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Safety assessment of third parties during construction in multiple use of space using Bayesian Networks

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ABSTRACT: Lack of space leads to the design and construction of projects which make intensive and optimal use of the limited space. Buildings above roads, railways and buildings themselves are examples of intensive use of space projects. The construction processes of those buildings are in general extremely complicated. Safety is one of the critical issues. A research has recently been completed [Suddle, 2001] about the safety for people present in the neighbourhood of these projects (such as users of infrastructure where above buildings are being built). This paper will purpose a methodology for the assessment of safety for such people using Bayesian Networks.

1 INTRODUCTION

In spite of many obstructions regarding construction safety, there have been already a number of different projects realised in The Netherlands. Examples of such projects are buildings situated on top of the motorway “Utrechtse Baan” in The Hague. An important lesson from these projects is learned; activities during construction phase of such projects form a hazard for people present on infrastructure beneath – called *third parties* – such as drivers and passengers [Meijer & Visscher, 2001; Suddle, 2001^A]. However, on the basis of law there are no explicit norms for the safety of third parties during construction, especially not for such projects [Suddle, 2001^B]. Besides, methodology of safety assessment of third parties in such conditions is up until now not developed. Case studies of projects built over the motorway Utrechtse Baan showed that specifying requirements regarding safety at an early possible stage during the design phase decreases risks for third parties during construction. It is essential to have clarity among those who are responsible for taking safety measures. Moreover, it is necessary to have an adequate and effective organisation at the construction site. This can restrict potential danger during construction [Meijer & Visscher, 2001; Suddle, 2001^A].

Before realising such projects, one has to consider, which aspects mainly influence the safety of third parties during construction and how the safety of third parties can be assessed during construction of such projects. Moreover, the use of infrastructure must be maintained during construction of the building above. Therefore the knowledge about safety system in construction phase of such projects and effectiveness of safety measures in accordance with human and financial risks is essential. It has to be noted that the measures have to be financial attractive and must comply with the level of risk acceptance criteria, to be divided into criteria on an individual and on a social basis [Vrouwenvelder et al., 2001; Vrijling & Vrouwenvelder, 1997].

2 CLASSIFICATION OF SAFETY ASPECTS DURING CONSTRUCTION PHASE

To determine the safety and thus the risks for third parties in multiple use of land projects, a classification has been made for aspects, which influence the safety of third parties during construction. This classification consists of four main aspects (see figure 1). A full scope of these aspects is presented in [Suddle, 2001^A].

2.1 *Regulations*

In order to carry out a flexible process, regulations basically provide an effective tool for all actors and their relations during any stage of any project. In essence, regulations, like guidelines for contractors, that control the safety during construction. However, in case of multiple use of space projects, these regulations

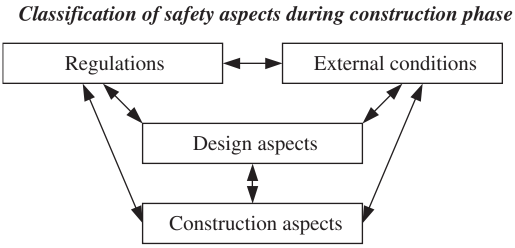

Figure 1. Classification of safety aspects of third parties during construction phase [Suddle, 2001^{A}].

are hardly effective and thus not explicit. Other types of regulations are meant for structural calculations, materials, quality sets, organisation at the site etc. Both national and international standards are a part of this main aspect.

2.2 *External conditions*

External conditions are a main parameter for the safety of third parties. The location of the building, which depends on the (traffic) condition beneath, forms a fundamental aspect of external conditions. These parameters determine both the intensity and the speed of traffic. Furthermore, it is important to realise that safety (of third parties) during construction depends on whether the building is being constructed (e.g. above roads or above railway tracks) or the height level of the infrastructure. Typically, the surroundings impose these conditions. The position of cables in the underground can be also considered in this main part. Therefore, some of these parameters can hardly be influenced. However, one may prevent risk for third parties by logistic measures e.g. close off the road and reroute the traffic during construction.

