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Learning from case studies and monitoring of Dutch tunnel projects

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Individuals and project-based organisations in the construction industry can learn in a (more) systematic way from case studies and the monitoring of underground construction works. Underground construction projects such as tunnels and excavations suffer as much or more from failure costs compared to other parts of the construction industry, making this subset of projects suitable for learning in general and evaluation of the learning process more specifically. Several case histories from Dutch underground deep excavation projects are presented in this paper, including the lessons learned and the learning processes involved. Finally, ideas for learning approaches are proposed based on risk management principles.

1. Introduction

Individuals and organisations in the construction industry can learn in a (more) systematic way from case studies and monitoring of underground construction works. Underground construction suffers from cost overruns in a manner similar to other parts of the construction industry. For example, the Boston Big Dig (Wikipedia, 2017), the Channel Tunnel Rail Link (Flyvbjerg *et al*., 2004) and the Amsterdam North–South Line (Van Tol and Korff, 2011) are well-known projects for their cost overruns, partly due to failure costs. This makes this subset of projects suitable for learning in general as well as evaluation of the learning process.

2. Failure costs and their origin

2.1 International projects

A detailed summary of failure costs is presented by Kazaz *et al*. (2005) and shows that failure costs in construction projects typically range between 2 and 25% of the overall project cost. Research in the USA shows that inefficient management practices in projects (often referred to as failure costs) in the construction industry are over 12% of the total turnover of the industry (Burati *et al*. (1992), based on research for the Construction Industry Institute in 1989). Research carried out in the Netherlands (USP Marketing Consultancy bv, 2008) amounts to failure costs of 11·4% of the industry's turnover compared to 7·7% 7 years earlier. Other studies into failures costs come up with comparable numbers: 5·5–11% of the production costs for apartment buildings (Hansen, 1985) and 2·3–9·4% on 7 building projects in Sweden between 1994 and 1996 (Josephson and Hammarlund, 1999). Australian projects were analysed by Love (2002), who derived direct and indirect rework costs to be 6·4 and 5·6% of the original contract value.

Not many studies focused on projects related to underground construction. Avendano Castillo *et al*. (2010) identified for underground projects that ground uncertainty and the interpretation of ground parameters play a prime role in the occurrence of failure costs. According to the experts whom they interviewed, failure costs in underground-related projects represent on average 4–6% of the total project costs. Although they stated that failure costs to the client were much higher, the values given here seem low in comparison to the general values from the construction industry presented earlier.

2.2 Causal analysis of failure costs

In the majority of the cases, failure costs share common causes (Love and Li, 1999, 2000). The top three reasons for the costs of failure mentioned by USP Marketing Consultancy bv (2007) are 'lack of communication and information transfer', 'inadequate attention for feasibility during design phase' and 'the delivery of quality to end user as not being the highest priority'. Hall and Tomkins (2001) identified that the majority of incidents were attributable to errors and mistakes by specific individuals (22%) or to supplier errors (27%). 'Force majeure-type' incidents were very rare (2%). Management and communication problems by the main contractor totalled 25% of the incidents. A number of potential improvements were identified, including among others the identification of common and recurring mistakes and errors that could be considered at the beginning of future, similar projects and better consideration of the training needs and meeting training targets of employees. The UK National Economic Development Office (Nedo, 1983) analysed 'quality-related events' in building projects and found that design and poor workmanship together formed more than 90% of the total events investigated. Under poor workmanship, 'lack of care' and 'lack of knowledge' were the main causes. In design, 'unclear/missing information' and 'design will not work' were identified as the major causes. Specifically related to underground construction, the interaction with existing structures is often a major cause of the failure costs, as shown in the examples in the next section.

2.3 Results of study of 50 deep excavations

Korff *et al*. (2011) described the analysis of about 50 deep excavations in the Netherlands, for which a claim situation arose for constructions between 1995 and 2012. The aim of this paper is to analyse the cause of the failure costs more than the costs themselves. The main source of failure costs in a technical sense was related to the retaining wall of the deep excavation, the rest more or less evenly distributed over the other parts of the structure and the surrounding structures.

In 34% of the cases, some sort of physical damage was caused to adjacent buildings; the other main aspects of failure include time delays, need for additional measures to prevent deformations and/or leakages. In cases like these, an important question usually is whether the problem is caused by the design or the execution of the project. Although not mentioned for each case, in most of the cases, the design played a crucial role in the origin of the failures. The designer of the wall (which can be either an engineering firm or a contractor in an integrated contract) often disregards the constructability of the project, often due to perceived liability issues.

The most important aspect of the failures related to the learning process is the extent to which the event was predictable or not. Predictable adverse events in practice actually occur, often due to insufficient knowledge of the designers, despite the deployment of appropriate personnel, risk assessments and design reviews.

Based on the work of Bea (2006), the failures were classified into predictable and unpredictable events. In the 50 projects analysed in the Netherlands, more than 60% of the failures arose due to not (correctly) applying existing knowledge; see Figure 1. Moreover, in 24% of the cases, the cause of the failure was qualitatively known, meaning that these kinds of failures are known, but it cannot be predicted exactly when and where they will occur. In only 13% of the cases was unknown knowledge the main reason; all of the others were 'predictable surprises' as described by Bazerman and Watkins (2004).

In total, 87% of the cases failure could have been avoided. The use of proper risk management would have identified the risks, including those related to the knowledge of the staff working on the project.

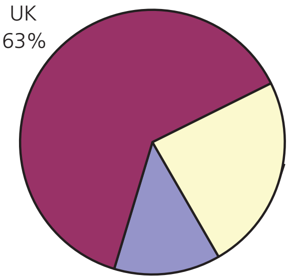

Figure 1. Subdivision in known and unknown knowledge (Korff *et al.*, 2011). UK, unknown knowables; UU, unknown unknowables

But a good risk management process needs to be fed with proper (geo)technical knowledge, which requires sufficient learning from the individuals and organisation. What do the results of these cases say about the learning process in the type of projects that were identified?

