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Impact of occupational risk prevention measures during process disturbances in TBM tunnelling

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ABSTRACT

When process disturbances occur, workers on the Tunnel Boring Machine (TBM) will need to operate outside safe zones, reducing or eliminating the safety barrier 'distance' between them and potential sources of risk. Consequently, disturbances have a higher risk potential than regular TBM operations. By comparing the risks of registered process disturbances with regular TBM process, we try to predict accident scenarios. The exposure risk is defined by the exposure time and the injury severity. Exposure times have been determined from case histories, where on average 11% of the construction period is attributed to disturbances. The potential number of casualties, including less common incident scenarios, have been determined using an accident scenario building toolkit. We find that factors that contribute most to occupational risk reduction are the (correct) use of available risk prevention measures, correct design of safety barriers and making these barriers available to personnel, as well as detailed planning of procedures such that specific tasks are performed in a uniform and predetermined manner.

1. Introduction

During normal operations, tunnel boring using closed face tunnel boring machines (TBM) is a continuous, controlled and relatively safe process. Workers are protected from Health, Safety & Environmental (HSE) risks as barriers exist between them and potential risk sources. Barriers include all physical and non-physical measures taken to prevent, control and mitigate unwanted events or accidents (Sklet, 2006). However, in case of process disturbances workers on the TBM will need to operate outside normal work zones, reducing or eliminating the barrier 'distance' (Swuste, 2003). At these times, workers are potentially exposed to dangerous situations and thus process disturbances form a significant risk factor for TBM personnel.

The construction industry in general has a relatively high risk of HSE accidents (Eurostat, 2018; Choi et al., 2019), and is one of the sectors with the highest number of work-related accidents and fatalities in the Netherlands (Inspectie SZW, 2016,2017). Tunnel boring using closed faced TBM is a specialized construction process, where TBMs serve to reduce construction risk and lower the number of fatalities, certainly compared to open face construction methods. However, as aggregated, HSE accident numbers often do not distinguish between TBM tunnelling or other construction methods, it remains unclear how (un)safe TBM tunnelling is and to what extent occupation risk can be controlled.

Kikkawa et al. (2015) reports that the number of accidents in NATM tunnelling in Japan is high compared to regular construction activities. The main accident causes, however, are all related to the open face construction method in rock. Zhou et al. (2018) analyzed the stability and collapse failure by predicting geohazards during excavation. Sousa (2010) reports that underground construction in general is characterized by high risk and accident levels, although most risk factors are related to geological conditions and do not directly relate to occupational risk. ITA (2008, 2011) and Eskesen et al. (2004) focus primarily on tunnelling in rock and hard soils and the safety measures proposed by ITA (2008) consist mainly of project control measures.

TBM tunnel boring is a continuous process, where excavation, spoil removal, lining construction and umbilical extension follow in a repetitive process, with limited contact between personnel and potential hazard sources (Swuste, 2003). When process disturbances occur and the regular progress is interrupted, workers will have to intervene in order to solve the cause of disturbance and return to normal operation. Where manual intervention is necessary, the barrier 'distance' between workers and hazards is reduced or eliminated, and workers can be exposed to hazardous situations, potentially leading to occupational incidents and casualties. Risk analysis by CUR/COB (1997) concludes that unplanned maintenance operations and operating outside normal working conditions contribute most to the probability of process failure in case of soft soil tunnelling.

According to WORM (2008) an unwanted event can occur if one or more barriers fail. A barrier can fail because it is not present, malfunctioned, or used incorrectly. Measures can be used to reinforce barriers,

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thereby reducing the chance of failure. The barriers are maintained by tasks. These tasks are seen as a management control circle (provide, use, maintain and monitor). The tasks that maintain a barrier can fail because the resources of the management system fail (plans and procedures, availability of people, competence, communication / collaboration, conflict resolution, etc.). If the resources of the management system fail, the tasks fail and the barrier loses its safety function. This can cause an unwanted event. WORM (2008) holds there are many combinations of failing control systems, but that in most cases a dominant combination of underlying root causes can be identified.

According to Winge & Albrechtsen (2018) the causes of minor incidents often differ from those for major incidents, and it is not possible to prevent minor incidents with the same measures that prevent the root cause for accidents with major consequences. Furthermore, they show that incidents, for which only a single physical barrier was present, could have been prevented by the use of multiple physical barriers, with different types of barriers needed for different risk sources.

