A risk model for pile foundations

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ABSTRACT: This paper describes a model which has been developed for the purpose of assessing major risks associated with various pile foundation types and their resulting financial consequences. The work is based on a review of possible geotechnical sources of risks encountered during the placing of pile foundations. Both literature and experts are used in order to compile lists of risks associated with the different types of piling methods. The model is intended to support geotechnical designers or contractors in making sound decisions as to the selection of piling foundation types that are appropriate to the specific situations at hand.

The study has identified four major groups of risk events that can be possibly encountered when producing a specific pile foundation type; damage to surroundings, damage to the piles themselves, incorrect piles placements and damage to equipments.

The study has also identified the parameters that have influence on the presence and magnitude of the undesired events. The research uses influence diagrams to model these events and to create what is termed as a risk network. A computer program, based on Bayesian probabilistic approach, is used to produce such a network whereby risks can be quantified in terms of costs and delays.

The paper describes application of the model and draws conclusions on the results produced and the usefulness of the developed model as a tool for supporting design and construction decisions.

KEYWORDS: Risk model, Geotechnical design, Pile foundations

1. INTRODUCTION

Uncertainties and risks are identifiably inherent in construction work. They complicate the decision making process particularly if decisions are required to be taken at an early stage in the project, when information available is minimal. This is certainly the case in the construction of pile foundations whereby, in the absence of all the information, foundation systems are often selected without informed decisions about potential and damaging risks (Hayes, 1987). For example there is no structured and explicit approach that considers risks during the design or the construction of pile foundations. There are also no suitable models or tools that enable efficient and effective risk management for this purpose. The knowledge on risks is not shared and stays in the minds of geotechnical experts. Even when such knowledge is available within construction companies, it is often not structured or available in ready-to-use format. All of this may cause technical problems and hence considerable additional costs.

There is therefore a need for improved and informed decisions whereby the effects of risks on the choice and construction of pile foundations are taken into considerations. This work suggests that this can be made possible through identifying, classifying of possible risks and undesirable events and the development of a model that is able to predict the consequences of the major events for each pile foundation type under consideration.

In general there are two types of project risk analysis that can be carried out, qualitative and quantitative. Each of these approaches has its advantages and disadvantages. For example the qualitative approach has the advantage that not a great deal of information is required and that risks

can by analysed in a broad spectrum. The disadvantage however is that no in-depth analysis of the risks can be carried out and hence no detailed information can be found on the exact consequences of the events underlying the risks. Quantitative risk analysis methods on the other hand offer the opportunity to achieve a detailed view of the consequences of the events that might take place during construction. A disadvantage of this approach however is that it is not suitable to be used for assessment of risk in a broader sense (Vermande, 1998).
In his work (Bles, 2003) has shown that both methods are required in order to make informed judgments regarding risks of the various types of pile foundations. A combination of both approaches has also been adopted in this research.

2. INFORMATION FRAMEWORK

The adoption of a suitable information structure is conditional to selecting and classifying major risks in a project in an orderly manner. The fact that many different pile foundations exist means that such structure is not readily available. Some risks apply to many pile types whilst others are only related to certain pile types. It was therefore necessary to create a framework whereby logical links between events and pile types can be created. The framework is shown in Figure 1.

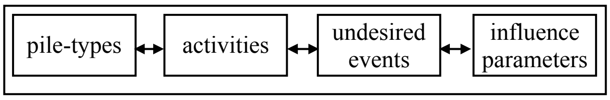

Figure 1. Adopted information framework

Figure 1 indicates that each type of pile foundation can be linked to its construction activities and each activity is in turn linked to possible undesired events that are in turn linked to their influence parameters. These parameters influence the chances of events being occurred. The four sections of the framework are interrelated and have the following characteristics:

- The chosen information framework as described enables easy identification of the risks for a project.
- The events are logically connected to the pile foundation type. They are linked to the activities necessary to install the pile foundation. From this it follows that the size of risk will not depend on the type of pile foundation but on the activities required to construct this pile foundation.
- The use of activities, events and parameters provides the right abstraction level. All factors included in the risk analysis could be placed within the information framework using the structure described.
- The inclusion of influence parameters in the structure has meant that it possible to input estimates of risks that apply to the project under consideration. The probabilities of various events occurring are rather project specific and are reflected by the relevant parameters. Identifying project parameters enables the simulation of the project specific circumstances in the model.