At the individual level, it is hard to analyse these projects and determine the amount of learning that has taken place either due to the failure or in advance of it. The 50 cases surely had some amount of personnel that was involved in more than one of the projects or similar projects beforehand. It is, however, unlikely that the same mistake was made (or the same risk was missed) more than once by the same person.

At the organisational level, however, it is clear that the projects apparently rely on the knowledge of the team rather solely. The fact that was established that, in 60% of the cases, the knowledge necessary to prevent the failure was present somewhere outside of the project shows clearly that learning from project to project is not taking place on a regular basis.

2.4 The importance of knowledge and learning

The importance of knowledge in the projects and with the professionals involved is also stressed by Bea (2006), who concluded that, in many of the construction projects, the identified failure costs could directly be related to (lack of) knowledge and development.

Korff *et al*. (2011) showed that in Dutch underground construction projects, the application of existing knowledge could have prevented or limited failure costs in at least 60% of the cases. A good example of learning from project to project is reported by Ball (1987), where a British contracting company managed to reduce total failure cost for a construction project from 4·1% of the tender amount to 0·6% for another project by studying the faults in the first project on the basis of trends to reveal the errors and preventing those errors in the second project. Roberts (1991) found that by spending 1% more on prevention efforts, the failure costs of construction can be reduced from 10 to 2%.

The analysis of the causes for failure costs and the fact that over the last few decades no reduction has taken place in failure costs (not only in absolute terms but also in relative terms) brings the author to the conclusion that, apart from the occasional project, learning from project to project does not or not sufficiently take place. Often this can be attributed to the widely present idea that in the construction sector each project is unique. This paper takes a more detailed look into the learning that can take place from case studies in underground construction.

3. Learning from case studies – concept and applicability

Kolb (1984) directly linked experience to learning in his definition of learning: learning is the process whereby knowledge is created through transformation of experience; see Figure 2. It is generally

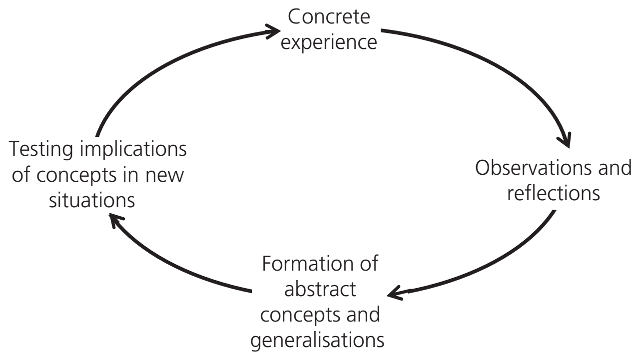

Figure 2. Kolb's experiential learning cycle

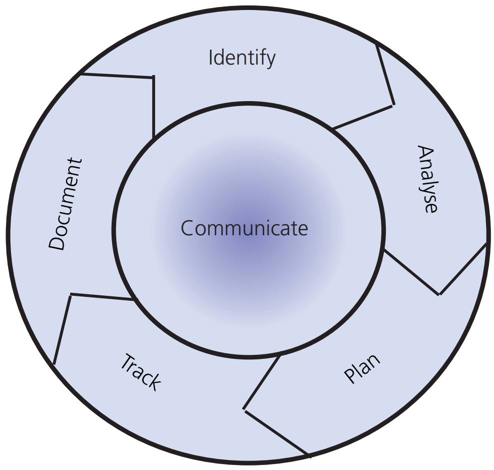

Figure 3. Risk management cycle

accepted (for example, reported by Polanyi (1967) and Nonaka and Takeuchi (1995)) that knowledge comprises both explicit and tacit knowledge. Explicit knowledge can be obtained from education and written down in books; implicit knowledge has to be gained by experience and is as such subjective. Crawford and Gaynor (1999) showed that 85% of project personnel gain their knowledge, both explicit and tacit, through experiential learning.

Another important aspect for the use of knowledge to reduce risks is that not only individuals need to learn, but also organisations, as stated by Gareis and Huemann (2000). However, many project-based organisations have difficulties obtaining experiential learning at both individual and organisational levels, which was shown by Pinto (1999) and Gibson and Pfautz (1999).

Individuals and project-based organisations in the construction industry currently are indeed learning by experience, but not often in a systematic way. This conclusion is derived from a large amount of real projects, mainly focusing on underground construction works. A learning organisation is essential to be effective and to limit risks and failure costs.

4. (Geotechnical) risk management

The well-known risk management cycle requires individuals and organisations to track risks during the course of a project, document them and use them in either the next stage of the project or a new project. Apparently, based on the 50 cases presented before, at least two systematic issues are often lacking

- performing proper risk management (all of the steps from Figure 3 in a systematic, explicit way, based on technical expertise)
- evaluating and documenting the risks during the project for a next stage or project (the document step in Figure 3 more specifically).

Several authors have emphasised the need for proper risk management to prevent failures – for example, Van Staveren (2006). In this paper, the focus, however, is on learning from case studies and thus on the step where learning is made explicit; this is the document phase. It must be stated that documenting risks alone is not enough for a learning experience, but it is a necessary first step.

First, how this type of learning can be improved is explored. Necessary aspects to increase the learning potential of real world projects include

- systematic learning process awareness
- monitoring of project performance
- documenting and sharing.

In the next sections, each of these aspects is analysed in detail for projects where systematic learning took place. Each example deals with underground construction works in densely populated areas, where monitoring of the construction performance played an important role.

