Cost-Effectiveness of Safety Measures in Multiple Use of Space

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Abstract: Lack of space leads to the design and construction of projects which make intensive and optimal use of the limited space. Buildings above roads and railways are examples of multiple use of space. Safety is one of the critical issues for such projects. This paper will give a quantitative overview of physical safety measures. Safety measures are formulated and their risk reduction is estimated for the building above the infrastructure considering four main scenarios dominant; traffic accidents, fires, leaks of toxic substances, and explosions on the infrastructure. Such measures can be implemented to the infrastructure or the building or between the boundaries of those two. These measures strongly originate from structural and functional point of view. The risk reducing effects of safety measures are determined quantitatively, if possible. These effects, applicable to multiple use of space projects, are presented in this paper. Finally, the cost-effectiveness of safety measures is presented in an overview.

Keywords: Cost-effectiveness, risk analysis, safety measures, urban planning.

1. INTRODUCTION

As a consequence of an ever-growing population, land is becoming more and more scarce, especially in urban areas. This has led to the development of design and construction techniques that make intensive and multiple use of the limited space possible. In the last decade, the space available above transport infrastructure - such as roads and railway tracks - and existing buildings has been exploited at a growing rate in city centres. Multiple use of space, building above roads, railway tracks and existing buildings, becomes feasible if significant safety measures are implemented, particularly when buildings are realised above transport routes of hazardous materials, which is sometimes the case in The Netherlands. In general, these measures are drawn up to reach a certain level of safety. There are several measures that can be implemented in multiple use of space projects. These measures will reduce either the probability and / or the consequences of an incident in the building above the infrastructure, the vicinity or in the covered infrastructure. In order to implement measures in such projects, it is beneficial from an economical viewpoint to integrate these during the design stage. These measures can be drawn up for four risk dimensions [1] (see figure 1):

- (1) External safety and risks from the building in relation to the infrastructure beneath (e.g. falling elements and fire);
- (2) External safety and risks from the infrastructure towards the building (e.g. release of toxic gasses, fire, explosions and accidents);
- (3) Internal safety and risks from the constructions enclosing the infrastructure (e.g. explosions, fire, explosions and accidents);
- (4) External safety and risks from the infrastructure towards the vicinity (e.g. release of toxic gasses, fire, explosions and accidents);

This paper will give a quantitative overview of physical safety measures. Some effects of some measures are presented in this paper. The safety measures are formulated and their risk reduction is estimated for the building above considering main scenarios on infrastructure (risk dimension (2)). The accidents on infrastructure can be grouped into four dominant classes; traffic accidents (mechanical load on the structure of the building), fires, leaks of toxic substances, and explosions. In this regard, the overview of measures is sub dived into 4 types; measures against heat radiation, measures against peak overpressure, measures against toxic load and measures against mechanical loads. These measures can be implemented to the infrastructure or the building or between the

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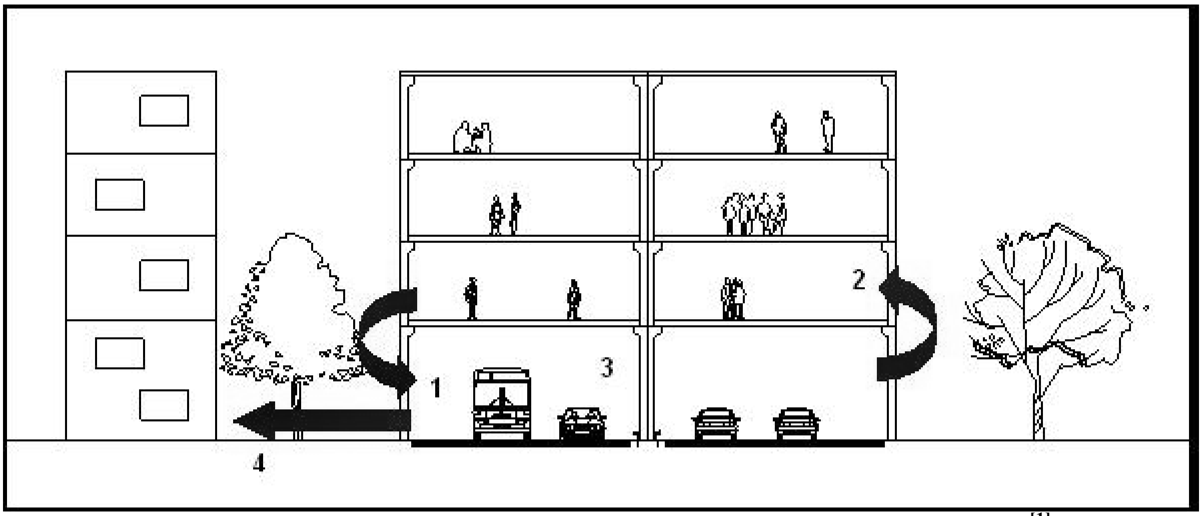
boundaries of those two. Note that these measures do not emphasise traditional measures, such as detection of fire etc. but strongly originate from structural and functional point of view.