Exposure to a potential hazard, combined with the failure or absence of one or more safety barriers, will eventually lead to direct exposure to the hazard, resulting in property damage, personal injury or casualties. Swuste (2003) uses this scenario approach as a valid method to determine risk exposure. A scenario is defined as a combination of a hazard and a loss of process control, and shows the route of a hazard to a risk or damage (Swuste, 2003). Such scenarios or incident paths can be visualized as a bow-tie diagram, a combination of a fault-tree and event-tree approach, in which the central event and safety barriers are visualized in a diagram (Duijm, 2009). This is a proven methodology to quantify occupational risk (WORM, 2008) that has been used in the tunnel construction industry e.g. by Eskesen et al. (2004) and Hyun et al. (2015).

The bow-tie is a popular class of safety barrier diagram, as it allows analysis of combined accident scenarios, which helps to establish combinations of events and provides insight in the outcome of such combined events. WORM (2008) developed a quantitative risk analysis model for occupational risk based on a bow-tie. The model uses 9,142 incident reports collected by Inspectorate SZW (the Dutch HSE Inspectorate) between 1998 and 2004. Only incidents that resulted in hospitalization, permanent injuries or fatalities were recorded. The model is about a combination of events which lead to a potential hazard and can result in an incident with a well-defined consequence (probably) non-permanently injury, (probably) permanently injury or fatality). It has been used by Aneziris et al. (2010) to quantify occupational risk during tunnel construction in hard soils, and they show the potential of the method in analyzing safety aspects for cases with limited available information from incident reports and exposure frequencies.

The software toolkit Storybuilder has been developed based on the WORM (2008) approach and has been shown to be a powerful tool to structure incident data, and subsequent analysis and quantification of incidents (Bellamy et al., 2007). It allows the user to visualize incident pathways, determine which are the dominant scenarios and incident causes and supports the user in defining preventive strategies to avoid accidents. This allows to identify the root cause of incidents (Ale et al., 2008). In this paper we will use Storybuilder to analyze production data during process disturbances which is collected during the Victory Boogie Woogie tunnel boring process and quantify the occupational risks. Results have been subsequently validated using expert interviews.

2. Methodology

The collection of production data took place during the first drive of the tunnel boring phase of the eastern tube of the Victory Boogie Woogie tunnel, between February and June 2018. This 11.3 m. diameter bored tunnel track is 1640 m. long and part of the Rotterdamsebaan project in the Hague, the Netherlands, which connects the highway near Ypenburg junction to the city centre of The Hague (see Fig. 1.) The bored tunnel section is predominantly located in medium dense Pleistocene sands, and fully below the water table.

During the boring phase, the client registered the boring process, management information and work conditions in detail. Observations were made 24/7. Data for the short sections at the start and end of boring, when the TBM is contained by the diaphragm wall and grout plug, are omitted from the data set. The remaining data has been analyzed and visualized using Storybuilder, incorporating additional data and information provided by the client. The registered process disturbances have been assigned to categories defined by CUR/COB (1997), see Table 1. Process disturbances have been categorized as planned (maintenance) or unplanned (disturbances), and assigned to one of three main process activities: excavation, segment erection, stop (including maintenance and disturbances). Process disturbances that occurred outside the tunnel, such as yard logistics, soil separation and soil transport, have been excluded. Process disturbances were linked to a bow-tie in Storybuilder and a part of the incident path was visualized

Table 1
Activities in the three process phases.

Excavation	Segment erection	Stagnation/down time/ maintenance
Excavation Face support Hydraulic jack positioning Tail void grouting Logistics Spoil separation Alignment controlled	Face support Hydraulic jack positioning Logistics Spoil separation Segment erection Umbilical extension	Face support Hydraulic jack positioning Logistics Spoil separation Maintenance

Fig. 1. Tunnel track of the Victory Boogie Woogie tunnel.

based on the data and management data obtained from the boring process.

The registration of duration of various activities has an inbuilt uncertainty, as various supporting processes are executed in parallel. When determining the duration of individual activities, it is not always possible to completely separate them based on recorded management data, and thus the listed duration remains indicative. A further uncertainty exists, as the registrations have been recorded by multiple employees over multiple shifts, and slight differences in interpretation will therefore be present in the registrations. The combination of incidents and exposure times is used as the basis for quantification of the risk.

