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Risk Analysis in Foundation Engineering with Application to Piling in Loose Friction Soils in Urban Situations

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Summary

Civil engineering works are always connected with risk-taking and uncertainty. There is a probability that damage may occur and this involves a consequence. The damage is induced from a risk object such as a piling operation. The neighbouring buildings and structures that are affected due to their proximity are denoted the damage objects. The principle of risk analysis is to identify risk objects, damage objects and connected risk factors in the project to estimate, evaluate and, if required, reduce the risk, see Rowe (1977) and Rosenberg et al (1989).

In foundation engineering, particularly when piling and sheet piling are involved, the risk is usually more difficult to predict and the uncertainty is often greater than in general civil engineering. Foundation works in urban situations therefore require an extra high standard of risk analysis. The expected cost of damage to neighbouring buildings is often higher and the ground conditions are more uncertain in such projects. Today risk analysis in foundation engineering in Sweden is often based on intuition and subjectivity, see Eriksson et al (1987).

Piling in loose friction soils often has a significant influence on the surrounding ground and neighbouring structures, buildings and installations. Vibrations from the piling propagate in the ground, compacting the soil and causing settlements in the neighbourhood that result in damage, see figure S:1.

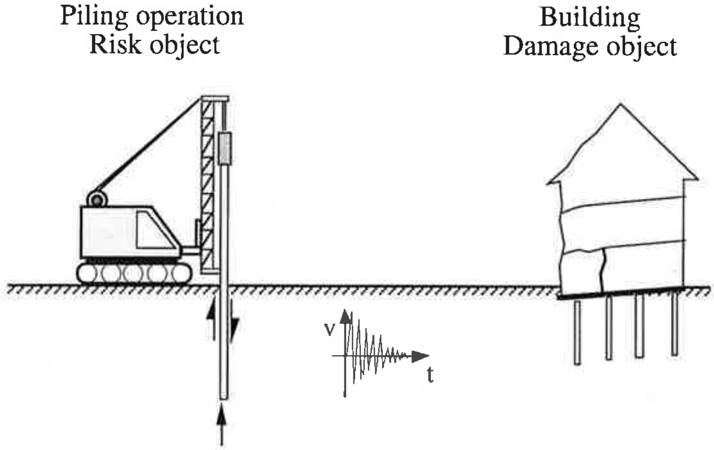

Figure S:1 *Vibrations from piling propagate in the ground, compacting the loose friction soil and causing settlements in the neighbourhood that result in damage*

Settlement is defined in this study as the sudden vertical displacement at a point in a building during the piling period due to the compacting effect in the surrounding loose friction soils, see figure S:2. The settlements give angular distortion in neighbouring buildings and result in damage to the structures that requires repair. It is assumed that the deformation in the soil corresponds to the displacement in the foundation structure. The settlements before and after the piling period are not considered in the study.

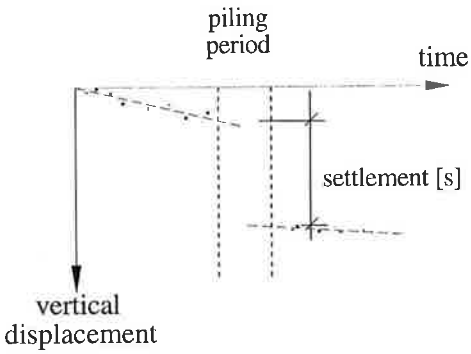

Figure S:2 Observations of settlement in neighbouring buildings founded on loose friction soils show a sudden vertical displacement due to piling. Modified after Andersson & Olsson (1991)

The expected total cost of a project is defined in this study as the sum of the cost for construction and costs for expected damage to neighbouring structures. An important part of foundation engineering is therefore to calculate the construction cost and the expected damage cost (the risk) in order to minimise the expected total cost of the piling project.

The risk is analysed by an engineering method that consists of a system of risk identification, risk estimation, risk evaluation and risk reduction during the foundation engineering process. The study is based on theoretical and field studies of risk analysis, decision theory and damage cost in buildings due to deformation of loose friction soils. A literature survey is carried out critically and references to previous research results are continuously made in each chapter.

The aim of the work is to validate the hypothesis that risks in foundation engineering can be accurately predicted and that risk analysis is a valuable tool for good decisions in the foundation engineering process. The method of risk analysis presented deals only with the expected economic consequences. Possible consequences of another nature, such as loss of goodwill and benefits are only commented on briefly in the report.

The method is based on an engineering estimation of the expected damage cost described from a PDF of angular distortion and from a consequence function of angular distortion. The settlements are considered as the result of several independent factors and a normal distribution is assumed based on previous experience and the central limit theorem.

Although the settlements and the expected damage cost cannot be determined exactly, the estimation is often sufficient to give guidelines for making decisions in the foundation engineering process.

The PDF of settlement depends on a number of important risk factors which include physical and contract-dependent risk factors linked both to the risk object and the damage object. These factors must be included in the risk analysis which would otherwise be very uncertain. The PDF of settlement is corrected on the basis of experience from the relevant geological area by using regional PDF correction factors for mean value and standard deviation.

The estimation of the weight of different risk factors influencing the physical and contractual situation is based on an evaluation of judgements by 12 experts, using the Analytical Hierarchy Process (AHP). The judgements of the 12 experts were given in 12 interviews during the period September 1992 to May 1993. The judgements correspond quite well with findings from the literature studied.