2.3 *Design aspects*

Other parameters, which influence safety of third parties, are related to design aspects. These aspects depend on e.g. dimensions of the building, architectural design, structural elements, functional design of the building and technological aspects. These parameters, which are characteristics of the considered project can be influenced and controlled in the project design phase.

2.4 *Construction aspects*

Finally, characteristic aspects related to construction work can be mentioned as a main part for safety of third parties. Aspects fixed in the design phase hardly can be changes during construction. Hence, mistakes made in the design phase will always come to light in the construction phase. The construction (phase) is characterised by many parties involved. Therefore, the organisation between these parties is crucial as well. In this phase, regulations, boundaries and preventive measures regarding safety of third parties during construction, is relevant.

3 RISK ANALYSIS

3.1 *Qualitative risk analysis*

Considering the safety aspects during construction phase, the relation between these aspects of construction in multiple use of land and their risk has been analysed. Accordingly, risk analyses have been made for several cases. First, a qualitative risk analysis for the safety of third parties has been performed by FMEA-techniques (Failure Mode and Effect Analysis). This technique represents a complete view of hazards and consequences. In this study this technique is applied for the construction of a building over a motorway (a full scope of the FMEA is presented in [Suddle, 2001^{A}]). Normally a FMEA consists effects of failure like cost increase, time loss, loss of quality, environmental damage and loss of human life. Considering the aim of this study, risk regarding cost increase and loss of human life are taken into account. A part of the FMEA is presented in table 1 (adapted from [Suddle, 2001^{A}]).

It appeared from the FMEA [Suddle, 2001^{A}] that safety of third parties during construction largely depends on *falling elements*. The falling objects may consist of bolts, screws, part of concrete (structures), parts of a scaffold, building parts, hammers, beams, or even construction workers.

3.2 *Quantitative risk analysis*

Hence, these falling elements may cause casualties among people present at the infrastructure and in some cases economical risks as well as. This observation is analysed in more detail by a quantitative risk analysis using Bayesian Networks for a case [Suddle, 2001^{A}]. This case consists of a building of 10 stories that is built above a 2×2 lane motorway. The span and the linear direction of the building are respectively 20 meters and 50 meters. Two risks, loss of human life and economic loss, are considered in these networks. (see figure 2)

In this regard, possible quantifiable parameters should be transformed into conditional probabilities, which are determined from both the classification aspects for safety of third parties during construction (section 2) and the FMEA (table 1). These quantifiable aspects are the following:

- the position where the element falls (inside or outside the building);

Table 1. An example of the FMEA for safety of third parties during construction (adapted from [Suddle, 2001A]).

Failure mode	Failure mechanism	Effect of failure
Activity: Ground activities		
Activity: Fabricate elements		
Activity: Fabricate elements		
Activity: Concrete work		
Logistic problems	Planning fault	Time loss
Collapse of concrete element	Design fault	Costs, time loss, casualties
Fixing concrete elements	Element falls	Costs, time loss, loss of quality, casualties
Huge deformations of elements	Element collapses and falls	Costs, time loss, loss of quality, casualties
No right composition of concrete	Production fault	Costs, time loss, loss of quality
Activity: Installing temporary structures/scaffolds		
Fixing temporary structures	Construction fault Collapse of temporary structures Construction falls Construction element falls	Costs, time loss, casualties
Activity: Remove temporary structures		

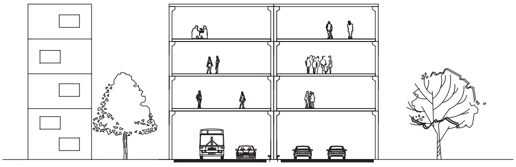

Figure 2. Case 2 × 2 lane motorway.