The observed incident path have been compared with accident paths, from the reference data in Storybuilder and dominant scenario's and root causes were determined. This comparison has provided information about the causes of failing barriers and conditions that may have contributed to to the failure of the safety barriers (WORM, 2008). The data was subsequently validated using expert interviews. Based on this analysis, a number of measures have been recommended that can be used to safely deal with process disturbances.

2.1. Data analysis

During the tunnelling phase, 385 process disturbances have been registered that relate to the boring process. Bases on the data, 89% of construction time is spent on regular activities. Special activities and process disturbances make up to 11% of the total time. Process disturbances are mostly brief in nature, with 41% lasting shorter than 15 min and 90% of the cases (not combined duration) lasting less than 5 h. The remaining 10% together account for 62% of the total stop/lost time.

The process disturbances have been categorized according to the activities listed in Table 1. The frequency of each type of process interruption is shown in Table 2, with a further subdivision in causes as defined by CUR/COB (1997).

The most suitable method available to analyze the possible root causes of the process disturbances is by using the software toolkit Storybuilder. The program is based on a large data set of accident investigations conducted by the Dutch Labor Inspectorate (I-SZW). By comparing the overall conditions of process disturbances with the data from Storybuilder, information can be gained into the underlying causes that lead to the barrier failure.

The observed part of the incident path was visualized in Storybuilder and the characteristic events, that can lead to barrier failure, have been determined. Subsequently, accidents with similar characteristic events have been selected from the data set available in Storybuilder, in order to gain insight into the circumstances that can cause an accident. For these accident types, the data related to the factors that contribute to the development of a scenario was used to analyze what the determining factors are, which barriers fail most, how they fail and what the chances of serious injuries are.

Based on the registrations made during the tunnelling process it is not absolutely clear when a process disturbance starts and ends, as this has not always been documented accurately and immediately at the start of the event. The recorded duration of a process disturbance is therefore indicative and the total loss time calculated (see Table 3) is only an indication.

2.2. Description of dominant incident pathways

The process disturbances are visualized in Storybuilder. Fig. 2 shows a simple schematic representation of the left side (causes) of the bow tie. Every incident path consists of several elements which lead to the central event. Data of the type of activity, circumstances and conditions, barriers, management factors and failing barrier tasks were available and entered into Storybuilder. Exposure to barrier failure and subsequent loss of control events did (fortunately) not occur during the case study. The red line in Fig. 2 shows an observed incident pathway. Given the lack of incidents resulting in serious injury, the severity of an incident path cannot be positively established. This information is gained by comparing the incident pathways with the reference data from similar paths in Storybuilder.

During the tunnel boring process 20 incident pathways have been registered (See Table 3). Based on the duration of exposure and the severity, the following scenarios are considered dominant and are presented below.

Considering the excavation production function, there are three process disturbances (E1-14, E1-16, E1-24) where contact with moving parts can occur, see Fig. 3. These underlying causes of exposure are an unsafe TBM layout, no effective personal protection equipment (PPE) and incorrect plans and/or procedures.

The most common process disturbance during the face support production function is contact with moving parts due to pump repairs. Another scenario is contact with slurry (E2-09). Due to a leak in the slurry distribution system, a large amount of slurry or bentonite can flow out of the slurry circuit or eject under high pressure (see Fig. 4). The slurry itself has a low toxicity, but the rapid outflow of large quantities of liquid is potentially risky.

The large number of registrations for the hydraulic jack positioning production function can be traced to the failure of the jack (E3-05). Due to a defect, the jack has to be replaced. The main risk during this activity is caused by hoisting activities and working at heights in a limited space. A small number of registrations relate to an operating error (E3-08) during segment lining construction. During this activity there is a risk of losing control of a segment being lifted and about to be installed. Both process disturbances follow accident paths in which contact with falling objects can occur (see Fig. 5).