3. RISK DATABASE

The information structure described in the previous section is ideally suitable to be placed in a database. To do this all relations between pile types, undesired events and influence parameters have to be known. These relations are stored in the database, providing the opportunity to select a list of events for each pile type. From this information it is also possible to show which parameters have influences on the events.
The relations between the types of pile foundations and the activities needed are ‘hard’ relations. This means that for a certain pile type these particular activities always apply in order to install the pile in the soil.
The other relations are not ‘hard’. A certain event will not necessarily occur doing a particular activity, only in some cases this event will occur. Therefore these are referred to as ‘soft’ relations. To reflect this, each relation is assigned a value; a weight value. A factor 5 means a high weight, a factor 1 represents a low weight. In this way it is possible to see in the database which parameters and event are most important to which pile foundation type. Most relations are found in literature, others are provided by experts. Based on the literature, initial values are assigned as weights to these relations. These values however are eventually adjusted using information provided by expert opinions. The majority of these values should be put into context. That is to say that the probability of occurrence of undesired event is not fixed and is to a large extend dependent on the specific situation in which the pile foundation is constructed.

4. RESEARCH METHODOLOGY

A Bayesian Belief Network (BBN) is used to model risks in this work. This is a method, which uses probabilistic theory for reasoning under uncertainty and risk in expert systems.
The method provides the opportunity to set joint probability distribution functions to a set of stochastic variables, ordered in a network. This network shows the relations between the variables. Basically a BBN consists of two parts, a qualitative and a quantitative part. The qualitative part includes a graphical representation (network) of the relationships between the parameters. The quantitative part consists the assignment of conditional probabilities to all variables in a so called likelihood-table. These tables describe the effects of preceding variables on the underlying variables.
The basis of BBN is provided by the Bayes-theorem of Thomas Bayes (Rouanet et al., 1998):

$$P(H_i \mid D) = \frac{P(D \mid H_i)P(H_i)}{\sum_i P(D \mid H_i)P(H_i)}$$

With this theory it is possible to calculate the probability of a variable within the network based on data from the Bayesian network. Despite

Working with Bayesian Belief Networks provides the following advantages:

- In spite of uncertainty it is possible to give a judgment on the expected risks.
- The networks provide the opportunity to implement both analytical and intuitive knowledge based on expert experience.
- Estimates based on only one expert is enough to provide a basis for a functional model.
- It is possible to build the networks step-by-step due to the fact that child-parent relationships are used. This also makes improvement and extension of a network possible.
- The graphical representation of the network makes it easy to understand, even for people not specialised in the field.

The major disadvantage of the BBN is that the conditional likelihood tables can easily become very large. For example, if we have three parameters with four conditions each affect another parameter then there are already 64 chances to be determined.

4.1 Research Delimitation

During construction of a pile foundation many undesired events might occur. The major risks are however determined by a few of these events. As long as it possible to make correct estimates of these major events, insights in the overall financial, time-dependent and qualitative consequences can be obtained. In this paper the quantitative risks results of only major events are presented. These major events are:

- Piles do not reach the required depth
- Damage to surrounding structures due to vibrations
- Damage to surrounding objects due to settlements caused by vibrations

The work also only cover the common three major pile types applied in Dutch practice. These include prefabricated concrete piles, the vibro-piles (vibration piles) and the bored piles. Together these piles have a market share of approximately 95% of the Dutch market.