- the situation below the building;
- (design) errors;
- the weight of the falling element;
- the actions of elements in relation with the installation of elements;
- the collapse of the main structure of the building caused by falling elements;
- the probability of elements falling;
- the height from which the element is falling;
- fatalities and economic risk.

These aspects are taken into account in Bayesian Networks. Each aspect is represented as a node or is integrated in these networks (see figure 3). Each node is divided into categories corresponding with events of that node. The relations between the nodes are connected with arcs, which specify the probable influence between these nodes.

These probabilities are determined by historical data, expert opinion or by engineering judgement.

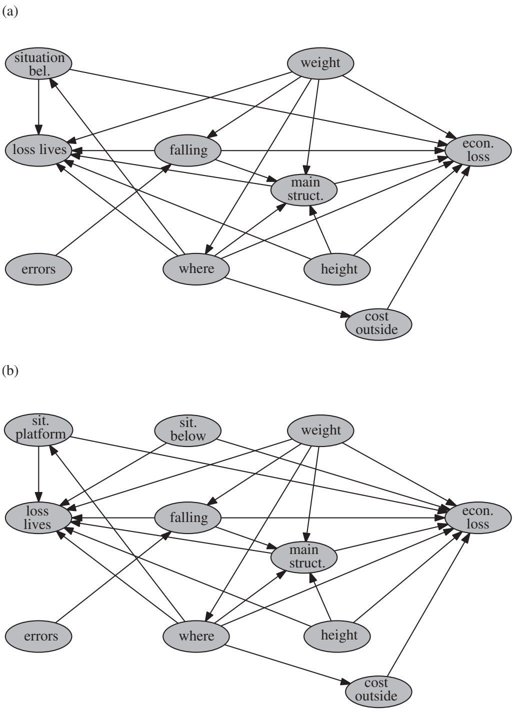

Figure 3. Bayesian Network for building above roads (a) and above railway tracks (b).

In some cases, especially cases, where historical data cannot be found in literature and for that reason expert opinion or engineering judgement is used. Same order magnitude following from occurrence frequencies of hazardous events combined with different probabilities are used to determine the failure probability.

3.3 *Quantification of probabilities and relations of aspects*

- the position where the element falls (inside or outside the building);

  The position where the element falls depends on the considered surface. The ratio of the building surface and the surface of risk zones outside the building $A_{building}/A_{outside1,2}$ determines the *P*(*element falls outside or inside the building* | *element falls*). In this analysis, the value of risk zones outside the building ($A_{outside1,2}$) is estimated on 2 meters out of the façade of the building (see figure 4).
- the situation below the building;

  In order to compute the probability of a person of the third party is being hit by a falling element, it is relevant to know the situation below the building. The situation below the building corresponds with the *P*(*element falls on a car or the road* | *element falls outside*) and *P*(*element falls on cars* | *element falls inside* | *building collapses*) can be determined respectively by the ratio of total cars in the risk zones $A_{cars}/A_{outside2}$ and total cars beneath the building $A_{cars}/A_{building}$.
- (design) errors;

  An assumption has been made for fatal (design) errors. The P((*design*) *errors*) $= 10^{-4}$, which correspond with category "remote".
- the weight of the falling element;

  To investigate the effect of falling element, five different weight-classes (of falling elements), which are used in the building, are formulated: (see table 2)
- the actions with elements in relation with the installation of elements;

  It is not only the weight class that determines the risk of third parties, but the actions per element particularly are the main cause whether the element falls or not. Therefore, the distribution of total elements in the building is determined regarding the case-study (see figure 5). Subsequently, this distribution is transformed into the distribution of the actions of elements (see figure 5). This means that the output probabilities should be multiplied with the total actions per project per year.
- the collapse of the main structure of the building caused by falling elements;

  A collapse of the building can only occur if the element falls inside the building during construction. In this respect, the *P*(*collapse of the building* | *weight*

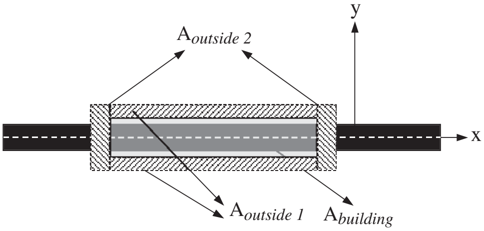

Figure 4. The building surface and the surface of risk zones outside the building.

