Does more sophisticated modeling reduce model uncertainty? A case study on vibration predictions

P.H. Waarts and M.S. de Wit

TNO Building and Construction Research, Delft, The Netherlands

In this paper, 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 investigated: 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 of Technology and Holland Railconsult. Predictions were generated for a variety of characteristic situations and were compared with measurements. Besides the total uncertainty, which can be derived out of the difference between prediction and measurement, a break-down of uncertainty sources was made.

Key words: Vibration predictions, civil engineering, uncertainty analysis, model uncertainty, expert judgment, model reliability

1 Introduction

In civil infrastructural engineering it is common practice to predict the vibration levels from e.g. building activities and traffic, which can be expected either during the construction or the exploitation phase. The predicted values, which are often calculated by means of prediction models, are compared with target levels specified in standards or directives. The reliability of the prediction models is presently unknown. Even the question whether or not a sophisticated model produces more reliable results than an empirical model cannot be answered.

From a mathematical point of view, the reliability of a prediction depends on both model uncertainty and parameter uncertainty. Parameter uncertainty expresses the uncertainty about the input and the boundary conditions of the system. This uncertainty can be analyzed by performing test or measurements on the parameter. Model uncertainty expresses uncertainty arising from simplifications and approximations in the physical modeling and / or discretizations and approximations in the numerical modeling. To assess model uncertainty, two methods can be applied. The first method is based on comparisons of many model outcomes (including model and parameter uncertainties) with measurement results. From a

statistical analysis of these comparisons, the total uncertainty, i.e. combination of model- and parameter uncertainty, can be analyzed. Subsequently the model uncertainty can be derived by extracting the parameter uncertainty from the total uncertainty. As this type of analysis of the model uncertainty is usually too costly, it is often replaced by the second method, which is based on expert opinion. An example of expert judgment on model uncertainty is given in Frijters et al. (1999). This paper compares both ways of analyzing the model uncertainty for predictions of vibrations.
The research was part of the framework of the Delft Cluster project 01.05.02 "reliability of vibration predictions and reducing measures". Four institutes worked together in this project: TNO, GeoDelft, Delft University of Technology and Holland Railconsult. For an overview see Hölscher & Waarts (2003).

2 Prediction of vibration levels

Vibrations are a short disturbance of balance. The vibrations 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_{max}) is used for the assessment of damage to buildings due to vibrations. The effective value of the vibration velocity (v_{eff}) is mostly used for the assessment of nuisance for people in buildings due to vibrations (Waarts & Ostendorf, 2002).
Prediction of vibration levels can be performed at various levels of sophistication. We distinguish three levels:

1. Without explicit models
2. With an empirical model
3. With a model derived from first principles

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. Examples of these models are the 'D11' model [CUR 1995] and dedicated models used at the several institutes.
At the highest level of sophistication the predictions are 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, 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 1.

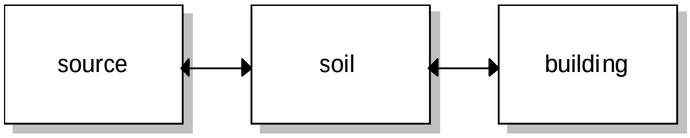

Figure 1: Subsystems in a model for the prediction of vibrations, and their connections.

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.

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 essentially arise from 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 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 paper 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.

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:

$$v_{obs} = g * v_{point} \tag{1}$$

where:

v_{obs} observed or actual vibration level

v_{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_{obs} / v_{point}, we may consider this probability distribution a measure of the (average) uncertainty in vibration predictions. Hence the approach in this paper will be to assess frequency distributions on the basis of recorded values for both v_{point} and v_{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.

For each prediction 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), also 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 paper only a partial breakdown is investigated as shown in Table 1.

Table 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 paper.

Level	**technique /**		**source**			**soil**			**building**		**total**
(section 2)	**subsystem**	**par**	**mod**	**tot**	**par**	**mod**	**tot**	**par**	**mod**	**tot**	
1	expert										X
2	D11 (empirical)										X
3	FEM				X	X	X				X

Before the study after the reliability of vibration predictions started the model uncertainty was estimated based on expert judgement. Table 2 shows the expert judgement of the difference between 'best guesses' and 'conservative' estimations (see Waarts 2000). When the level of 'conservatism' is known, the model uncertainty can be estimated in statistical terms.