4.2 Piles not reaching the required depth

An engineer designs a pile with a certain bearing capacity, including a required pile tip level. Due to a number of reasons a pile might have difficulty achieving the required depth. The worst case occurs when it is impossible to make the pile reach the required depth and therefore fail to achieve the structural requirements the pile is designed to meet. In these cases new attempts have to be made to install the pile or alternative measures have to be taken. Alternative measures may include, for example, pre-boring the new piles or changing the pile hammer. This can cause the piles to break or the pile heads to be damaged.
The event described here may result in major financial and planning penalties. The problem may to stopping the construction work for a certain period of time, which in turn may lead to a considerable delay for the construction programme as a whole.
Interviews with experts have revealed that there are three main causes for not achieving the required pile depth; existence of obstacles in the ground; high soil resistance and damage to equipment. Damage to equipment may also be the result of the first two reasons. The more resistance encountered in the ground when installing a pile the higher the chance of equipment damage.
On the basis of the above parameters it can be determined whether or not a pile can reach its

required depth. However, these are not the only reasons for the occurrence of such event and that there may be other circumstances, which contribute to this end. These can be referred to as ‘ human factors’. The expertise of the construction team as well as the knowledge of the construction company of the local circumstances can play important role in this respect. Also the level of detail of the soil investigation has to be taken into account. A more intensive soil investigation increases the chance that the piles will achieve the required depth. The BBN network developed to model this event and determine whether a pile will achieve it's required depth includes all these parameters as shown in Figure 2.
Providing an estimate of the percentage of piles that will probably not achieve the required depth it would then be possible to calculate consequences in time and cost for the foundation.

4.3 Damages due to vibrations

Installation of a pile using a hammer causes vibrations in the ground, which can cause damages to structures or apparatuses around the construction site. The damage can also be in the form of hindrance to work and people in the proximity of the construction site. The BBN network which is developed in this work to represent this risk event and which is shown in Figure 3 only models the damage to adjacent structures
The most important influence parameters when determining the potentials for damages are related to the distance from the source of vibration and the types of adjacent structures. Based on values and estimates given to these parameters, the damage due to vibrations can be calculated. The literature study has shown that more factors of influence exist. For this reason these are also included in BBN.
Based on the factors above the expectation value of the damage due to vibrations is calculated. This expectation value is, based on the construction type (monument, house, office building), translated into expected financial damage.

4.4 Damages due to ground settlements

Ground settlement due to the vibrations in the ground occurs when soil particles take different arrangements and bring about consolidation of the soil. The extent of the ground settlement is dependent on the extent of the vibration, the soil type and soil properties. As soon as a suitable combination of these occur, soil will consolidate and cause ground settlement and possible damage to adjacent structures. Even relatively small vibrations might results in settlements.
The calculation of the settlements is performed using the model of Hergarden et al. (2001). Important input to this model is the acceleration of the vibration and the relative soil density. The extent of the damage to surroundings is dependent on the vulnerability of adjacent structures, namely the type of foundation.
The BBN for this event is shown in Figure 4.

5. APPLICATIONS AND TESTING OF THE MODEL

Located on and industrial area site in “Weststad III” in Oosterhout, the Netherlands, an industrial building has been constructed for a Dutch company (Martens Beton) in the year 2002. The site investigations have shown that a pile foundation was necessary. It has been decided to use prefabricated (reinforced, not pre-stressed) piles. In total the foundation consist of 1688 piles.
Randomly some acoustic measures have been taken, using a dynamic pile-test method. From the random tests it was concluded that in one corner of the installed pile field (partly) broken piles existed, probably caused by mistakes during installation of the piles. After deliberation it is decided to install 6 extra piles.
The fact that the problem was found during the pile installation it was fairly easy to solve it and continue with the work without delay. Extra cost was paid which included more detailed acoustic measurements and deliberation among participants as well as installation of extra piles. In total the extra cost amounted to approximately € 4000.
The case described above is simulated using the BBN “not achieving the required depth”. The results were that the expected percentage of piles not achieving the required depth is 2 percent and a subsequent cost of € 11.500 with a project delay of 2 weeks.
In comparison to what happened in reality, the expected percentage of piles not to achieve depth is high. From the BBN it followed that the cause for not achieving depth is not in the ground. The expectation from the network was that the piles would achieve the depth required. These results do match the case. The 2 percent of piles not achieving the required depth was fully related to the ‘human factors’. Because of the high percentage of piles not achieving the depth the