Table 2. Examples of different weight classes.

Weight-class	Example of elements
<5 kg	Very light material, bolts, screws, concrete remains, etc.
5–100 kg	Light material, interior material, light dividing walls, construction workers, etc.
100–1000 kg	Structural elements for the façade construction, etc.
1000–10000 kg	Structural elements, beams, hollow core beams, etc.
>10000 kg	Heavy structural elements, main structure of the building, etc.

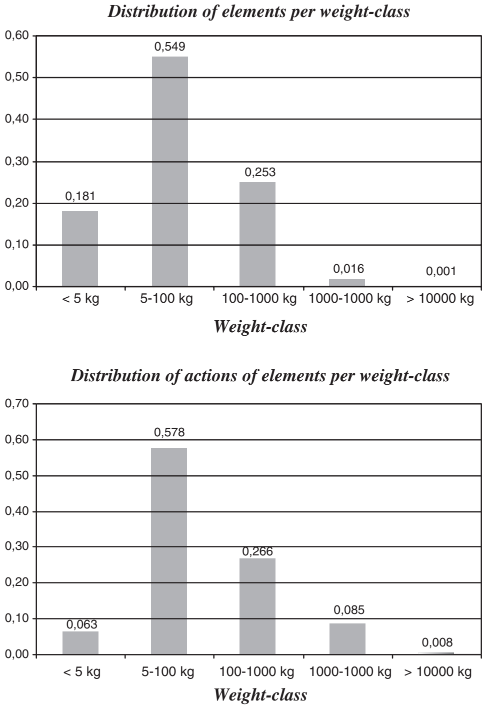

Figure 5. Distribution of elements and distribution of actions per element.

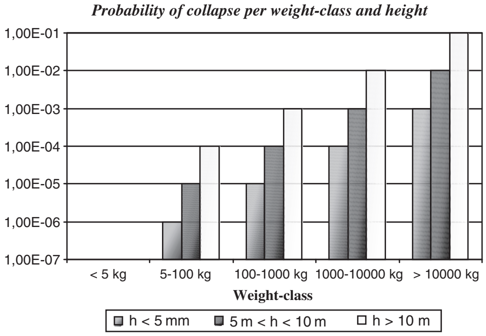

Figure 6. Probability of collapse of the building if element falls inside the building.

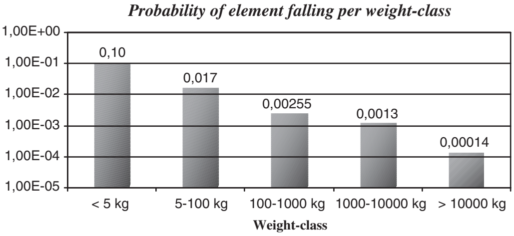

Figure 7. The average probability of element falling [project^{-1}].

class | *element falls inside building* | *element falls*) is determined by a combination of engineering judgement and laws of mass and impulse.

A logic assumption has been made that the heavier the element and the higher from it falls, the higher the probability that the building collapses due to the falling of an element inside the building (see figure 6).

- the probability of elements falling;

  Because of no data could be found about the probability of elements falling per weight class, an extensive expert opinion has been performed (see Appendix A). The experts varied from scientist specialised in construction technology in multiple use of space projects and construction workers. It seemed that their opinion regarding the probability of failure corresponded with each other. The average probability of elements falling per weight class per project is given in figure 7.
- the height from which the element is falling;

  The height from which the element is falling is integrated in the Bayesian Network as a variable in the risk analysis. This variable corresponds with the ratio of the height of the building. Three different height levels are proportionally considered; $h < 5$ m; 5 m $< h <$ 10 m and $h >$ 10 m.
- fatalities and economic risk;

  The probabilities of the node fatalities and economic risk are determined by engineering judgement (for a full overview see [Suddle, 2001^{A}]). The node fatalities is divided into injury and loss of live. It has to be noted that *P*(*person being killed* | *an element falls on a person*) is almost 1, if an element is even less than 5 kg falling (see figure 8).