Table 2: A-priori estimate of uncertainty in vibration prediction (factor between 'conservative' estimate and 'best guess')

Level (section 2)	**Technique**	**Model uncertainty**	**Parameter uncertainty**	**Total uncertainty**
1	expert opinion			4
2	empirical	3	1.5	3
3	first principles	1.6	1.5	2

4 Total uncertainty of the various prediction techniques

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 next sections describe the experimental set-up and results for the various prediction techniques separately.

4.1 Expert

As shown in Table 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 and qualitative information about the cases two days prior to the elicitation session. The experts' assessments were obtained through an E(lectronic) B(oard) R(oom)-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.

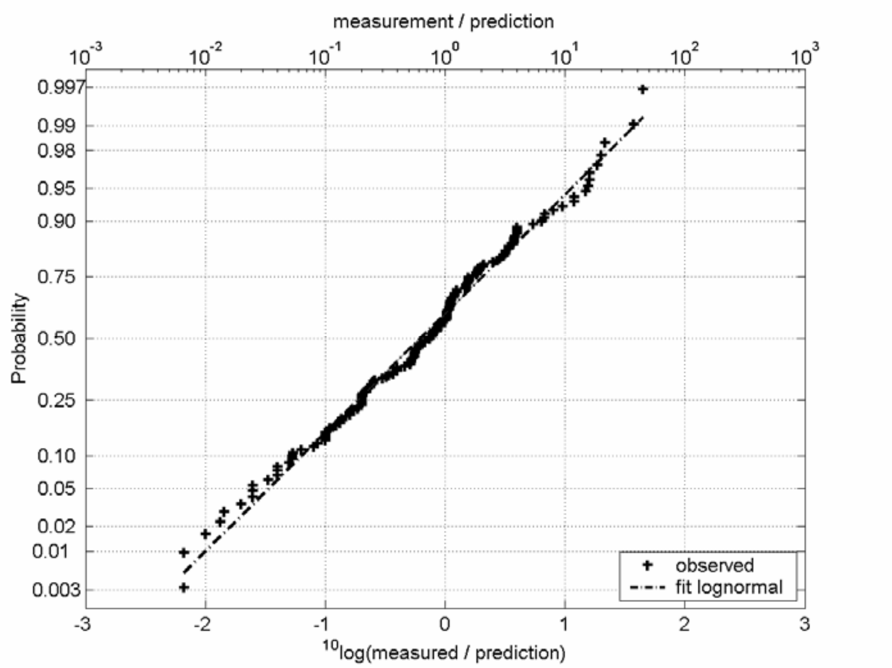

Figure 2: Frequency distribution of log g, the logarithm of the ratio of measured values and the experts' best guesses. The frequency distribution is plotted on normal probability paper.

The assessments consisted of values for $v_{eff,max}$ or v_{max}. 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. 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).

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 2. 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 log g (logarithm with base 10) and the normal distribution. We will interpret the observed frequency distribution as an estimate for the probability distribution of g, assuming that the realizations of g are (sufficiently) independent.

The frequency distribution can be characterized by the estimates of the mean and standard deviation of log g, which are given in Table 3. The mean value is a measure for the bias in the predictions. A mean of 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 log g.

In Table 3 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 over estimate the vibration levels (conservative), whereas values of g_{50} exceeding 1 indicate a tendency to under estimate.

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 normal distribution, the relation between the moments (mean m and standard deviation s) and the quantiles (g_{50} and g_{95}) is:

$$g_{50} = 10^{m} \quad (2)$$

$$g_{95/50} = 10^{1.64\,s} \quad (3)$$

Table 3: Estimates for the mean and standard deviation of log g and estimates for the percentiles of g.

	best guesses of all experts	**best guesses of the 'best' expert.**
Mean log g	-0.2	-0.2
standard deviation log g	0.77	0.6
g_{50}	0.6	0.6
$g_{95/50}$	18	10

Both Figure 2 and the mean value of log g and the value of g_{50} in Table 3 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) we can see some decrease in variation.