5. Case study: A2 Maastricht project

5.1 Project description

The project comprised the construction of the A2 roadworks in Maastricht, in the southern part of the Netherlands. A 2 km long double-stack cut-and-cover tunnel was constructed in highly variable soils consisting of chalk layers of different qualities. The 10 m deep tunnel was constructed with steel sheet piles and three bracing levels, and the bottom of the excavation was sealed off by the chalk. Most of the structures adjacent to the tunnel were founded at distances of at least 20 m, which reduced the risk of damage to these structures. The project itself was, however, very sensitive to the variations in the soil conditions. For this reason, the observational method (OM) was applied, because the chalk layers were also difficult to characterise by site investigations. Details of the project can be found in the papers of Van Dalen *et al*. (2015a, 2015b) and Galenkamp (2015).

5.2 Risk awareness

The design and construct contract put the responsibility of the main risks with the contractor, who invested heavily in monitoring and made a full implementation of the OM from the start of the project. Being rather a new concept for application in the Netherlands on such a scale and with the corresponding challenges in the site conditions, the contractor could obtain permission for the construction only with a very stringent risk management process, in which learning from earlier stages was required to excavate safely to more challenging parts of the project.

5.3 Monitoring

In application of OM, the use of extensive monitoring equipment to track the performance of the structure is obviously essential. In this case, monitoring involved deformations of the walls, forces in the struts and monitoring of the water levels on the inside and the outside of the tunnel. The monitoring was checked on a daily basis and partly automatically. Decisions to start work were made every day in the morning after inspection of the project and evaluation of the monitoring data.

5.4 Documenting and learning

Lessons learned in the project included the following.

- The OM can successfully be used for underground construction works in case of soil heterogeneity, uncertainty in soil strength and deformation characteristics, when displacements are leading and in multistage processes.
- Optimisation of a project with the OM is limited to what can be proven in time before the next construction phase takes place since some uncertainties can be ruled out only at a stage too late to use the benefits.
- Always expect everything to fail (in this case, failure of the pumping system was reported as well as power cuts while the reserve generator was connected incorrectly as well as theft of (reserve) power cables).
- Increased monitoring efforts to optimise construction were intended to decrease the risk, but were perceived by some of the workers as a sign that there actually was an increased risk.

The application of the OM in this project resulted in a successful completion with much more optimistic soil parameters than the original design values, so the contingency measures were not used. This result was mainly obtained by a close co-operation between the contractor and the client in the alliance form of the contract. There was increased awareness and transparency of the risk due to participation in a national applied research programme (Geo-Impuls, 2017). The lessons learned in this project are collected in detail in the new guideline for the OM application in the Netherlands; see SBRCurnet (2015).

6. Case study: Amsterdam North–South Line project

6.1 Project description

The North–South Line in Amsterdam is a 9·5 km metro line. The line starts at street level in the north of Amsterdam and passes under the historic centre of the city in a 3·1 km twin shield tunnel. Five underground stations were constructed in deep excavations supported by diaphragm walls. The soil conditions are challenging due to the soft soils (clay, peat and sand) and the water table only decimetres below the surface. Old, historic and sometimes listed buildings are found at not more than 3–5 m away from the tunnel. The construction of the line started in 2003 with preparation works for the stations; tunnelling started in 2009 and finished in 2011. The three inner-city stations were structurally finished in 2014. It is expected that the line will be fully operational in 2018.

6.2 Risk awareness

Risk management played an important role already from the start of the project. For example, a so-called geotechnical baseline report was made to understand and specify the risks related to varying soil conditions. Also, the extensive monitoring system was part of this awareness.

During the excavation for one of the stations (Vijzelgracht station), leakage through the wall resulted in large settlements of and damage to several monumental buildings, which threatened the support of the authorities for the project. With the application of robust preventive measures at two of the deep stations, it was possible to continue the project.

6.3 Monitoring

In order to determine the displacements of the historic structures along the deep stations, an extensive, mostly automatic monitoring system was installed in the city centre from the year 2000. This included in total 74 robotic total stations for over 1700 prisms on the buildings (usually a minimum of four per building). Secondary instrumentation comprises precise levelling points used as a backup system.

In order to handle the large amount of monitoring data, software applications have been developed with the use of a geographic information system (GIS); see also Netzel and Kaalberg (1999). The GIS has been developed to store, analyse, structure and visualise the data used in settlement risk management, in order to provide rapid reaction opportunities. The monitoring instruments further included extensometers behind the wall, inclinometers in the soil and in the wall and manual levelling of the surface and the buildings. Details of the monitoring system can be found in the papers of Korff and Kaalberg (2014) and Kaalberg *et al*. (2003).

6.4 Documenting and learning

Lessons in this project were learned through the problems that took place as well as from the majority of the construction activities that went well.

6.4.1 Organisational learning from problems

It was learned that the organisation needed to be strengthened, with even more emphasis on the risk management process (by appointment of project leaders for each of the stations), the working methods and the (geo)technical quality of the personnel involved in both day-to-day construction control as well as independent reviewers. An important lesson was learned regarding communication: open communication with the community; house owners, shop owners and other inhabitants proved to create trust and understanding and built pride and goodwill within the community for the project.

The leakage events lead to a process of learning related to the construction method of the diaphragm walls. By analysing the installation process and evaluating the quality of the walls upon excavation in a systematic way, additionally, a better theoretical understanding of the construction process with bentonite and concrete mixtures leads to important lessons. These lessons were published in a guideline, *Handbook Diaphragm Walls Design and Installation* (CUR, 2010).

- Reporting data in detail: In case of calamities, these data are extremely useful in determining the cause. This also includes monitoring of the position of the grab that is used for excavation, slump values of the truck mixer, inclination of concrete level and testing of the bentonite mixture with the soil from the site.
- The ideal construction process involves desanding of the bentonite, cleaning of the trench, jetting of the joints and making sure that removing steel stop end and concreting take place quickly after reaching final depth of the panel.
- Perform proper risk management and prepare countermeasures.