Most process interruptions (128 registrations) during excavation

Table 2
Number of process disturbances per activity/sub-activity (* reference numbers for activities and causes according to CUR/COB (1997) classification).

ref*	Activity	Number	ref*	Activity	Number
	Excavation			Tail void grouting	
E1-05	Unexpected soil pollution	9	E4-05	Blocked supply line	128
E1-14	Malfunction main bearing	2			
E1-16	Other malfunction	3		Logistics	
E1-24	Malfunction spoil distribution system	2	E5-07	Derailing of service vehicles	1
E1-26	Exposure to harmful atmosphere	4	E5-09	Malfunction transport equipment	8
	Face support			Segment erection	
E2-03	Supply and removal of support fluid is not sufficient	32	E8-02	Malfunction transport equipment	45
E2-04	Malfunction main bearing seal	6	E8-03	Segments do not fit	20
E2-09	Loss of large slurry quantity	6	E8-05	Keystone does not fit	3
			E8-08	Malfunction segment erector	35
	Hydraulic jack positioning		E8-15	Disapproval of elements	24
E3-04	Hydraulic leakage	3			
E3-05	Defect hydraulic jacks	46		Umbilical extension	
E3-08	Operating error	4	E9-04	Malfunction hoisting equipment	4

Table 3
Observed scenarios ranked according to risk potential.

Ref	Scenario	Number of path ways	Percentage fatalities	Percentage (presumably) permanent injury	Percentage (presumably) non-permanent injury	Total loss time (hour)	Risk indication by experts
Observed process disturbances with high risk potential							
E3-04	Exposure to hydraulic oil due to leakage in hose	11	0%	18%	82%	0:49	High
E3-05	Due to unforeseen activities, the employee must perform work at heights	14	7%	14%	21%	19:44	High
E3-05	Hydraulic jack is defect and must be lifted out the TBM	11	9%	27%	45%	3:35	High
E5-07	MSV drives to the TBM and makes an unexpected movement	40	3%	45%	40%	1:10	High
E5-09	Caught between machine and another object due to repair of a stopped MSV	5	0%	20%	20%	4:30	High
E8-05	Keystone does not fit	17	6%	41%	24%	2:17	High
E8-08	Load dropped out of the erector caused by malfunction vacuum system.	7	14%	57%	43%	22:18	High
Observed process disturbances with low risk potential							
E1-16	Pump pipeline is broken and must be replaced	13	0%	54%	23%	1:15	Low
E2-03	Contact with moving parts through repairs to bentonite pump, pipes, valves, etc.	9	0%	67%	11%	17:55	Medium
E2-09	Exposure to large amount of slurry due to leaking pipeline	15	0%	13%	60%	6:42	Low
E3-08	Wrong jack is pulled due to operating error	7	0%	29%	29%	1:00	Low
E4-05	During cleaning work, the employee comes into contact with mortar/ slurry	4	0%	50%	0%	6:14	Low
E8-02	Malfunction of the vacuum system of a crane that places elements on the belt	17	6%	41%	24%	8:43	Low
E8-02	Pipes are lifted from the MSV and fall out of the crane	70	7%	44%	23%	4:20	High
E8-03	Elements do not fit and need to be disassembled	2	50%	0%	0%	16:50	Low
E8-15	Elements are assembled and removed again, double exposure to danger	30	0%	57%	17%	23:43	Low
E9-04	Contact with moving parts due to crane maintenance	8	0%	63%	13%	6:34	Medium
Not observed process disturbances with high risk potential							
E1-05	Employee is exposed to contaminated slurry when extending pipelines.	8	0%	25%	50%	13:30	High
Not observed process disturbances with low risk potential							
E1-14	Contact with moving parts during lubrication or maintenance of the main bearing	44	0%	84%	9%	0:55	Low
E1-24	Contact with moving parts due to failure of the lubrication system	30	3%	77%	13%	0:50	Low
E1-26	Exposure to harmful atmosphere due to penetration or escape of a harmful gas.	21	14%	10%	67%	3:41	Low
E2-04	No possibilities to evacuate due to inflow of large amount of water	9	89%	0%	11%	3:46	Low

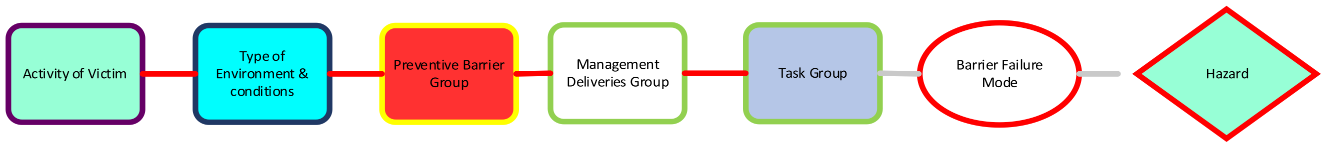

Fig. 2. Schematic view of left (causes) side of the bow tie.