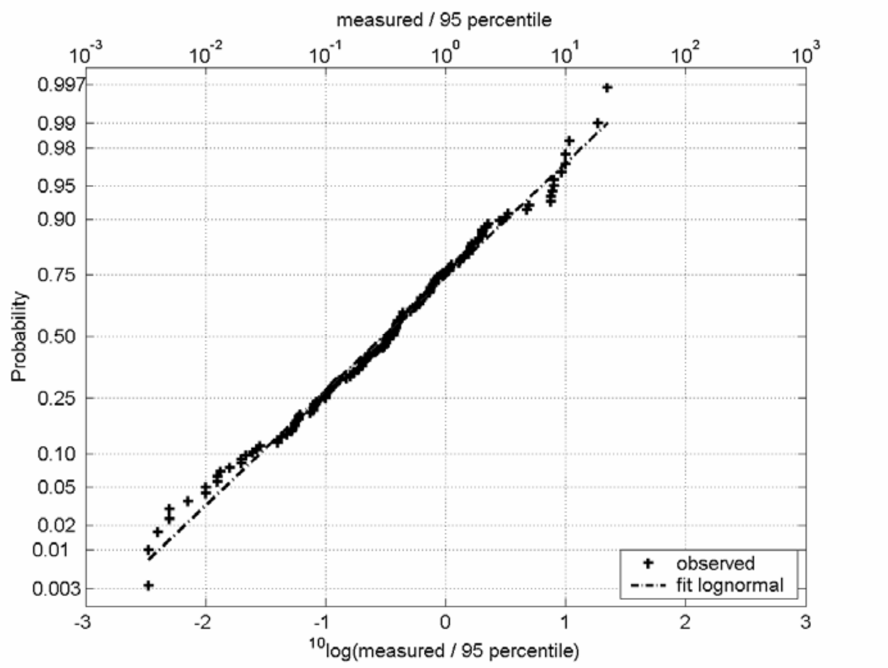

Figure 3: Frequency distribution of log g_{high} the logarithm of the ratio of measured values and the experts' 95-percentiles. The frequency distribution is plotted on normal probability paper.

The same procedure can be repeated with the experts' 95-percentiles (the values they themselves assign as probability of exceedance of 5 %) . We will refer to the ratios between measurement and 95-percentile as g_{high}. If the experts would be well-calibrated in their 95-percentile assessments, the frequency distribution of g_{high} would cross $g_{high} = 0$ at a probability level of 95%. Only then the measured values would exceed the predicted values in only 5% of the cases. Figure 3 shows, however, that the observed frequency distribution crosses $g_{high} = 0$ at a probability level of 75%. This indicates that the experts as a group are overconfident: they choose their 95-percentile values too low, a factor 6 on average.

4.2 Empirical models

At this level, one single prediction tool was used, called D11 (CUR 1995). 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 trough 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 and FEM calculations. 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. 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 amplification 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. 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.
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). The predictions were made with prediction tool 'D11' for the same cases as presented to the experts (see previous section). 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 4 shows the frequency distribution of g.
Figure 4 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 4 summarize the statistics of g for the D11-results.

