LIABLE OR RELIABLE

Applying scenario concepts in infrastructure design

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Abstract

Safety increasingly plays an important role in the design and construction of major infrastructure projects throughout Europe. A series of tunnel fires, the development of high speed railway links, expansion of ports and airports and the interest in multifunctional underground structures has triggered the necessity to integrate safety in the early phases of the design process. In addition an innovative approach has to be realized, incorporating new technologies and concepts in such designs. The scale of such projects has increased, exposing a large population at the risks involved in operating major infrastructures. In particular safety requirements from a rescue and emergency point of view have been articulated as a new set of requirements in addition to structural integrity, external risk standards and certification standards.

Introduction

Experiences from several major infrastructure and transport projects have demonstrated two new developments in the area of integrating safety into the design process.

On one hand, the process of safety decision making and the involvement and commitment of actors with conflicting interests has to be structured carefully to achieve sustainable support for the eventual design outcome (Stoop and Beukenkamp 2003).

On the other hand, a substantive testing and benchmarking of safety performance has to be improved. Conventional quantitative risk standards do not discriminate between design alternatives in the early phase of the design process. Major safety decisions have to be made with serious consequences for residual risks and costs in the final design phases, operational practices and emergency resource allocation. For this reason a complementary approach has been developed, focusing on the development of safety critical scenarios (ST/COB 2002).

This contribution analyses and evaluates pilot studies in the Netherlands where a new approach has been developed to incorporate safety in various phases of the engineering design process. The approach focuses self-relianceness of risk-bearers and accessibility for rescue and emergency services.

The scenario approach has been based on experiences with underground railway stations and tunnel designs for a high-speed railway line and redesign of a railway station environment in a dense urban environment.

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Scenarios as a decision support tool

Analyzing the lessons learned from the design and construct of the High Speed Line-South railway project, questions were raised about the theoretical justification of the project fundamentals (Stoop and Beukenkamp 2003). New actors and safety notions in the area of rescue and emergency, external influences such as the Eschede ICI-train derailment and various tunnel fires in the Alp region emphasized the necessity to incorporate safety in the decision making process of the project management in a major infrastructure project.

Initially defined as a linear, loosely coupled and closed system design, based on proven technology, the HSL-South project demonstrated the need to incorporate external influences and new actors in the safety decision making process. Rather than compliance with quantitative risk standards and performance requirements at a detail engineering level as a part of the Construction and Operation Licensing procedure, a dynamic and open process approach proved to be necessary. Such a process should stimulate consensus among actors and involve rescue and emergency aspects in the early phases of the design and should document principal safety related decisions (Leeuwendaal 2001).

In this approach, the use of scenarios as decision support tools proved to be fundamental in order to achieve consensus among stakeholders and to allocate specific safety measures to improve the quality of the design. Such an approach eventually proved to be beneficial for introducing innovation in the design of a major tunnel for the HSL-South railway (Stoop and Beukenkamp 2003). However, the application of scenarios as design support tools remained obscure regarding their substantive development, procedural embedding and scope with respect to an integral safety approach. In a second project, the Spoorzone Delft, scenarios have been primarily applied as a design tool to explore their further substantive development.

Scenarios as a design tool

Scenarios were developed as a design support tool in order to support a substantive safety assessment in three phases of the design process and decision-making during the project management. In general, three steps are identified in a civil engineering design process:

- Step 1: a conceptual design phase in which design alternatives are based on a Program of Requirements, shared by all actors and encompassing all relevant design aspects. Such alternatives are collected in a Initiating Document (RIB 2002)
- Step 2: a functional design phase, in which a limited set of most preferable alternatives is selected, fit for further elaboration and detailing of critical design aspects of the final design option (RIB 2003).
- Step 3: a detailing phase in which the construction details and safety measures in the final option are elaborated into a construction planning phase (DHTrail 2003).

In each of these phases, safety should be assessed in combination with other relevant design aspects and external conditions. Eventually, a most cost-effective design should be realized. In order to integrate safety in these decision-making phases, a scenario analysis was applied to the Spoorzone Delft project (Prorail 2003).