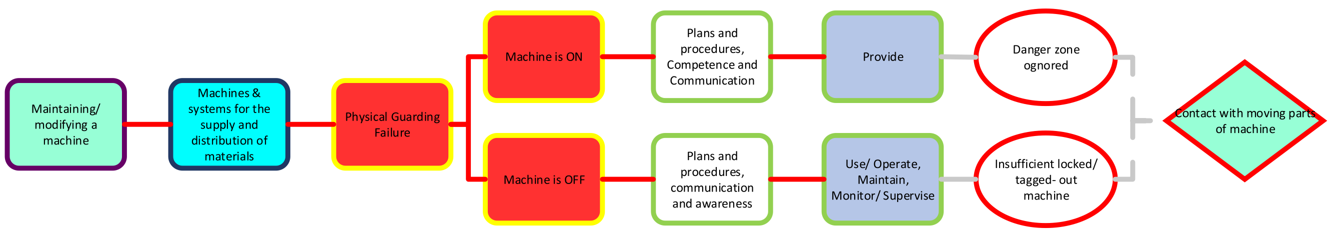

Fig. 3. Incident path for the excavation phase.

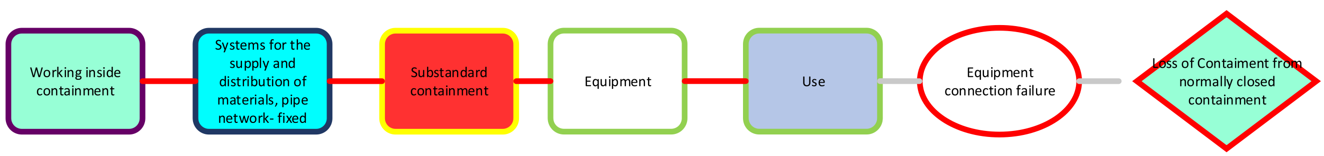

Fig. 4. Incident path for contact with slurry during production function face support.

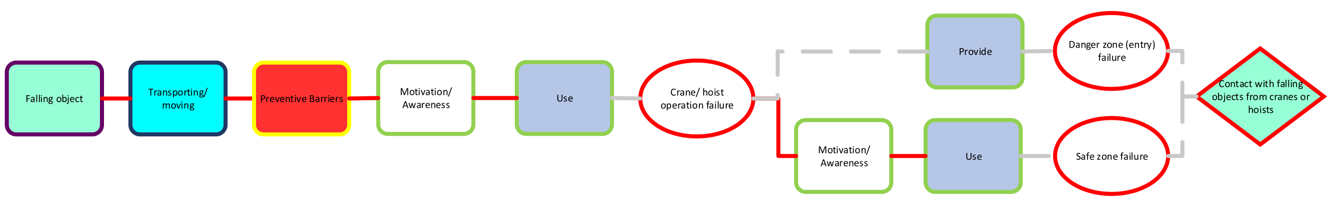

Fig. 5. Incident path for contact with falling objects during jack replacement.

relate to pipe cleaning due to mortar blockage. Employees may come into contact with (partially hardened) mortar when cleaning the pipes. This is a low-risk scenario.

Construction materials are supplied to the TBM by a Multi-Service Vehicle (MSV). In the case study a free-driving MSV on inflated tires was used. The disturbances that have occurred relate to incorrect steering of the MSV (E5-07) and repair of the stopped MSV (E5-09) (see Fig. 6). Because the MSV is controlled manually, a control error in the tunnel can lead to blockage.

The most dominant scenario when erecting lining segments is the contact with falling objects. This scenario applies to logistic failures (E8-02), elements do not fit properly (E8-03), keystone does not fit properly (E8-05) and erector fails (E8-08). The accident paths for these scenarios are shown in Fig. 7.

After the data collection and visualizing the incident paths, the results were validated by means of interviews with experts. During these interviews the data, observations and incident paths were validated and the risk potential was estimated.

The reference data from Storybuilder was used to establish the potential number of victims and the severity of the injury. By selecting key events from the accident path of the case study and comparing these with similar accidents paths from Storybuilder, information can be gained into the potential number of victims and type of injury associated with the accident path. For example, for scenario E3-05 (Due to unforeseen activities, the employee must perform work at heights) the incident path is visualized in Storybuilder bowtie 01.1.5.3 (Fall from height – working on height unprotected.) The key events are event nr. 316 (portable or mobile machines for extracting materials or working the ground) and nr. 538 (safe access ignored). Using the 'and' operator in the selection a total of 14 matching accident paths are found in Storybuilder. These 14 accident paths lead to 1 fatal accident (7%), 2 accidents with (probably) permanent injury (14%) and 3 accidents with (probably) non-permanent injury (21%).