Furthermore, academic learning took place based on these events in the form of analysis of the concreting process (Van Dalen *et al*. (2015a, 2015b) and the feasibility of sonic and geophysical logging to check the wall for potential leakages (Spruit, 2015).

6.4.2 Organisational learning from ordinary construction

A wealth of information was gathered by the very extensive monitoring system. Learning took place among others on the soil structure interaction between the excavation and the houses (Frankenmolen, 2006; Korff, 2013) and between the shield tunnel and the houses as well as the effectiveness of the compensation grouting that was used (Bezuijen *et al*., 2011). This led to several guidelines, such as the design guideline for construction of deep excavations in inner cities (COB, 2012) and validation of design methods. The outcome of the learning process related to the monitoring was documented in the monitoring evaluation report (COB, 2016). Some of the lessons learned are presented here.

- Preliminary and installation-related activities proved to be very disturbing and lead to large soil displacements (60–70% of total soil displacements during construction).
- Old timber piles behave differently from newer piles with sufficient end-bearing capacity.
- The construction of the bored tunnel led to very small settlements (<2 mm).
- Compensation grouting was effective in case of the Amsterdam saturated soil conditions for piles with their tip in the sand and not so effective in case of disturbed soil conditions.

The technical learning from the ordinary construction work was almost exclusively performed in co-operation with universities, placed besides the day-to-day activities and performed by different people. This was necessary to maintain focus on the academic learning and not on the more urgent project matters as well as to ensure that the project progress was not hampered by the academic learning.

The non-technical learning that took place was gathered in several publications (Van der Kam, 2016; Van der Kam *et al*., 2013) and a website (City of Amsterdam, 2017) and preserved for use in other projects in the city of Amsterdam and beyond.

7. Case study: Spoorzone Delft project

7.1 Project description

The Delft railway tunnel project is a 2·4 km long, four-track railway cut-and-cover tunnel which opened in 2015, combined with an underground railway station and underground parking in the historic city centre of Delft. Monuments and historical buildings on shallow foundations are found close to the tunnel excavation. The deepest excavation level is about 10 m below the ground surface, and the groundwater level is found 1·5 m below ground surface. Diaphragm walls have been used to minimise ground deformations and to allow construction of buildings on top of the tunnel. Details of the soil profile and the construction method can be found in the paper of Everaars *et al*. (2011), while the monitoring is more extensively described by Delfgaauw *et al*. (2010).

7.2 Risk awareness

For the design process and the construction of the tunnel, systems engineering was used. Potential differential settlement of the nearby buildings and existing (in use) railway viaduct was one of the main risk items. Therefore, extensive site investigation was performed to derive soil profiles and soil parameters and settlement risk assessments were made. Since the Delft tunnel was constructed after the Amsterdam North–South Line, experiences with the diaphragm wall quality were transferred to the project in time through an expert evaluation committee.

In order to reduce the risk for failures, additional measures, such as monitoring, tests and adjustments of construction methods, were taken. Quality control of underground works is difficult, so for this reason, extensive monitoring was performed during the excavations.

7.3 Monitoring

An extensive monitoring programme was installed. Inclinometers were installed at close distances to the diaphragm wall and at one location directly inside the diaphragm wall. A series of settlement markers up to a distance of 25 m of the diaphragm wall were installed to monitor horizontal and vertical ground deformations. The buildings were measured with total stations and conventional bolts (at the front facades only) as well as three-dimensional laser scans. Groundwater levels were registered in standpipes, and drainage volumes were measured. Vibration measurements took place during demolition and during installation of piles. Effort was put to get a complete picture at the start of the work (initial condition) with a minimum of 1 month before the start of the works for the deformations and multiple months for the groundwater levels. The Amsterdam experiences with the diaphragm wall quality led to the use of innovative measurement techniques during installation of the wall in the form of sonic logging installed at panel joints.

7.4 Lessons learned

Application of diaphragm walls for the cut-and-cover tunnel reduced the ground deformations and minimised settlement of nearby buildings. Some damage, however, was reported to specific buildings. The old historic railway station on-site displaced large amounts (over 60 mm in places), but did not show damage, even though simple and advanced structural models predicted this.

The use of the sonic logging to measure the quality of the diaphragm wall joints had minimal effect on the construction speed, and the costs proved limited as well. One damaged joint was detected by the system that would (without the mitigating measures that could be taken) potentially have caused a substantial leakage risk.

The accuracy of the settlement markers for both the buildings and the surface was determined to be about 1 mm between the different zero readings. During construction, some markers got damaged and in some cases gave unexpected readings. Groundwater levels proved to differ from the anticipated initial conditions, most likely due to heterogeneities in the subsoil. The inclinometer accuracy was about 4–5 mm. The system proved useful particularly in combination with short-term repetitions and independent measurements of the inclinometer heads.

During the construction works, the existing railway viaduct displaced more than what had been expected, while the measurements did not show this. Due to insufficient understanding of the viaduct's mechanics, the specific placement of the settlement markers led to an unstable system. Measures were taken to reduce the risk.

The monitoring system was updated in the second phase of the construction works, based on the experience of the first stage. This included the change to interval measurement instead of continuous measurements with the total stations. During stage 2 evaluation, however, this proved to make the interpretation of the results so difficult that for part of the work the continuous system was used again.

In this project, communication between all parties was successful by using intensive interface management. There was a client's change control board to decide in case contract changes were required to improve the overall design or to minimise risks. One example of a decision made by this board is the change of the contract requirement to reduce train-induced vibrations in the design of the structure above the tunnel to taking the measures underneath the railway tracks.

7.5 Documenting of the lessons learned

The lessons of the monitoring of Spoortunnel Delft are published in the monitoring report (COB, 2016). The lessons of the process related to the opening of Spoortunnel Delft are collected in a new publication (ProRail, 2016).