The risk factors are divided into three groups:

(1) Physical risk factors in risk object
- A. pile material
- B. bends in pile
- C. pile length
- D. hammer characteristic
- E. stop striking criterion (pile driven to refusal)
- F. groundwater level
- G. frost
- H. relative density of soil
- I. variation in relative density
- J. pre-drilling

(2) Contract risk factors in risk object
- K. time schedule
- L. organisation
- M. quality assurance
- N. settlement control
- O. settlement incentive
- P. experience of personnel

(3) Physical risk factors in damage object
    Q. foundation type
    R. foundation condition
    S. previous disturbance
    T. variation in building properties

Based on the expert judgement, the eight most important risk factors for piling in loose friction soils in urban situations are:

- pile length
- stop striking criterion (pile driven to refusal)
- relative density of soil
- pre-drilling
- experience of personnel
- foundation type
- foundation condition
- variation in building properties

The PDF of settlement is used to define the PDF of angular distortion $f_\gamma(\gamma)$ that is used for the risk estimation.

The consequence function $c(\gamma)$ of angular distortion is based on 3 factors:

- the structural type
- the angular distortion
- the market value

The risk is defined as the sum of the integral of the PDF of angular distortion multiplied by the consequence function of angular distortion in neighbouring buildings in SEK. The risk definition proposed in the study corresponds with the proposal commonly given in the literature. The risk $E_i(c)$ is calculated by:

$$E_i(c) = \int_{-\infty}^{+\infty} f_\gamma(\gamma) \times c(\gamma) d\gamma$$

where

$f_\gamma(\gamma)$	= the PDF of angular distortion
$c(\gamma)$	= the consequence function of angular distortion

A proposal for the evaluation of optimal project methodology from an economic point of view is described. The report also includes a discussion of non-technical factors important to the risk acceptance of the decision-maker. Optimal measures and methods in the project are based on the economic EMV-criterion.

This report also describes a proposal for use of additional settlement information on the actual settlements obtained through direct measurements at certain points during the construction phase. This information can be processed and used for a better risk estimation by using a statistical technique called bayesian updating. This technique allows the combination of subjective estimations based on professional experience with measured data. The prior PDF of settlement is updated with additional data to a posterior PDF of settlement.

In order to evaluate and verify the usefulness of the proposed method two field studies have been performed. The method of verification is to compare the magnitude of vertical displacements in the neighbouring buildings according to prognosis with the measured results from field studies.

The first field study concerns piling in the block named Palamedes 1. The second field study concerns piling in the block Proserpina 4. Both blocks are situated in the Old Town of Stockholm. In the vicinity of each piling operations there are a set of damage objects that due to their location are expected to be damaged.

In the field study Palamedes 1 the total risk cost is estimated at 3.4 % of the total cost based on prior knowledge of regional PDF correction factors from piling in Pandora 2, Pyramus 1 and Tritonia 8 during the years 1981-88. If a regional PDF correction factor based on the posterior knowledge of Palamedes 1 is used, the risk will increase to approximately 4.2 % of the total cost. The optimal decision in the case of Palamedes 1 was to use the decided methodology. The study also shows that the risk is moderately sensitive to evaluated changes in methodology.

In the field study Proserpina 4 the total risk cost is estimated at 7.2 % of the total cost based on prior knowledge of regional PDF correction factors from piling in Cadmus 1 in the year 1979. If a regional PDF correction factor based on posterior knowledge of Proserpina 4 is used, risk will increase to approximately 24 % of the total cost. The optimal decision in the Proserpina 4 was to use an extensive incentive program combined with a normal time schedule. The study shows that the risk is very sensitive to evaluated changes in methodology.

The use of pre-drilling seems to be important in both cases. In the case of Palamedes the risk will increase from 4.2 % to 14 % of the total cost if pre-drilling is not used. In Proserpina 1 the risk will increase from 24 % to 34 % of the total cost if pre-drilling is not used.

Evaluation of the divergence between prognosis and measured settlement in the field studies shows a small divergence in the Palamedes study and a large divergence in the Proserpina study. The large divergence between prognosis and measured settlement in the field studies seems to depend on the regional PDF correction factors. Further studies are thus necessary to get a better approximation of regional PDF correction factors.

Based on the study the following general conclusions are made:

— In new ground situations it seems to be necessary to investigate specific regional PDF correction factors. Those can be obtained from experience from previous projects

— updating of the PDF parameters can be based on the statistical technique called bayesian updating. This technique allows the combination of subjective estimations based on professional experience with measured data. In heterogeneous soil conditions the updating approach is often necessary

— This study has shown that a combination of foundation engineering knowledge and statistical knowledge may be useful for making good economic decisions regarding piling in loose friction soils in urban situations

— The foundation methods and risk-reducing measures can be optimised through use of the proposed risk analysis method. It is thus possible to calculate the monetary value of a particular risk-reducing measure, and decision theory combined with the EMV criterion is recommended. However, the study also has discussed and pointed out that the best decision criteria can vary between decision-makers due to individual and physiological factors

— The method proposed in this report is an engineering method that gives guidelines for optimising the choices between possible foundation method and risk-reducing measures. That implies some limitations and assumptions in the theory used

— Through a systematic identification of risk factors the apprehension of physical and contractual risk factors is improved. Action is thereby easier to prepare and take in the foundation process

Contents