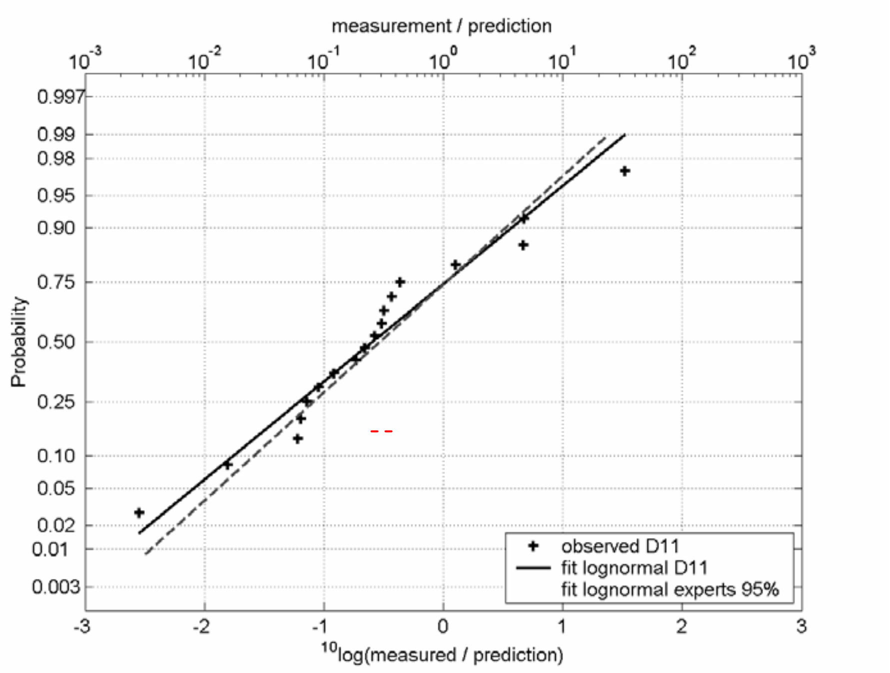

Figure 4: Frequency distribution of log g, the logarithm of the ratio of measured values and the D11 predictions. The frequency distribution is plotted on normal probability paper. For reference the distribution fitted to the experts’ 95-percentiles is also shown (dashed line).

Table 4: Estimates for the mean and standard deviation of log g and estimates for the percentiles of g for D11 predictions.

Mean	**-0.6**
standard deviation	0.8
g_{50}	0.25
$g_{95/50}$	20

4.3 Finite Element Modeling (FEM)

Finite element modeling can consist of a full model including source, soil and building. In most 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 layers, which can be distinguished from experimental data such as a CPT or a boring diagram. Generally the minimum layer thickness is approximately 0.5 m. The material properties of the soil layers are based on empirical formulas.

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 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. For more information see Koopman (2002b).

Note that in these measurements the subsystem ‘building’ was not involved. Moreover, all measurements were carried out in the same soil. Various vibration sources were used though: pile driving, sheet piling and a heavy vehicle over a speed ramp.

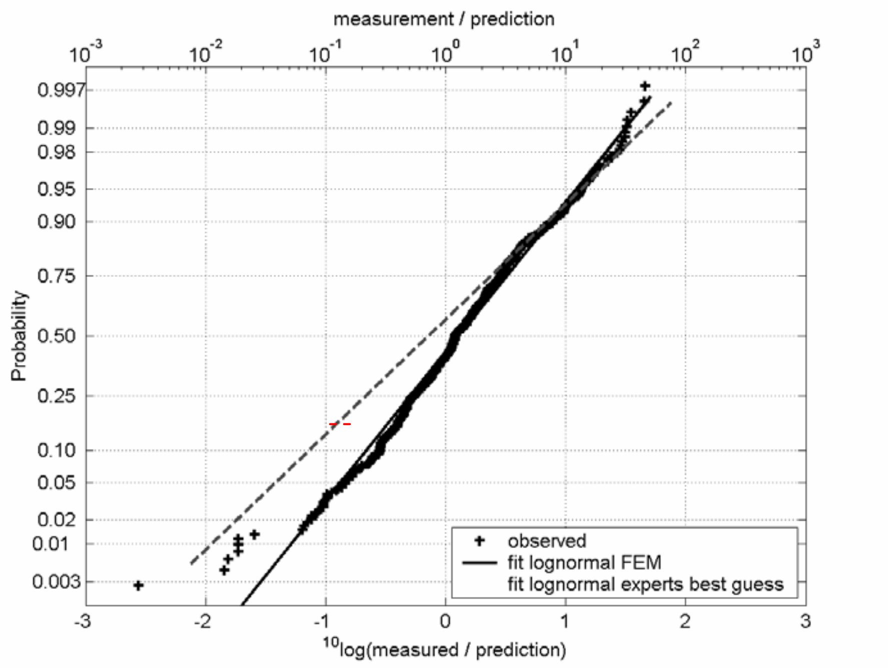

Figure 5: Frequency distribution of log g, the logarithm of the ratio of measured values and the FEM-predictions. The frequency distribution is plotted on normal probability paper. For reference the distribution fitted to the experts’ best guesses is also shown (dashed line).

