line).

The most important observation is that the slope of the distribution for the soil system only is significantly steeper than the slope of the distribution associated with the system source + soil. This means that the uncertainty in the predictions increases once the input from the subsystem ‘source’ is fixed without uncertainty. This remarkable result implies that a dependency exists between the source model and the soil submodel (‘negative correlation’). At first glance, this is awkward as the physical systems underlying these models are driven by separate and most probably statistically independent variables. However, the common factor in these two models is the user. This user is an expert, who, based on his experience in the field, has a certain expectation of the outcome of the prediction. Hence in choosing point estimates for the model parameters, he will avoid those values which give unrealistic results. As source models generally contain more parameters for which no direct empirical evidence is available, tuning of parameter estimates is most easily done in the source submodel. At the moment that this tuning opportunity disappears (source is fixed) and predictions have to be made for a rather unfamiliar vibration source (drop weight), the corrective opportunities of the user are ruled out and the real uncertainty in the submodel appears.
This mechanism would also explain why the uncertainties in FEM-predictions and expert judgments are similar. As the user strongly guides the FEM-prediction process, it is the expertise of the user, which determines the results in the end. At this stage we consider the above explanation a plausible and promising hypothesis, but no verification steps have been taken yet.

One of the striking differences between the measurements for the source-plus-soil-system on the one hand and the soil-subsystem alone on the other hand is the variation in the measurements at similar locations. This variation is significantly larger for the measurements for the soil sub-system. This is illustrated by the following two figures.

Figure 5.14 Vibration levels during pile driving, source-plus-soil-system.

Figure 5.15 Vibration levels during pile driving, soil sub-system only (average absolute value in transfer function over 8-15 Hz).
Especially the erratic behavior of the measured values as a function of the distance raises questions if the current approach yields reliable results. It is recommended to investigate this in a future project.

5.3.5 Parameter versus model uncertainty in soil subsystem

The uncertainty in the predictions in the previous section is caused by both model uncertainty (simplifications in the model) and parameter uncertainty (lack of knowledge about the actual constitution of the soil). To analyze the relative contribution of the parameter uncertainty, additional FEM-predictions for the soil subsystem were made (in phase 2, see Section 4.5.3) based on extra, measured data on the soil parameters. These additional measurement data reduce the parameter uncertainty.

Table 5-13 and Table 5-14 show the statistics of the frequency distributions of \( g \), the ratio between measured values on the one hand and the predictions with additional information on the other hand.

Table 5-13 Estimates for the mean and standard deviation of \( 10 \log g \) for FEM-predictions of in phase 1 (standard parameter uncertainty) and phase 2 (reduced parameter uncertainty).

<table>
<thead>
<tr>
<th></th>
<th>phase 1</th>
<th>phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>-0.4</td>
<td>-0.3</td>
</tr>
<tr>
<td>standard deviation</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 5-14 Estimates for the percentiles of \( g \) for FEM-predictions in phase 1 (standard parameter uncertainty) and phase 2 (reduced parameter uncertainty).

<table>
<thead>
<tr>
<th></th>
<th>phase 1</th>
<th>phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g_{50} )</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>( g_{95/50} )</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

The table shows that the extra information about the soil parameters does not significantly improve the predictions. This indicates that either the reduction in parameter uncertainty obtained by the measurements was negligible or the model uncertainty is the dominant source of uncertainty in the predictions. At this point, only one single soil system was investigated, different results might be obtained for other soil systems. Future investigations are required to further resolve this issue.

5.4 Summary

The results from the previous sections are summarize here in the form of two tables. The first table shows the percentile values \( g_{50} \) and \( g_{95/50} \) for the total uncertainty and its break-down in terms of vibration source and sensor location. The second table compares the total uncertainty with the uncertainty from the soil submodel and the influence of the reduced parameter uncertainty.

Table 5-15 Overview of the total uncertainty associated with the various prediction tools and methods.

<table>
<thead>
<tr>
<th>vibration source</th>
<th>pile-driving</th>
<th>sheet piling</th>
<th>traffic</th>
<th>overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert</td>
<td>( g_{50} = 0.6 )</td>
<td>( g_{95/50} = 18 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Empirical (D11)</td>
<td>( g_{50} = 0.25 )</td>
<td>( g_{95/50} = 20 )</td>
<td></td>
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<tr>
<td>Dedicated (pile-driving special)</td>
<td>( g_{50} = 0.6 )</td>
<td>( g_{95/50} = 3 )</td>
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<tr>
<td>FEM</td>
<td>( g_{50} = 0.7 )</td>
<td>( g_{95/50} = 5 )</td>
<td>( g_{50} = 1.6 )</td>
<td>( g_{95/50} = 15 )</td>
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<td></td>
<td>( g_{50} = 1.9 )</td>
<td>( g_{95/50} = 6 )</td>
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<td></td>
<td>( g_{50} = 1.3 )</td>
<td>( g_{95/50} = 10 )</td>
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Table 5-16 Breakdown of the uncertainty in FEM-predictions. ‘par’ stands for parameter uncertainty, ‘mod’ for model uncertainty and ‘tot’ for total uncertainty.