Definition of scenarios

Two complementary approaches were applied: a probabilistic approach, focusing on the external safety consequences of the transportation of hazardous material through the tunnels, and a deterministic approach, focusing on the integral safety of the tunnel, hub and surrounding urban environment (Prorail 2003).

Probabilistic analysis

A probabilistic approach discriminates between individual risk, expressed by Personal Risk standards and indications for Group Risks. The results of this risk assessment indicated a containment of the Personal Risk within the tunnel contours, even for the worst of four future transport scenarios with hazardous materials. At the tunnel entrances a slight increase occurred compared to an open track situation because of the concentration of smoke and gasses at the outlets. Incorporation of risk allocation to the tunnel entrance however, was not an option in the mathematical model. For the Group Risk calculation, the population density at the tunnel entrances proved to be prevalent. However, the calculation model did not count for a tunnel in which only the entrances could be considered as risk sources. Limiting the population density proved to be a constraint for designing the tunnel entrance environments. This quantitative risk assessment served as a worst case scenario estimate, in which flammable liquids proved to be the dominant substance. The quantitative risk assessment proved not to be selective regarding the five design alternatives, since all alternatives complied with the available risk standards.

Scenario analysis

Consequently, in order to facilitate a selection of design alternatives, an additional and experimental approach was applied, by assessing the design alternatives by a qualitative scenario analysis.

Fundamentals for such a scenario analysis are:

- the analysis is a process analysis, focusing on optimizing the overall process, covering design, construct and operations.
- The analysis serves the goal of selecting alternatives and integration of safety in the design process
- Performance indicators for integral safety are applied such as internal safety and prevention, self-relianceness, rescue and emergency, social safety and traffic safety.
- The analysis includes the tunnel, combined with the underground railway station, the adjacent traffic and urban environment.
- The assessment is conducted by defining a set of safety critical scenarios which are accepted by all actors in the decision making process. They serve as a means of communication between these actors, achieving consensus on required measures for enhancing safety and acceptable minimum levels of safety.

Most relevant requirements for such scenarios are:

- criticality: a certain extend should be defined in order to facilitate assessment on acceptability
- realistic: the described events should be credible and recognizable, based on previous events in comparable objects and projects
- discriminating: the scenarios should contribute to an well argued assessment and selection of alternatives
- descriptive: the criticality of the event is pivotal in the selection process, in which the multi-causal nature of the events is taken into account.

The drafting and selection process of critical scenarios is not self-evident. This process deals with not-yet existing, but complex projects, involving many aspects and elements, introducing a high degree of uncertainty. Such projects are location-specific; not all details are known and the context is still changing. For such major projects, little or no historical information is available about specific failure modes and accident or incident data of similar designs.

To draw up scenarios, redundant sources of information are available:

- accident case histories. A limited number of critical events, which have occurred in similar situations and projects, can be applied as benchmarks for assessing the acceptability of events with potential catastrophic consequences. Examples for the railway project were provided by the railway fuel explosion at Affoltern near Zurich, the terminal fire at Dusseldorf airport and the riots near Amsterdam Central Station in 2002.
- encompassing criticality analysis. Potential consequences covering all safety aspects being technical, internal, external, social, transport and rescue and emergency were identified.

Such an analysis should provide a basis for consensus among stakeholders and other actors in their perception and acceptance of all potential risks involved in the project

- identification and combination of safety critical design components and project elements. Scenarios were drafted by combining hazards (fire, explosion, collapse, inundation) , project elements (tunnel, entrances, station and urban environment), functions (operations, rescue, maintenance, parking), accident types (collision, spills, derailment, fire) and environmental conditions (process industry, housing and office environment) into specific events which should facilitate selection of design alternatives.

Due to the fact that is impossible to evaluate and assess all possible scenarios, a selected number of five critical 'top' scenarios were identified by expert opinion and group discussion among stakeholders.

Their relevance was based on their ability to demonstrate the perceived critical consequences and their ability to indicate design strategies. They should facilitate optimization of design solutions for a wide variety of aspects. In a next design phase of detailing engineering, all possible scenarios should be evaluated in order to assess their influence on the project elements, technical installations and operational requirements to assess the safety of the final alternative.