Prior to the measurements, the vibration levels at the various sensor positions had been predicted by three different Dutch institutes. All three 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 total uncertainty has been estimated from a comparison of all the predicted and measured maximum vibration velocities (v_{max}), regardless of the institute that carried out the prediction, the source type, the distance to source, etc., Note that these uncertainty estimates concern a system that only consists of a source and soil subsystem, without the component 'building'. For more information about the predictions, see Koopman (2002a), Hölscher & Waarts (2003). More info about the measurements can be found in Koopman (2002b) and Wit (2003).

Table 5: Estimates for the mean and standard deviation of log g and estimates for the percentiles of g for FEM predictions

	all predictions	**predictions of 'best' performing institute**
Mean	0.1	0.1
standard deviation	0.6	0.5
g_{50}	1.3	1.3
$g_{95/50}$	10	7

A total of 560 FEM-predictions of v_{max} were produced by the three institutes, which were compared with measured values as in the previous sections. The frequency distribution of the ratio between measured and predicted values is shown in Figure 5. Again, the lognormal distribution appears to describe the frequency distribution well. The predictions are not significantly biased as the median value of log g is close to 0. A summary of the total uncertainty statistics is given in Table 5. The numbers in Table 5 are a measure for the uncertainty in the predictions of an arbitrary institute and for the best performing institute in the study (median value close to 0 and smallest standard deviation). The limited reduction of the variance in log g that is obtained when using FEM-based predictions instead 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 $(0.6)^2 / (0.8)^2 \approx 0.6$. 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 Breakdown of uncertainties with respect to vibration source

The breakdown in term of vibration source has only been analysed for the FEM predictions. The same data is used as described in section 4.3. In this section the uncertainty in the FEM predictions is calculated per vibration source:

- Pile driving
- Sheet-piling using vibratory hammer
- Heavy vehicle crossing a speed ramp

The frequency distribution of the prediction factor g for the various vibration sources is shown in Table 6.

Table 6: Estimates for the mean and standard deviation of log g and estimates for the percentiles of g for the various vibration sources.

	Pile driving		**Sheet-piling**	**Heavy**	**Total (table)**
	all predictions	**'best' performing institute**	**using vibratory hammer**	**vehicle crossing a speed ramp**	
Mean	-0.2	0.2	0.2	0.3	0.1
std deviation	0.4	0.20	0.7	0.5	0.6
g_{50}	0.7	1.5	1.6	1.9	1.3
$g_{95/50}$	4.7	1.6	14.3	6.0	10

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 amounts to 10 in general.
The predictions for the best performing institute 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 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.
Apparently, vibrations resulting from sheet-piling using vibratory hammers 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.
The bias in the predictions for vibrations induced by a heavy vehicle crossing a speed ramp is almost a factor 2 (predictions somewhat underestimated). The spread is again almost a factor 2

smaller than on average: $g_{95/50} = 6$ instead of 10 for all FEM-predictions. Differences between institutes are not striking.

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

6 Uncertainty contribution from soil-subsystem

*6.1 **Total uncertainty of soil-subsystem***

To assess the contribution or the soil-subsystem to the total uncertainty, separate predictions and measurements were done. These predictions and measurements concerned the same subsystem ‘soil’, but a different source: a drop weight. 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.

To assess the uncertainty in predictions of the soil subsystem only, predictions for and measurements of the drop weight experiment were compared and statistically analyzed. The predictions were carried out in phase 1, i.e. on the basis of the same soil data that were used for the analysis of the total uncertainty (section 4.3). The frequency distribution of the ratio between measured and predicted values is shown in Figure 6.

The most important observation is that the slope of the distribution for the system source + soil is significantly steeper than the slope of the distribution associated with the separate soil system. 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 that 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 sub-model. 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 sub-model 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.