The potential number of victims, the exposure time and the opinions of the experts have been used to determine the extent of the risk. Based on the results the scenarios are ranked by risk potential, based on the duration of the process disturbance (exposure to risk) and the consequences. The results are presented in Table 3.

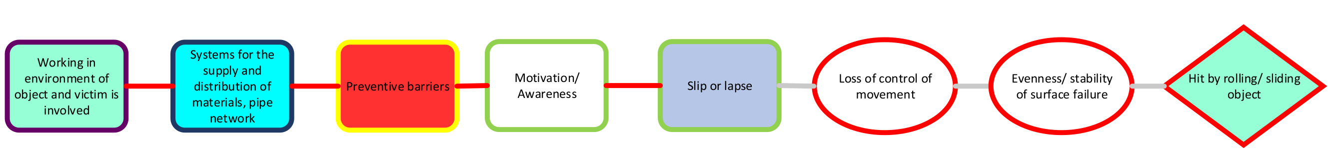

Fig. 6. Incident path for hit due to a sudden movement by a MSV.

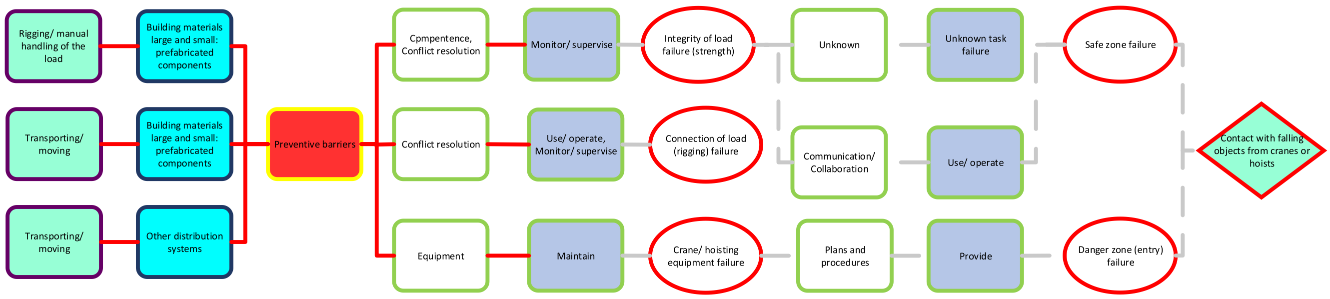

Fig. 7. Incident path for contact with falling objects during segment erection.

The ranking of the highest risk scenarios, whether based on the data from Storybuilder, the duration of the process disturbance or the outcome of the expert meeting, show a remarkable difference. This difference stems from the fact that several scenarios are qualified as high-risk scenarios based on the analysis from Storybuilder for similar incidents in other construction sectors, but are not assessed as likely or risky by the experts in the expert meeting.

The tunnel boring process is a specific process for which insufficient reference data is available in Storybuilder or in another data set. Because of the discussion about the objectivity of the assessment of high-risk scenarios and the specific character of the tunnel boring process, it is therefore obvious (but not necessarily objective) to consider the scenarios that were mentioned during the expert meeting as being the highest risk scenarios. Therefore, for the purpose of determining the required measures (barriers), the highest risk scenarios based on Storybuilder and based on the duration of the process distrubance have been included in the further analysis, along with those scenarios the experts deemed the most important.

2.3. Preventive measures

To prevent or control undesired events, one or more preventive measures have to be implemented and maintained. Based on the predicted incident pathways, a specific set of measures can be determined for each scenario from the Storybuilder toolkit. Individual analysis provides a large number of measures that are specific for a specific accident path. In order to determine a limited set of preventive measures, three types of analyses have been carried out:

- Analyses based on the risk level established by expert judgment, duration of exposure and based on the severity of similar Storybuilder scenarios.
- Analyses based on the most common central events (in this case study contact with falling objects from cranes / hoists (6), contact with moving parts of machines (4) and loss of containment from normally closed containers or pipeline systems (3).
- Analyses based solely on expert judgment.