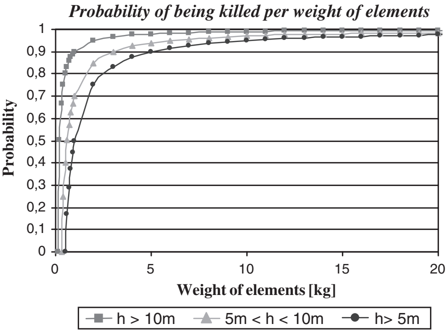

Figure 8. The probability of being killed due to an falling element.

Table 3. Examples of different weight classes.

Cost-class	Example of costs
No costs	In case of no elements falls
<€ 10,000	Very light damage to vehicles, etc.
€ 10,000–€ 100,000	Light damage to infrastructure and total loss of (expensive) vehicles, etc.
€ 100,000–€ 1,000,000	Damage to infrastructure, etc.
>€ 1,000,000	Heavy damage in case of close off the road and reroute the traffic for a long period, etc.

A large economic damage mainly depends on the case of closing the infrastructure for a long period of few weeks, due to e.g. collapse of the building above. In this regard five different cost-classes (of economic risk) were considered and particularly the effect is determined if elements fall in the risk-zones (see table 3 and Figure 9):

A full overview of conditional probabilities of fatalities and economic risk is presented in [Suddle, 2001^{A}].

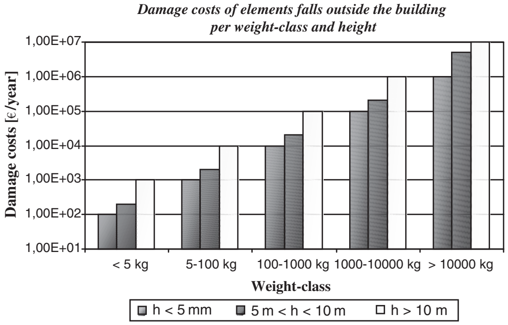

Figure 9. Damage costs of elements falls in the risk-zones of the building.

3.4 *Quantification of probabilities above railways and existing buildings*

To determine the risks for third parties in the construction phase by building over railways and existing buildings, such networks are composed for cases both cases. In the Bayesian Network building above railway track an extra node is added, which represents the situation at platform (see figure 3). It has to be noted that the financial damage given an element falls is in railways is much bigger than by roads, because there is no option for rerouting the train traffic [Suddle, 2001^{A}]. Finally, the risks for third parties are also determined by making these networks for building over an existing building, in which the situation beneath the building is less dynamic.

4 RESULTS OF THE RISK ANALYSIS

4.1 *Individual Risk*

Basically, the probabilities those are determined consists probabilities per year per action of a considered element. The individual risk (*IR*) during construction can be determined by multiplying the computed probabilities with the number of actions (see table 4). In this regard the individual risk in both building above road and railway tracks is almost the same order (10^{-6}).

This can be presented as individual risk contours at the construction site (figure 10). The expected loss of human life ($E(N_d)$) can be computed by multiplying the individual risk (*IR*) with the number of participants. The results of the risk analyses comes down to the following:

The results show that building over road infrastructure is the unsafe way to build, followed by building over rail infrastructure. Building over existing buildings is with less risk. From financial point of view, building over rail infrastructure is not significantly different from building over road infrastructure.

Table 4. Results of the risk analysis.