8. Case study: GeoBrain

The last case study is in fact a database of projects collected in a period of about 10 years related to the installation of foundation elements, called GeoBrain (Hemmen, 2005; Mens *et al*., 2008). Over 30 industrial partners and contractors collected successes and failures in their projects in a systematic way to learn from the data. This resulted in over 3000 projects, and analyses were performed on the database to get failure statistics such as those shown in Table 1. An 'experience' or 'observation' is uniquely defined by the type of element (e.g. sheet pile or prefabricated concrete pile), the type of equipment used and the soil conditions present. Additional to these digitalised data, details concerning the building pit, the crew experience and the surroundings have been included. From all of the sheet pile installations, damage statistics were collected for different types of damage. From the potential damages, the sheet pile not reaching the required depth was the

Table 1. Performance indicators of sheet pile installation projects in the Netherlands, collected from Deltares (2017) on 26 April 2017

Number	Performance indicator	Total	Total: % of sheet piles
1	Sheet pile not achieving depth	1397	1·31
2	Damage to sheet piles	438	0·41
3	Lowering of adjacent sheet piles	233	0·22
4	Breaking out of elements	230	0·22
5	Burned interlocks	196	0·18
6	Driven out of interlocks	115	0·11
7	Problems with hammer/vibrator	34	0·03
8	Leakage through sheet piling	12	0·01
9	Sand transport through sheet piling	8	0·01

The total number of sheet piles installed is 106 274, in a total of 818 collected experiences/(sub)projects most common, which was the case in 1·3% of the installed sheet piles. Since the database combines information on the type of sheet pile, the installation equipment used and the soil conditions present, it is possible to predict the risk profile of a future project by searching for comparable experiences.

For example, in a project in Wormerveer, 20 sheet piles were installed in pairs to a depth of 8 m. The PU12-type profiles (second-hand) were installed with a high-frequency ICE 14RF vibrator. From the sheet piles installed, two did not reach the required depth, potentially related to obstacles in the soil. Also, problems with the vibrator occurred in the form of hydraulic leakage. The soil conditions consisted of 5 m of clay, underlain by loose to medium dense sand with a cone resistance of not more than 10 MPa at 10 m depth. For each project, this information and more details are collected in the GeoBrain experience database.

The database was also used to validate current (analytical and numerical) prediction models for sheet pile installation as a second form of learning. The method of 'receiver operating characteristic' was used, which was taken from medical sciences (Metz, 1978), to determine the quality of different models and to optimise parameters and variables in the model. A total of 252 of the field observations (selected for their completeness) were compared for six different models (Mens *et al*., 2012). The model that ranked highest was the numerical Hypervib-I model (Holeyman *et al*., 1999), closely followed by the model with added expert knowledge. As an example, the results of the expert knowledge system are presented in Figure 4.

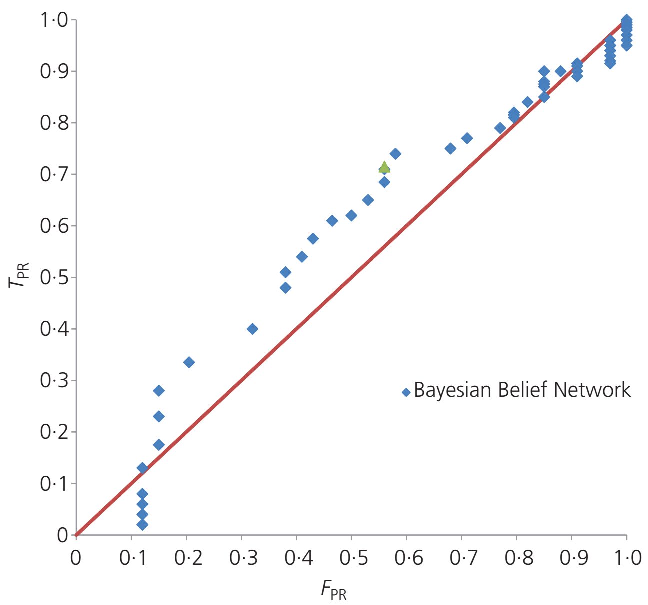

Figure 4. Receiver operating characteristic curve for the validation of the GeoBrain expert knowledge system (Bayesian Belief Network) against the GeoBrain database for validation (graph from Mens *et al.* (2012)). F_{PR}, false positive ratio; T_{PR}, true positive ratio

Using project information from the GeoBrain observations database made it possible to validate the models and to attach a performance label to them, making it much easier for an engineer or designer to choose the right code.

From the GeoBrain experiences, it was concluded that it is possible to learn from data collected in the field by contractors in different ways. The first and most accessible form of learning is the use of the database results directly to compare to future projects and thus determine the risks. The second, more advanced type of learning is validating existing or even creating new models based on the data. This second type of learning, however, requires large amounts of data; literally hundreds of projects are needed to validate rather simple models with limited parameters, while thousands of projects are not enough for more complex models.

A positive by-product of the data collection was the shared interest of the clients and contractors involved; this process actually led to better relations in the sector.

9. Lessons learned from monitoring of deep excavations

Based on the monitoring of the deep excavation projects presented in this paper, a list of generic lessons can be made. These lessons are drawn by a group of experts and written down in a publication (COB, 2016). A summary of the most generic lessons (related not only to the monitoring but to the project management of the projects as well) is given here.