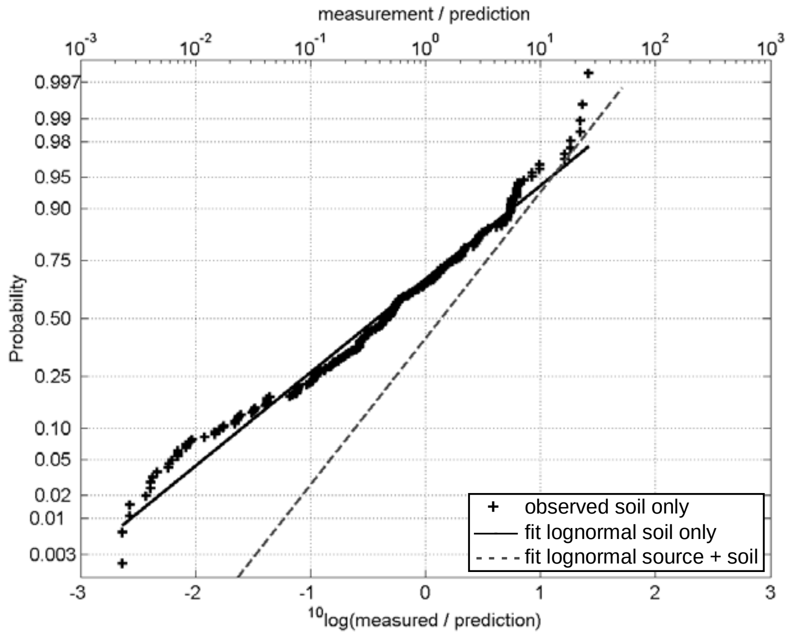

Figure 6: Frequency distribution of log g, the logarithm of the ratio of measured values and the FEM-predictions for the soil subsystem only. The frequency distribution is plotted on normal probability paper. For reference the distribution fitted to the FEM-predictions for the system 'source+soil' is also shown (dashed line).

6.2 Model uncertainty of soil subsystem

To separate parameter uncertainty from 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 extra sophisticated measurements (see Pruiksma et al. 2003b, 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’.

To analyze the contribution of the soil parameters to the uncertainty, FEM-predictions for the soil system have been made in phase 2, based on extra, measured data on the soil parameters. This reduces the uncertainty in the model parameters compared to phase 1. Table 7 shows the statistics of the frequency distributions of g, the ratio between measured and predicted values. 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.

Table 7: Estimates for the mean and standard deviation of log g and estimates for the percentiles of g for FEM-predictions of in phase 1 (standard parameter uncertainty) and phase 2 (reduced parameter uncertainty).

	phase 1	**phase 2**
mean	-0.4	-0.3
standard deviation	0.9	0.9
g_{50}	0.4	0.5
$g_{95/50}$	30	30

7 Summary

The results from the previous sections are summarized here in the form of two tables. Table 8 shows the percentile values g_{50} and $g_{95/50}$ for the total uncertainty associated with the three prediction methods. The table also gives a breakdown of the uncertainty in terms of vibration source and sensor location. When the results in Table 8 are compared with the a-priori expectations of the total uncertainty (see Table 2), a difference of approximately factor 5 can be seen, when assuming that ‘conservatism’ in Table 2 is intended to correspond to the 95 % fractile. Alternatively, we can conclude that ‘conservatism’ in Table 2 in fact corresponds to only the 60 % fractile. This tendency to be overconfident was also found in the expert judgment study reported in section 4.1.

Table 9 compares the total uncertainty with the uncertainty in the predictions for the separate soil sub-model and the influence of the reduced parameter uncertainty.

Table 8: Overview of the total uncertainty associated with the various prediction tools and methods.

Vibration source → **Prediction method** **↓**		**Pile-driving**	**Sheet piling**	**Traffic**	**Overall**	**A-priori expert opinion on over-all uncertainty**
Expert	g_{50}				0.6	1
	$g_{95/50}$				18	4
Empirical (D11)	g_{50}				0.25	1
	$g_{95/50}$				20	3
FEM	g_{50}	0.7	1.6	1.9	1.3	1
	$g_{95/50}$	5	15	6	10	2

Table 9: Breakdown of the uncertainty in FEM-predictions.