consequences in cost and delay were over estimated.
Using the same case the other network models have also been tested. The tests have shown that it is relatively easy to use the model and to estimate how high the costs are on the basis of single statistical parameters. Experts have validated the estimates of cost produced by these models as being reasonably accurate.
The effects of certain risk control measures on cost and time have also been calculated. It was shown that it is possible to use the developed model as a decision support tool to test the consequences of certain measures and decisions in a relatively short span of time.

6. CONCLUSIONS

The work described in this paper has shown that by separating the model into quantitative and qualitative parts it was possible to cover the more broad aspects of the subject as well as to be able to look in depth into some other aspects of undesired events.
The work has also shown that the risk database is suitable for use as a checklist of known undesired events. The database also serves to provide information on which parameters affect which events, hence enabling to roughly estimate the size of possible risks involved.
The developed Bayesian networks are easy to use as a decision support tool in risk management. They enable to provide quick estimates of the expected cost and time overruns. The effects of control measures considered are also easy to determine.
Testing of the model has shown that the model produced reasonably accurate risk estimates of reality.
The database and the Bayesian networks are not fully validated and although it is not expected that the structure of the networks will require major improvements, however the norms and conditional likelihood tables may need further refinements.

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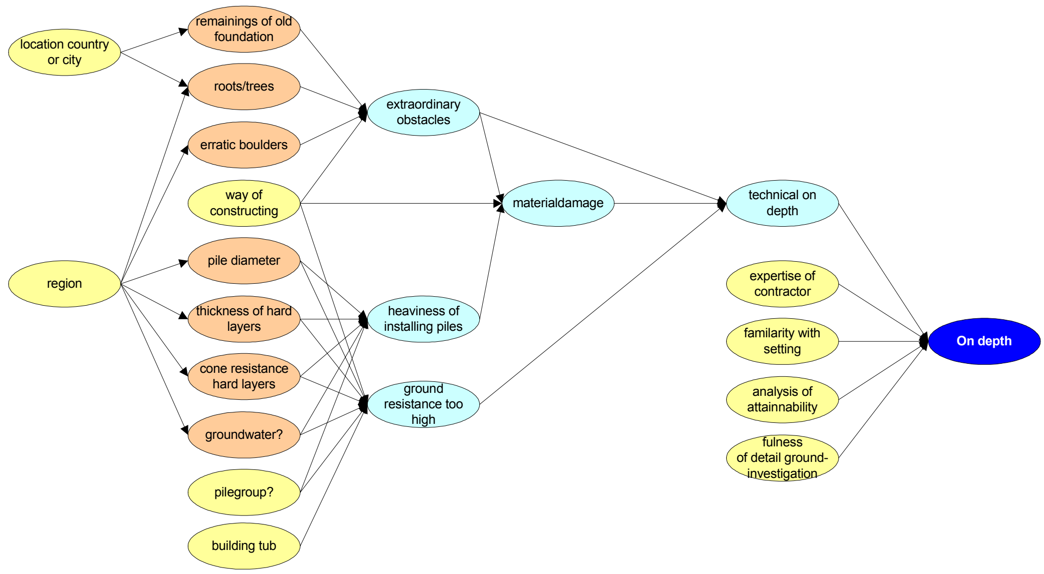