- Make sure that a complete as possible picture of the initial conditions of the project area is obtained; this helps to identify and distinguish between failure mechanisms later. Daily, seasonal and even more yearly phenomena can be identified. This needs to be set up by client, and it is important to choose the right area.
- Discuss and make clear requirements about the distribution of the risk, which includes the risks related to the incompleteness of the knowledge about the initial conditions.
- Working together with all stakeholders (project leaders, specialists, quality controllers, planners, workmen, supervision parties, insurance companies etc.) helps construction to move forward consistently, and safely, based on a shared trust in the work and the monitoring.
- Be sensitive to the surroundings and proactive and communicate on the right level. Realistic communications work better than too optimistic ones. The interaction needs to be tailored to the stakeholders. Specialists can help understanding the work and the risks in smaller groups of stakeholders, while general communication can be more generic. If questions arise, be as transparent as possible, also on technical details, because people interacting with urban deep excavations tend to educate themselves through various sources and often know much more about technical topics than what is expected at first.

- Experience in the Dutch projects shows that dealing with damage in a generous instead of a strictly legal way significantly improves the perception of the project to its 'neighbours'. Contrary to the general belief, the budget necessary for such minor repairs is usually very small compared to the project budget.
- Choose redundancy in the system, both in the monitoring system and in the project itself.
- Get information out of the data; projects can be managed much more confidently and efficiently if monitoring data are used to provide real information on the risks. Usually monitoring provides indirect results and needs to be worked by specialists to get a good picture of the actual risks.

10. How does learning take place?

As the lessons given earlier were collected by experts in special discussion sessions and written down in a publicly available report, this is not the only way that learning takes place related to (deep excavation and other) projects. The first way that people (both professionally and privately) learn is experiencing the hard way. If the lessons of previous projects have not been taken on board, things can go wrong to the point where projects get cancelled after construction has started. This way of learning can prove costly for the project concerned, but can still be successful for future projects if the failures are analysed and the lessons implemented in new projects, as was the case for the diaphragm wall leakage in Amsterdam that led to the use of innovative sonic logging in the Delft project, thus preventing at least one significant bad joint to cause trouble.

The second way of learning that the author would like to point out is a more rigorous one, not driven by a specific failure but by a deeper understanding of the need to learn from all experiences. By studying data extensively, systematically and consciously on a project or on a number of projects, valuable insights can be gained. The value of this kind of specialist analysis is not always recognised, while in the projects presented in this paper, this proved essential in understanding the mechanisms and taking right and effective measures. Once such analyses have been made, the next step is to share these together with the project metadata with others in the field. This requires a methodological data collection, which has become easier over the last few years due to new information and communication technology (ICT) tools. An essential part is also the sharing of the results in conferences, public databases and other publications, such as (national or international) guidelines. Some guidelines have been published based on such analysis in the Netherlands the last few years: on monitoring, design of deep excavations, execution of diaphragm walls and so on. Last but certainly not least, for future engineers, it is essential to start off with as much experience from practice as possible, so bringing the project experiences into schools and university in the form of courses is recommended.

These methods of learning are all available every day. The big question, however, is, Are individuals learning enough? Some evidence is presented in this paper about the Dutch deep excavation projects. In the last 5–10 years, reduction of risks has been an increasing priority. Risk management is a good tool to support this. Risk management, however, also clearly includes the very last step: the transfer of knowledge to future stages of the project of future projects. This step is most often the one that gets the least attention. And not surprisingly so, failure costs are still too high in the construction industry. The question remains about whether something better can be done. Looking at other industries might provide an answer to that. For example, the medical and ICT sectors have installed important concepts of learning in practice. From the medical sector, it can be learned that using checklists may at first seem bureaucratic or time consuming, but actually reduces the risks in surgeries (Treadwell *et al*., 2014). And how fast could the construction industry develop if learning is done at the speed of the ICT world? Using the Internet more widely and sharing knowledge much quicker is much more common there. In the ICT sector, design patterns and anti-patterns are descriptions on how to do common things right and how to prevent common mistakes. These patterns are shared on the Internet and ready to be used by everybody. Perhaps sharing full designs and construction plans in a similar way could even be imagined as an open-source software project.

Learning is not only about having the right methods available; it is also a mind-set. It requires reflection, integration of soft skills and hard skills and close co-operation between the industry, projects and academia.

11. Conclusions

This paper has shown that there is a need to learn from past project experiences to reduce failure costs and to become a more effective industry. Each project that is being constructed provides a unique opportunity for learning.

One way of learning as presented here is learning systematically through collection and evaluation of actual experiences. Sharing of these experiences will speed up the learning process of the individuals and the whole system. To achieve learning, organisations (specifically if they are project-based) need to address and incorporate learning in their day-to-day work processes. Risk management provides a good framework for that, but is not always carried through completely to that stage. Increased learning potential can be obtained by systematically analysing monitoring data and using this as validation or contravalidation of existing methods, knowledge and approaches. Other industries can provide the examples that show the potential for learning in a systematic way, but in the end, people need to start building in reflection moments and processes.

The projects presented in this paper have all shown several different methods of learning and may be used for direct learning (for example, through the lessons given in Section 9) or indirect learning (learning from the process of learning) for future projects.

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REFERENCES

Avendano Castillo JE, Al-Jibouri SH and Halman JIM (2010) Underlying mechanisms of failure costs in construction. In *Challenges, Opportunities and Solutions in Structural Engineering and Construction* (Ghafoori N (ed.)). Taylor & Francis, London, UK, pp. 939–944.

Ball PL (1987) The economics and assurance of quality in construction. *Quality: a Shared Commitment, EOQC, London, UK.*

Bazerman MH and Watkins MD (2004) *Predictable Surprises: the Disasters You Should Have Seen Coming and How to Prevent Them*. Harvard Business School Press. Boston, MA, USA.

Bea R (2006) Reliability and human factors in geotechnical engineering. *Journal of Geotechnical Engineering and Geoenvironmental Engineering* **132(5)**: 631–643, http://dx.doi.org/10.1115/1.1904637.