A design case study: the Spoorzone Delft project

The municipality of Delft has been taken initiatives over the years to improve the quality of the urban area around the central station and railway track. At present the location of the tracks on a high fly-over disturbs the living environment and hampers the development of the city center nearby the station. Consequently, the municipality has commissioned a design for a railway tunnel in combination with local urban development and a multifunctional public transport hub as a replacement for the fly-over and station.

Step 1: Safety as a conceptual design aspect

In cooperation with the railway provider, Delft has taken a multidisciplinary approach in which the public transport hub is pivotal and an integral approach is favored for the spatial and transport issues. This approach should direct an urban infrastructure, and generate solutions for planning, construction method, alignment and possible optimizations. The municipality Delft, the regional authorities and the railway infra provider have drawn up a common Program of Requirements in order to conduct a modeling study into the location and outlines of the transport hub, in combination with the tunnel options and urban environment. Eventually, 14 alternatives were developed and assessed, based on the following characteristics:

- the construction method of the tunnel, such as cut-and-cover versus drilling, including the tunnel cross section
- the length of the tunnel, with a constant northern section length and a variable length of the southern section
- the vertical alignment, focusing on the local urban consequences of various spatial functions on the surface level
- horizontal alignment, depending on required removal of houses and crossing of traffic arteries and combination of transport routes
- location of the public transport hub, varying across the track as well as underground or surface level railway stations.

In total 16 alternatives were tested by expert opinion meetings, based on 12 criteria, among which social safety in the railway station environment and internal and external safety of the tunnels. As a result of this testing procedure, 5 preferential alternatives were chosen for further elaboration (RIB 2002).

Step 2 Safety assessment of design alternatives

In order to reach a further reduction in alternatives, the five preferential alternatives were assessed more in detail, in particular with respect to safety.

The following scenarios were selected for assessment of the five preferential alternatives:

1. fire in a passenger train stopping in the tunnel, possibly in combination with the presence of hazardous materials in a freight train. Due to smoke, heat and toxic substances, the focus is on the speed of evacuating passengers
2. collision of a freight train and passenger train at the underground station, releasing hazardous materials. This scenario foresees an expansion of the event into the underground platforms and adjacent station, requiring rapid evacuation of passengers and timely access for rescue workers
3. small crime and traffic accidents on the ground level station square, focusing on interactions between station, parking, transport hub and traffic environment
4. disturbance of public order and safety during the construction phase. This scenario deals with complications during construction and crowd control
5. accessibility of the site for rescue and emergency workers during major events in and around the tunnel, underground station, adjacent office blocks and parking facilities.

Assessing the safety of the Spoorzone Delft with these scenarios, several generic potential bottlenecks emerged, independent of the design alternatives.

The Northern tunnel entrance is located in the middle of a process plant. Interference between escape from the tunnel entrance and uncontrolled access to a chemical plant and shunting freight trains across the main track into the plant was identified as potentially critical.

The railway tunnel North of the underground station has to be evacuated along the tunnel axis, preferably by the second parallel tunnel tube. Due to the horizontal ventilation and escape routes, toxic fumes, smoke and heat may penetrate the underground station, exposing a wider population at the risks. Additional vertical escape routes might become mandatory to overcome this exposure.

The role of the underground station as a part of the escape routes has not yet been elaborated for the longer tunnel alternative. The station might become a safe haven facility, but simultaneously could hamper the escape of a large population at risk and create conflicts with accessibility requirements for the rescue and emergency services.

The compactness of the transport hub requires high quality vision lines for spatial orientation and social safety, short walking distances between facilities and an ergonomic environment for passengers and other occupants of the premises.

At present, more detailed insight lacks into the architectonic and urban planning with respect to location, nature, extend and dimensions of housing, office buildings, shopping malls and parking facilities. Such information is required in order to assess the mutual positioning of the project components regarding escape routing, self relianceness of the occupants, ventilation and access for rescue and emergency services.