Building over	Roadway	Rail track	Building	
Expected loss of human life	1,65	1,33	$8{,}01 \cdot 10^{-4}$	*human risks*
Expected injuries	5,46	1,72	$8{,}10 \cdot 10^{-6}$	*human risks*
Expected costs	€ 945,000	€ 1,035,750	€ 17,700	*economical risk*

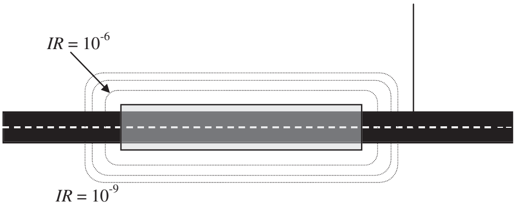

Figure 10. Risk contours during construction phase for building above road.

Again, building over existing buildings is with less risk.

4.2 *Group Risk*

In the same way, group risk is considered for constructing buildings above roads railways and existing buildings. The group risk for building above roads, railway tracks and existing buildings is almost negligible. Note that building over existing buildings is with less group risk.

4.3 *Check for limits of risk acceptance*

Because of a lack of explicit norms of risk acceptance for the safety of third parties during construction, the method of [Vrijling et al., 1996] based on voluntariness is used ($\beta_i = 0.01$) When considering these acceptance limits for risk acceptance, to be divided into criteria on an individual and on a social basis the results for building over rail and road infrastructure are slightly exceeded. Therefore, safety measures are analysed and optimised for building above road infrastructure.

5 SENSITIVITY ANALYSIS

In order to formulate safety measures and to determine their effect on risks, a sensitivity analysis is

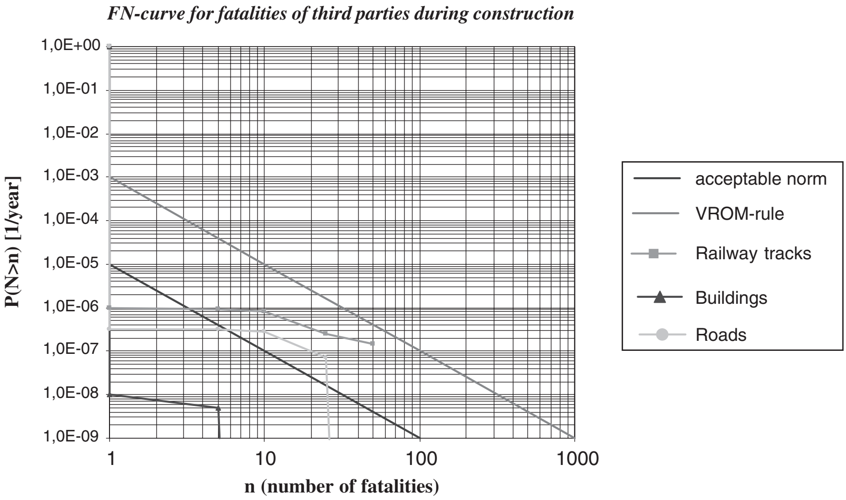

Figure 11. Group risks of building on top of transport routes.

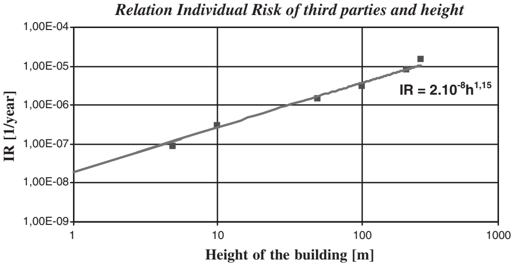

Figure 12. The relation between height of the building the individual risk of third parties.

performed. The sensitivity analysis provides both transparency of relevant scenarios and deviation of results of risk analysis using Bayesian Networks. The dominant aspects are:

- the number of actions per project;
- the position where the element falls;
- situation below the building;
- the weight of the falling element.