Bezuijen A, Kaalberg FJ, Kleinlugtenbelt RE and Essler RD (2011) Settlement behaviour after compensation and corrective grouting. In *International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground* (Viggiani G (ed.)). CRC Press, Leiden, the Netherlands, pp. 955–961.

Burati JL, Ledbetter WB and Farrington JJ (1992) Causes of quality deviations in design and construction. *Journal of Construction Engineering and Management* **118(1)**: 34–49, http://dx.doi.org/101061/(ASCE)0733-9364(1992)118:1(34).

City of Amsterdam (2017) http://www.noordzuidlijnkennis.net (accessed 16/05/2017).

COB (Centre for Underground Construction) (2012) F530-ER-12-49785: Aanbevelingen voor het ontwerp van bouwkuipen in stedelijke omgeving. COB, Gouda, the Netherlands (in Dutch).

COB (2016) *Monitoring in de praktijk – Ervaringen grote infraprojecten*. COB, Delft, the Netherlands, Report T540 (in Dutch).

Crawford L and Gaynor F (1999) Assessing and developing project management competence. *Learning, Knowledge, Wisdom, Proceedings of the 30th Annual PMI Seminars and Symposium, Philadelphia*. Project Management Institute, Sylva, NC, USA, pp. 1–7.

CUR (Civil Centre for Research and Regulations) (2010) *Handbook Diaphragm Walls Design and Installation*. CUR/COB, Gouda, the Netherlands, Report 231.

Delfgaauw SJ, Jonker J, Mastenbroek R and Mortier H (2010) Four-track railway tunnel re-unifies the city of Delft in the Netherlands. *ITA-AITES World Tunnel Congress, Vancouver, BC, Canada.*

Deltares (2017) http://www.geobrain.nl (accessed 16/05/2017).

Everaars MJC, Kwast E, Meulblok CM, Delfgaauw S and Mortier H (2011) Geotechnical design of a railway tunnel and an underground station supporting the new city hall, Delft, The Netherlands. In *International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground* (Viggiani G (ed.)). CRC Press, Leiden, the Netherlands, pp. 639–646.

Flyvbjerg B, Skamris Holm MK and Buhl SL (2004) What causes cost overrun in transport infrastructure projects? *Transport Reviews* **24(1)**: 3–18, http://dx.doi.org/10.1080/0144164032000080494a.

Frankenmolen S (2006) *Analyse Noord/Zuidlijn monitoringsdata: Effecten van de beïnvloeding van de Holocene Laag op het zettingsgedrag van vooroorlogse panden*. MSc thesis, Delft University of Technology, Delft, the Netherlands.

Galenkamp HF (2015) Real-time insight in geotechnical risks; monitoring during the observational method. In *5th International Symposium on Geotechnical Safety and Risk*. IOS Press, Rotterdam, the Netherlands, pp. 984–989.

Gareis R and Huemann M (2000) Project management competences in the project-based organization. In *The Gower Handbook of Project Management*, 3rd edn. (Turner JR and Simister SJ (eds)). Gower, Aldershot, UK, pp. 709–725.

Geo-Impuls (2017) http://www.geoimpuls.org (accessed 16/05/2017).

Gibson LR and Pfautz S (1999) Re-engineering IT project management in an RandD organization – a case study. In *Managing Business by Projects: Proceedings of the NORDNET Symposium, Helsinki* (Arrto KA, Kähkönen K and Koskinen K (eds)). Helsinki University of Technology, Helsinki, Finland, pp. 86–96.

Hall M and Tomkins CA (2001) A cost of quality analysis of a building project: towards a complete methodology for design and build. *Construction Management and Economics* **19(7)**: 727–740, http://dx.doi.org/10.1080/01446190110066146.

Hansen R (1985) *Kvalitetssikring og kvalitetskostnader Hovedoppgave*. Institute for anleggsdrift Norges Tekniske Hogskole, Trondheim, Norway (in Norwegian).

Hemmen BR (2005) The synergy between theory and practice in geo-engineering. In *Geotechnology in Harmony with the Global Environment; Proceedings of XVI International Conference on Soil mechanics and Geotechnical Engineering, Osaka*. IOS Press, Amsterdam, the Netherlands, pp. 2809–2811.

Holeyman A, Vanden Berghe JF and De Cock S (1999) Model testing of vibratory driven piles. *Proceedings of the XIth ECSMFE, Amsterdam, the Netherlands, June*, vol. 2, pp. 769–776.

Josephson PE and Hammarlund Y (1999) The causes and costs of defects in construction – a study of seven building projects. *Automation in Construction* **8(6)**: 681–687, https://doi.org/10.1016/S0926-5805(98)00114-9.

Kaalberg FJ, Braakman S and Cook DK (2003) Amsterdam Noord/Zuidlijn: one of the largest settlement monitoring projects in Europe. In *Field Measurements in Geomechanics* (Myrvoll F (ed.)). Balkema, Lisse, the Netherlands, pp. 769–774.

Kazaz A, Birgonul MT and Ulubeyli S (2005) Cost-based analysis of quality in developing countries: a case study of building projects. *Building and Environment* **40(10)**: 1356–1365, http://dx.doi.org/10.1016/j.buildenv.2004.11.010.

Kolb DA (1984) *Experiential Learning: Experience as the Source of Learning and Development*. Prentice-Hall, Englewood Cliffs, NJ, USA.

Korff M (2013) *Response of Piled Buildings to the Construction of Deep Excavations*. PhD thesis, Cambridge University, Cambridge, UK.

Korff M and Kaalberg FJ (2014) Monitoring dataset of deformations related to deep excavations for North–South Line in Amsterdam. In *International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground* (Yoo C, Park SW, Kim B and Ban H (eds)). CRC Press/Balkema, Leiden, the Netherlands, pp. 321–326.