Figure 2. BBN Not achieving the required depth

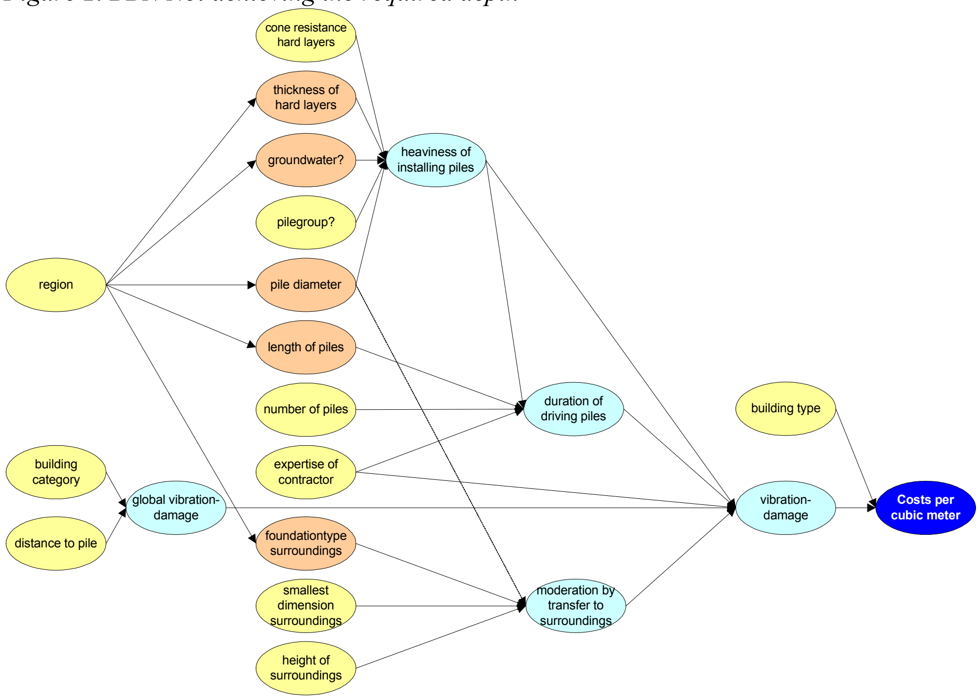

Figure 3. BBN Vibration damage

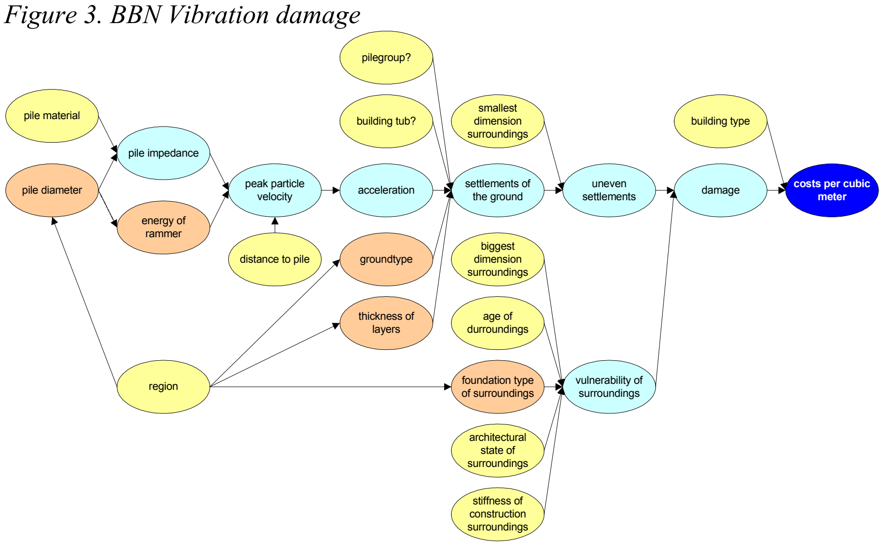

Figure 4. BBN damage by vibration induced settlements