Furthermore, the risk zones of the building, the façades that are crossing the road, form an important nexus for the safety of third parties (see also figure 10). Surprisingly, factors that turned out to be hardly of any influence are (design) errors and collapsing of the main structure of the building caused by falling elements. The error in the calculated probabilities is approximate 40%. This is determined by evaluating the conditional probabilities that were determined by engineering judgement. So, the result of expected loss of human live varies between 1,20 and 2,31. If the height of the building is considered with the individual risk (*IR*) of third parties, the following relation can be presented.

Figure 12 presents the higher the building, the higher the individual risk of third parties. It also means that the higher the building, the more safety measures have to be taken.

6 CONCLUSIONS

This paper presented the probabilistic approach for the safety of third parties during the construction phase. The relation between FMEA-techniques and Bayesian Networks is treated. This study showed that the risk zones of the building, the façades that are crossing the road, form an important nexus for the safety of third parties. The safety measures should be integrated into these zones.

LITERATURE

Meijer, F. en H.J. Visscher, *Bouwveiligheid en bouwhinder bij meervoudig stedelijk ruimtegebruik.*, Onderzoeksinstituut OTB, DUP Satellite, 2001, 113 pp.

Suddle, S.I., *Veiligheid van bouwen bij Meervoudig Ruimtegebruik*, afstudeerrapport, TU-Delft, april 2001^{A}, 298 pp.

Suddle, S.I., Veilig bouwen bij Meervoudig Ruimtegebruik, *Land + Water*, Volume 41, no. 9/2001, september 2001^{B}, pp. 24–27.

Suddle, S.I., Safety of construction in intensive use of space, *Proceedings of Congress Risk Analysis*, Volume III, Editor: C.A. Brebbia, Sintra (Portugal), WIT Press, Southampton, June 2002, pp. 305–314.

Vrijling, J.K., W. van Hengel, R.J. Houben, *Acceptable risk as a basis for design*, Reliability Engineering and System Safety, Volume 59, 1998, pp. 141–150.

Vrijling, J.K., A.C.W.M. Vrouwenvelder e.a., *Kansen in de civiele techniek, Deel 1: Probabilistisch ontwerpen in de theorie*, CUR-rapport 190, CUR, Gouda, maart 1997.

Vrouwenvelder, A.C.W.M, e.a., *Risico-analyse bouwfase boortunnel*, CUR/COB Uitvoeringscommissie N510, tussenrapportage, TNO-Bouw, Delft, 25 november 1996.

Vrouwenvelder, A.C.W.M., *Risk Assessment and Risk Communucation in Civil Engineering*, CIB Report, Publication 59, februari 2001.

APPENDIX A

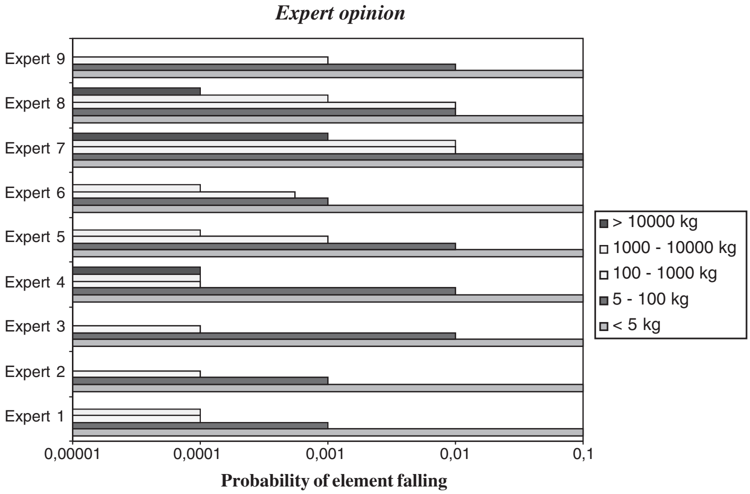

Figure 13. Results of expert opinion for probability of an element falling.

Figure 14. Construction of the Malie Tower in The Hagure (The Netherlands).