Each type of analysis resulted in a different set of potential barrier failures and preventive measures. Measures that have been determined by the first analysis type are generic in nature and primarily aimed at improving the controls, criteria and resources of the management delivery system (plans & procedures, use/operate, motivation and commitment, etc.) or barrier tasks (use, provide, maintain, monitor). For a TBM process, preventive measures include protocols for hazardous work, use of PPE or other personal measures, facilities and equipment for working safely at heights, timely remediation of malfunctions and robust planning system.

The main preventive measures that should be employed, based on analyses of the most common central event, have been specifically identified for tunnel boring, though these show significant variation per bow-tie.

- Entry to danger zone during segment erection can be risky. In case of a loss of pressure of the vacuum system, being hit by an element will in most cases lead to a fatality. The main preventive measures are maintaining danger zone (entry) and establish reliable connection of the load. The same preventive measures apply to hoisting activities of pipe systems at the back of the TBM.
- In order to repair machines, workers may come into contact with moving parts of a machine. The main incident causes are Physical Guarding Failure and insufficient locked and tagged out machine. The main preventive measures are related to protocol for securing machines and qualification of operation personnel.
- During operation the hydraulic hoses and the mortar system are under high pressure. Unwanted events can result in a loss of containment and rapidly outflow of the product. Double connection fixation, regular replacement of outdated hoses, and regular containment indication/ detection/ diagnosis/ response can prevent the Loss of Containment.

Preventive measures which have determined by expert judgement are specific measures and do not only relate to the construction phase, but also to the initiating and design phase of the construction project. These measures apply to effectiveness of the extinguishing system by using firefighting foams, optimization of the TBM layout for safer work conditions, detecting weak signals to detect disturbances earlier, diameter of the TBM to gain more workspace, dimensions of the key stone to secure its position, a protocol for hazardous work like a hot work permit and log-out Tag-out procedures.

3. Discussion and conclusions

The tunnel boring process is a continuous, controlled and safe process, but it can become dangerous for employees if a process disturbance occurs. Previous publications (Swuste 2003) identified the following as the most risk-prone process components in TBM tunnelling: vertical transport of loads into the excavation pit; positioning of loads on wagons; horizontal transport of loads and people; positioning of lining elements; extending rails and supply pipes.

The case study at Victory Boogie Woogie Tunnel registered 22 incident scenarios', each with its own incident pathway. The risk potential has been qualified based on actual exposure, injury severity and expert judgment. Based on the data analysis, the excavation production function shows the highest potential accident rate. Based on the exposure data, activities that belong to the face support or hydraulic jacking production functions are the dominant source of risk. According to expert interviews, activities that belong to hydraulic jacking, transport and lining have the highest risk impact, which overlaps with the findings from data analysis and exposure analysis.

Three different types of analysis have been used to study under which circumstances safety barriers lose their safety functions. Each analysis provides specific information. Analyses based on duration of exposure, number of victims and expert judgment mainly indicate which tasks (use, provide) and management systems (plans and procedures) will fail. Analysis based on the central event provides more specific information on the failed barriers (entry danger zone, physical guarding failure, connection or load failure) and failing parts of the management system (plans and procedures, competence). Based on expert judgment, specific measures should be taken in the various construction phases (effectiveness of the extinguishing system, TBM layout, detection of weak signals, diameter of TBM, dimensions of key stone). Based on these analyses there are no clearly dominant factors, or combinations of factors, that contribute most frequently to the development of an accident scenario.

Analysis shows that more than one barrier must fail during an incident scenario for an accident to occur. This means that several barriers, tasks and parts of the management system must fail at the same time in a given incident scenario. The analyses from Storybuilder show that mainly non-physical barriers fail. Improving the management system and task will decrease the probability of a loss-determining event.

Although incidents often follow the same accident pathways, future events during a tunnel boring process will probably follow their own pathways. Through the application of measures in the management system and tasks, it is expected that the process disturbances can be caught and handled safely.

The case study shows that the management systems and tasks are essential elements to maintain safety barriers. The quality, reliability and robustness of a barrier are essential in preventing incident scenarios. A systematic approach to the design, application, maintenance and monitoring of preventive measures should therefore be applied. Due to the role that preventive measures have in mitigating risks, a management system should be applied which focusses on maintaining these barriers.

CRediT authorship contribution statement

O.T. Terheijden: Conceptualization, Formal analysis, Resources, Writing – original draft. **P.H.A.J.M. van Gelder:** Methodology, Validation, Writing – review & editing. **W. Broere:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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