In general, it was concluded that transport of hazardous materials through tunnels did transfer external safety issues for citizens along the railway track to internal safety issues for the population in the tunnel. Quantitative risk assessment showed that none of the alternatives did exceed the personal risk and group risk standards for future transport of hazardous materials, for which the tunnel entrances were critical with respect to the population density in this area. Quantitative risk assessment proved not to be selective in a preference for one of the design alternatives.

The scenario analysis demonstrated that a short tunnel with a ground level station was to be preferred, while the various long tunnel options differed with respect to the self-relianceness, accessibility for rescue and emergency and traffic circulation. The tight compactness of the Northern alternatives caused a less favorable safety performance than the Southern alternatives.

The Western or Eastern alternatives for locating the tunnel track did not prove to make a significant difference, apart form the very compact North-West alternative, which hampered accessibility and evacuation.

	Long North-West	Long North-East	Long South-West	Long South-East	Short
External safety: 1. personal safety 2. Group risk	 -	 -	 -	 -	 0
Integral safety: scenarios 1. evacuation of the tunnel 2. collision at station 3. safety hub 4. safety during construction 5. rescue/emergency access	 -- -- - - -	 - - - - -	 - - 0 - 0	 - - 0 - 0	 + + + - +

Based on the scenario analysis, it became apparent that based on relatively simple decisions, the tunnel safety could be enhanced further. To this purpose, two general applicable safety design principles were available.

1. Integral concept for tunnel safety
Opportunities for optimization are offered once an integral tunnel design concept is applied, in which the tunnel is related to underground functions of adjacent construction elements such as parking facilities, technical installations and ground level functions such as traffic and buildings.

2. Safety critical decisions
Safety critical decisions can be made regarding:

- escape routing in a horizontal or vertical direction, compartmentalization of the tunnel to reduce consequence migration, additional escape facilities to ground level, and integration of functions with ventilation and pressure compensation, rescue facilities and ground level functions.
- Compactness of the transport hub by combining functions and situations such as traffic flows, parking, transfer, residential and shopping facilities.

Step 3: safety measures
In a third step, a further elaboration of the scenario analysis took place, focusing on the safety critical assessment of the tunnel, regarding a future, unrestricted transport of hazardous materials through tunnel and underground station. This step focused on composing packages of safety measures in order to achieve an acceptable and cost-effective safety level.

Such unrestricted transport of hazardous materials has to be assessed very carefully, since by definition the risk of such transport is according to the risk modeling linear related to the transport volume. Exceeding the risk standards would require a disproportionate investment in safety related measures.

The safety analysis focused on two questions:

- whether a difference in transport of hazardous materials in the present situation and a future option of unrestricted transport would affect the required safety measures
- or differences should exist for shorter and longer tunnel alternatives, taking into account underground or ground level positions of the railway platforms.

The Spoorzone Delft project has a number of characteristics, which argue for a group risk approach in terms of rescue and emergency resources and facilities. Passenger and freight trains may occupy the tunnel simultaneously, during which a large population at risk may be involved in an incident, including the population at the underground station. Since the station has no separation between tubes, interactive scenarios may occur between station and both tubes. The sizes of the transport of hazardous materials and a coincidence with passenger transport are critical issues for a safety assessment of the tunnel design. Consequently, group risk may be a critical factor in incident handling. Such internal group risk may be triggered by transportation of hazardous materials or fire incidents in passenger trains, but no national, legal standards are available. Acceptable risk standards for passengers and populations at a railway station are defined only on an individual basis. The costs of the tunnel and concurrent safety measures to guarantee a sufficient safety level are substantial. The analysis focused on fire hazards and incidents with hazardous materials.

Zooming in on scenario 1, representing these hazards, a further detailing of accident scenarios has taken place, distinguishing between:
- fire in passenger trains
- fire incidents in freight trains
- serious fire with hazardous materials such as liquids or gasses
- release of toxic materials such as gas dispersion
- fires with hazardous materials followed by explosions.

<u>Safety packages</u>

Measures to mitigate these scenarios should be cost-effective and dealing with aspects of self-relianceness and accessibility, ventilation in tunnels and station, fire resistance of the tunnel construction, availability of fire detection systems and sprinkler installations.

In order to integrate the safety measures in an overall cost-oriented decision making process, five packages of safety measures were identified and assessed, based on the five accident scenarios.