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<th>Subsystem → source</th>
<th>soil</th>
<th>building</th>
<th>total</th>
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<tr>
<td></td>
<td>par</td>
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Brief explanation of the symbols:

- the factor $g$ is the ratio between measured value and predicted value of vibration level.
- the factor $g_{50}$ is the median value of $g$, i.e. value at an exceedance probability of 50%. If this value of $g$ would be used to correct all predictions, the corrected predictions would be unbiased. Values of $g_{50}$ less than 1 indicate a tendency to over predict the vibration levels (conservative), whereas values of $g_{50}$ exceeding 1 indicate a tendency to under predict.
- the factor $g_{95}$ is the 95-percentile value of $g$, i.e. the value at a 95% probability level (5% exceedance probability). This factor could be considered as a ‘safety factor’ to obtain values, which, on the long run, will be exceeded by the measurements in only 5% of the cases.
- The factor $g_{95/50}$ is defined as the ratio of $g_{95} / g_{50}$. It is a measure of the spread in the predictions.

6 Conclusions and recommendations

6.1 Conclusions

1. The uncertainty in vibration predictions in civil engineering applications is quite large, typically 1 order of magnitude. The bias in predictions is relatively small.
2. The uncertainty in vibration predictions reduces from a factor 20 to a factor 5–10 when instead of expert judgment, sophisticated computational FEM-models are used. Although this is a significant reduction, the residual uncertainty remains large. A partial explanation is that the modeling choices that have to be made are decisive for the uncertainty in the predictions. These choices are, in the end, based on expert judgment.
3. Predictions of vibration levels resulting from pile-driving and traffic have an associated uncertainty of approx. a factor 3-5 (both FEM and dedicated. The uncertainty in predictions of sheet-piling induced vibrations is much larger, typically in the order of a factor 15 (FEM).
4. Uncertainty in predictions from a FEM-model of a source-plus-soil-system, where the source is part of the model with inherent uncertainties in parametrization and modeling assumptions is found to be smaller than the uncertainty in predictions from a FEM-model of subsystem ‘soil’ only, excited by a known vibration source. This indicates a dependency (‘negative correlation’) between soil and source models. A plausible explanation is that this dependency is introduced by the user, who compensates erroneous behavior of the soil-model by adjusting parameters in the source model to obtain results he perceives as realistic on the basis of his experience. To validate this explanation additional study is recommended.
5. Extra information about the soil parameters does not significantly improve the predictions. This indicates that either the reduction in parameter uncertainty obtained by the measurements was negligible or the model uncertainty is the dominant source of uncertainty in the predictions.
6. The experts in this study tend to choose their 95-percentile predictions too low: these predictions are exceeded by the measured values in about 25% of the cases.
7. Prediction uncertainty should not be attributed to a model or a modeling approach alone as it depends on the interaction between the model and its user.
6.2 Recommendations

1. In the course of this study, a large amount of valuable information has been generated, i.e. combinations of measurements and predictions with multiple techniques and for a variety of settings. The analysis presented in this report is only a first step in the contribution that this information can make to the understanding of uncertainty in vibration predictions. So far, the measurements and predictions have only be compared statistically. These analyses give overall insight in the uncertainties involved, but hardly provide clues to pinpoint the causes for the observed discrepancies between measurements and predictions. Detailed analyses from a soil/structural dynamics point of view would be beneficial in this respect.

2. In the original set-up of the project it was intended to include the L400-prediction tool in the study. Unfortunately no predictions from this tool could be taken along in this analysis. It is recommended that the analysis is extended at a later stage to accommodate L400-predictions.

3. A hypothesis has been proposed to explain the remarkable increase in prediction uncertainty in response to a reduction of the uncertainty in the parameters of the source submodel (see conclusion 4). It is recommended that additional study is conducted to a) verify if this observation can be reproduced in other settings and if so b) scrutinize the explanatory hypothesis raised in the present study.
7 References


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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:

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<td>Environmental impact of underground construction</td>
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<tr>
<td>Project name</td>
<td>Reliability of vibration prediction and reducing measures</td>
</tr>
<tr>
<td>Projectleader/Institute</td>
<td>Dr. ir. P. H. Waarts TNO Bouw</td>
</tr>
<tr>
<td>Project number</td>
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<td>Holland Railconsult</td>
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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.

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Project group

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Other Involved personnel

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