Subsystem →			**soil**		**total**
		parameter	**model**	**total**	
FEM	g_{50}	0.5		0.4	1.3
	$g_{95/50}$	30		30	10

8 Conclusions and recommendations

8.1 Conclusions

1. The uncertainty in vibration predictions in civil engineering applications is quite large, typically 1 order of magnitude. This is much higher than expected beforehand (see section 1). The bias in predictions is relatively small.
2. The uncertainty in vibration predictions reduces from a factor 20 to a factor 5–10 when sophisticated computational FEM-models are used instead of expert judgment. 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 approximately a factor 3-5 (both FEM and empirical). 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 parameterization 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 that 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 in this study did not significantly improve the predictions. This indicates that either the reduction in parameter uncertainty obtained by the measurements was negligible or the model uncertainty was the dominant source of uncertainty in the predictions.
6. The experts on vibration predictions (section 4.1) 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. The experts on model uncertainty (Table 2) are over-confident as well. The estimated 95 % confidence level is in reality only a 60 % confidence level.
8. 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.

8.2 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 paper 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 they 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. 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.
3. Performing a same kind of study for other kinds of predictions would give much insight about the state of the art in reliability of predictions.

References

CUR 1995, Prediction model vibration discomfort (in Dutch), *Report 95-2*, Gouda: Civieltechnisch Centrum Uitvoering Research en Regelgeving (CUR)

Esposito, G. 2002, Vibration predictions with the D11 model (in Dutch), *Report DC1-1.5.2-6*. Delft: Delft Cluster.

Frijters, M., Cooke, R. , Slijkhuis, K. en Van Noortwijk, J.M. 1999, Expert judgment study Uncertainty analysis Inundation probability (in Dutch), Report 114 ONIN-1-99006 of the Dutch Ministry of Transport, DG Rijkswaterstaat, DWW, The Netherlands.

Hölscher, P. 2002, Reliability of global assessments of dynamic soil parameters (in Dutch), *Report DC1-1.5.2-11*. Delft: Delft Cluster.

Hölscher, P. & Waarts, P. 2003, Final report of DC project 01.05.02, *Report DC1-1.5.2-20*. Delft: Delft Cluster.

Koopman, A. 2002a, Description of predictions (in Dutch), Report *01.05.02-007*. Delft: Delft Cluster.

Koopman, A. 2002b, Measurements at the building pit Tunnel Rotterdam Noord (in Dutch), Report *DC1-1.5.2-9*. Delft: Delft Cluster.

Pruiksma, J.P., Gardien, W., van Duin, F, 2003a, Reliability of vibration prognosis by FEM for extensive measurements at test site Rotterdam North: input parameters phase 1, *Delft Cluster Report DC1-1.5.2-15*, Delft: Delft Cluster.

Pruiksma, J., Hölscher, P., Stuit, H. Duin, F. van 2003b, Reliability of vibration prognosis by FEM for extensive measurements at Rotterdam North building pit; part 4, input parameters phase 2, Report *DC1-1.5.2-16*. Delft: Delft Cluster.

Waarts, P.H. 2000, Lecture NAG, Nederlands Akoestisch Gezelschap, Utrecht 2000

Waarts, P.H., Ostendorf, C. 2002, SBR guideline-A: Damage to buildings due to vibrations, SBR, The Netherlands

Wit, M.S. de 2001, Reliability of vibration predictions – general philosophy (in Dutch), *report DC1-1.5.2-1*. Delft: Delft Cluster.

Wit, M.S. de & Molenaar, D.J. 2002, Expert judgment study on vibration predictions (in Dutch),report DC1-*1.5.2-2*. Delft: Delft Cluster.

Wit, M.S. de, 2003. Post-processing of the measurements at the building pit Tunnel Rotterdam Noord, Report *DC1-1.5.2-17*. Delft: Delft Cluster.