1. a minimum package, including transport of passengers after escaping the incident along the parallel tube towards tunnel entrances and the station over a length of over 1000 meters
2. a basic package with additional emergency exit staircases and rescue access, integrated in the pumping facilities of the tunnel construction with an intermittent length of maximum 800 meters
3. a basic package with optimized self-relianceness facilities, including five additional exits reducing the intermittent escape distances to the ground level to 250-300 meters
4. a basic package with additional measures dealing with hazardous materials, such as sprinklers and detection equipment
5. a maximum package, providing a combination of 3. and 4., possibly supported by fire resistant lining of the tunnel surface.

Assessment of Packages of measures	**fire**		**hazmat**			**score**
	passenger train (1)	cargo train (2)	major fire (3)	toxic release (4)	explosion (5)	
1. basic package minimum						
minimum self-relianceness	+/++	+/++	+/++	+/++	0/+	6.5
fire fighting facilities	++	+	0/+	0/+	0/+	4.5
fire resistant lining	++	+/++	+	0	0	4.5
tunnel ventilation	++	+/++	+	0/+	0/+	5.5
station ventilation	++	++	++	0	0	6
	9.5	7.5	6	2.5	1.5	27
2. basic package reference						
three additional refuge and emergency exits	++	++	++	++	0/+	8.5

	10	8	6.5	3	1.5	29
3. basis package plus self-relianceness						
five additional emergency exits	++/+++	++/+++	++/+++	++/+++	0/+	10.5
	10.5	8.5	7	3.5	1.5	31
4. basic package plus hazardous materials						
sprinkler and detection	-	++	++	0/+	+	4.5
	9	10	8.5	3.5	2.5	33.5
5. Maximum package Hazmat plus self-relianceness						
Package 2, 3, 4 jointly	++/+++	++/+++	++/+++	++/+++	0/+	10.5
	9.5	10.5	9	4	2.5	35.5

Based on this assessment, a first series of safety consequences became apparent:
- optimal support of self-relianceness and ventilation in the station can be considered crucial measures for all scenarios. Accordingly, the station will serve as a safe haven for evacuation of passengers from the tunnel
- ventilating the tunnel will support the evacuation of passengers from the tunnel and station, provided that the direction of ventilation is correct
- fire resistant lining is effective for smaller fires and focuses on maintaining structural integrity of the tunnel
- fire fighting facilities may be effective for smaller or not yet fully developed fires. Incident handling in case of hazardous materials is excluded for fire fighters
- measures for self-relianceness and rescue/emergency are symbiotic to a high extend
- sprinklers, combined with automated detection enable fire control and fighting of major fires and reduce the probability of fire expansion. They deteriorate the evacuation process during fires in a passenger train by steam and obscuring visibility.

Incidents with hazardous materials show a significant difference between the present transport volumes and the intended maximum transport volumes for the future. The maximum transport volumes lead to an increase in probability as well as number and severity of accident scenarios compared to the present volumes and autonomous growth of this type of transport. Residual risks in scenarios with major fires may show an exceedence of the internal group risk for passengers in the tunnel as well as at the underground station. Apart from the increase in costs from a perspective of tunnel length, no differences in safety measure packages will occur. The emergency situation both for passengers and rescue and emergency staff will be defined by the additional number of entrances and emergency exits, reducing the refuge travel distances and increasing the evacuation capacity. The location of the station is more prominent. The population at risk can be increased considerably if the scenarios in the tunnel expand to the station and the other train tube in the tunnel. This puts constraints on the availability of adequate smoke and heat discharge installations. The ground level station facilities should be separated from the underground facilities.

Conclusions

The application of quantitative risk assessment facilitates an assessment of safety in design of major infrastructure projects to a limited extend. Not only group risk standards for internal risks are lacking, the approach does not take into account non-quantifiable aspects such as rescue and emergency functions. In addition, a scenario approach is developing, in which commitment of stakeholders as well as a substantive assessment of safety becomes feasible in all steps of the civil engineering design process.

However, such an approach is in its early phases of development, requiring a more generic testing on a variety of major infrastructure an transport projects. The first results are however promising.

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