Korff M, Mair RJ, van Tol AF and Kaalberg F (2011) Building damage and repair due to leakage in a deep excavation. *Forensic Engineering* **164(11)**: 165–177, http://dx.doi.org/10.1680/feng.2011.164.4.165.

Love PED (2002) Influence of project type and procurement method on rework costs in building construction projects. *Journal of Construction Engineering and Management* **128(1)**: 18–29, http://dx.doi.org/10.1061/(ASCE)0733-9364(2002)128:1(18).

Love PED and Li H (1999) Rework: a symptom of a dysfunctional supply-chain. *European Journal of Purchasing and Supply Management* **5(1)**: 1–11, http://dx.doi.org/10.1016/S0969-7012(98)00017-3.

Love PED and Li H (2000) Quantifying the causes and costs of rework in construction. *Construction Management and Economics* **18(4)**: 479–490, http://dx.doi.org/10.1080/014461900500248 97.

Mens AMJ, van Tol AF and Koelewijn AR (2008) Optimizing foundation engineering validating models against experience using artificial intelligence. In *12th International Conference on Computer Methods and Advances in Geomechanics 2008* (Jadhav MN (ed.)), Curran Associates Inc, Red Hook, NY, USA, vol. 5, pp. 3384–3391.

Mens AMJ, Korff M and van Tol AF (2012) Validating and improving models for vibratory installation of steel sheet piles with field observations. *Geotechnical and Geological Engineering: an International Journal* **30(5)**: 1085–1095, http://dx.doi.org/101007/s10706-012-9506-5.

Metz CE (1978) Basic principles of ROC analysis. *Seminars in Nuclear Medicine* **8(4)**: 283–298, https://doi.org/10.1016/S0001-2998(78)80014-2.

Nedo (National Economic Development Office) (1983) *Faster Building for Industry*. Nedo, London, UK.

Netzel H and Kaalberg FJ (1999) Settlement risk management with GIS for the Amsterdam North–South metroline. In *Challenges for the 21st Century, Proceedings of the World Tunnel Congress '99, Oslo, Norway* (Alten T (ed.)). Balkema, Rotterdam, the Netherlands, vol. 1.

Nonaka I and Takeuchi H (1995) *The Knowledge-creating Company: How Japanese Companies Create the Dynamics of Innovation*. Oxford University Press, New York, NY, USA.

Pinto JK (1999) Managing information systems projects: regaining control of a runaway train. In *Managing Business by Projects: Proceedings of the NORDNET Symposium, Helsinki* (Arrto KA, Kähkönen K and Koskinen K (eds)). Helsinki University of Technology, Helsinki, Finland, pp. 30–43.

Polanyi M (1967) *The Tacit Dimension: the Terry Lectures at Yale University 1962*. Anchor Books, Hempstead, NY, USA.

ProRail (2016) *In één keer goed: De openstelling van de Willem van Oranjetunnel en station Delft*. ProRail, Utrecht, the Netherlands (in Dutch).

Roberts R (1991) Quality does not cost – it pays. *Australian Construction Law Report* **110(4)**: 137–144.

SBRCurnet (Foundation for Building Research and Civil Centre for Research and Regulations net) (2015) *Handreiking Observational Method*. SBRCurnet, Delft, the Netherlands.

Spruit R (2015) *To Detect Anomalies in Diaphragm Walls*. PhD thesis, Delft University of Technology, Delft, the Netherlands.

Treadwell JR, Lucas S and Tsou AY (2014) Surgical checklists: a systematic review of impacts and implementation. *BMJ Quality & Safety* **23(4)**: 299–318, http://dx.doi.org/10.1136/bmjqs-2012-001797.

USP Marketing Consultancy bv (2007) *Gebrekkige communicatie grootste veroorzaker faalkosten*. USP Marketing Consultancy bv, Rotterdam, the Netherlands, pp. 1–2 (in Dutch).

USP Marketing Consultancy bv (2008) *Faalkosten in de bouw naar hoogtepunt*. USP Marketing Consultancy bv, Rotterdam, the Netherlands, pp. 1–3 (in Dutch).

Van Dalen JH, Servais R and Boone DC (2015a) Observational method A2 tunnel Maastricht. In *5th International Symposium on Geotechnical Safety and Risk* (Schweckendiek T, Van Tol AF, Pereboom D, Van Staveren A and Cools PMCBM (eds)). IOS Press, Rotterdam, the Netherlands, pp. 973–978.

Van Dalen JH, Bosch JW and Broere W (2015b) Concrete flow in diaphragm wall panels: a full-scale in-situ test. In *5th International Symposium on Geotechnical Safety and Risk* (Schweckendiek T, Van Tol AF, Pereboom D, Van Staveren A and Cools PMCBM (eds)). IOS Press, Rotterdam, the Netherlands, pp. 608–613.

Van der Kam S (2016) *De diepte in Een leergeschiedenis van de drie diepe stations van de Noord/Zuidlijn*. City of Amsterdam, Amsterdam, the Netherlands (in Dutch).

Van der Kam S, Weustink T and Cremer Eindhoven R (2013) *Samenspel en tegenspraak: Tien lessen uit de Noord/Zuidlijn*. City of Amsterdam and King, Amsterdam, the Netherlands (in Dutch).

Van Staveren M (2006) *Uncertainty and Ground Conditions: a Risk Management Approach*, 1st edn. Butterworth-Heinemann, Oxford, UK.

Van Tol AF and Korff M (2011) Deep excavations for Amsterdam metro North-South Line: an update and lessons learned. In *International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground* (Viggiani G (ed.)). CRC Press, Leiden, the Netherlands, pp. 37–46.

Wikipedia (2017) *Big Dig; The Central Arter /Tunnel Project*. Wikimedia Foundation, Inc., San Francisco, CA, USA. See https://en.wikipedia.org/wiki/Big_Dig (accessed 11/04/2017).

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