.**Figure 1: The four risk interactions in multiple use of space projects [1]**

2. EFFECTS OF SAFETY MEASURES FOR FOUR CRITICAL SCENARIOS

2.1 Measures against fire

Building materials loose their strength and stiffness properties rather quickly when exposed a sufficiently long time (more than say 5-10 minutes) to high temperatures resulting from fires. This may cause severe damage, beyond repair, or even premature collapse. Protection against high temperature levels is a common feature in fire safety engineering. One of the methods is to apply a fire protection layer. Fire protection measures are designed for the entire service life of the covered infrastructure and the building above. Since the late eighties, tunnel protection against fire is standard in the Netherlands. The protection is based on a petrol fire. In 1979 the RWS-curve was found during tests in a model tunnel. The temperature measured during the tests rose up to 1350 °C. This high temperature was also found during earlier fire tests elsewhere [2]. The most important parts of the RWS-curve are the gradient during the first 10 minutes and the maximum temperature level [3]. The temperature rises so rapidly that the structure has no opportunity to adapt. High thermal stresses develop, and e.g. in concrete, moisture in the concrete becomes steam and causes high pore pressures and as a result, may cause spalling of the concrete. Apart from the spalling of the concrete, the high temperature can also lead to yield stress, possibly resulting in the collapse of the structure as well. This spalling has a rapid chain effect reaction and can be detrimental. In case of reinforced concrete structures, if the reinforcement is heated, it looses its strength as well and the structure with the building above may collapse. Although the probability of a 300 MW fire which is represented by the RWS-curve is low (it occurred during tests), the structure is protected and designed on the basis of that curve by a *fire-resisting layer*, which has the property to reduce the heating rate in the structure as well as the thermal gradient therein and give the structure a chance to survive the fire. This protecting layer must not collapse during the fire, for between 60 - 90 minutes. The fire-resisting layer, an effective measure against immense heat radiation, also called *thermal insulation*, can be implemented on the boundary of the covered infrastructure and the building above, as presented in figure 2. The effect of thermal insulation depends on both the scenario occurring in the building or on the infrastructure and the quality of thermal insulation. The quality relies heavily upon insulation capacity (conductivity) but perhaps even more on application details (fixings) and skills of application companies. The thermal insulation covers various methods to protect the concrete. The main fire protecting measures of thermal insulation are concrete covering, sprayed covering and board linings [1,2,3]. Depending on the type of fire exposure expected, the combination of some fire protecting measures (mostly board linings) can offer a fire performance of up to 240 minutes RWS fire, instead of the generally assumed standard 30 minutes fire performance without applying any fire-resistant layers or other measures. Good quality thermal insulation can withstand temperatures of 1,350 °C up to 1,700 °C and heat radiations of 100 kWm^{-2}, which can occur during hydrocarbon fires and a BLEVE [3].

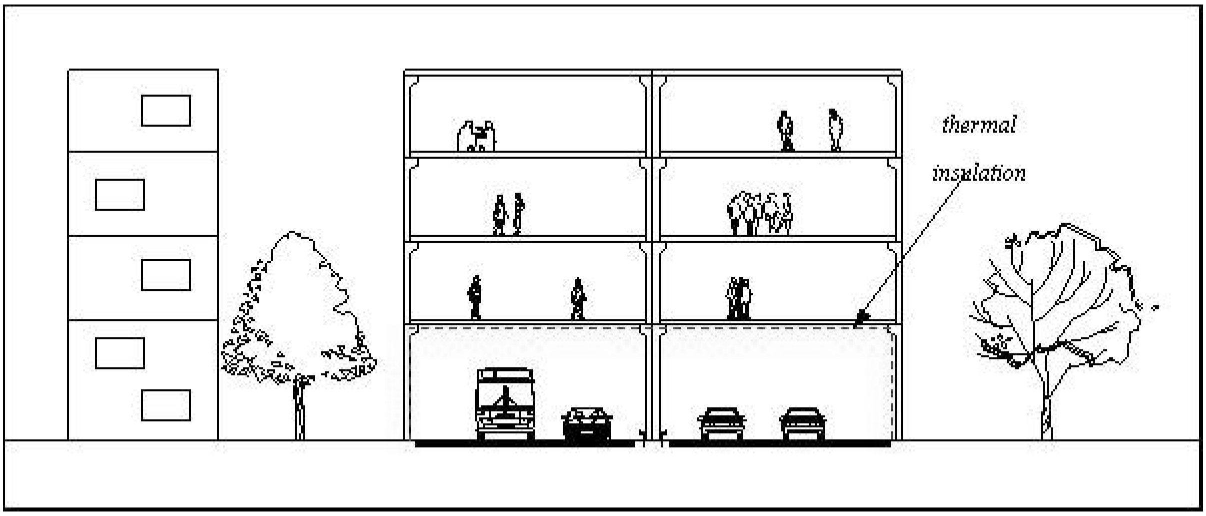


Figure 2: Thermal insulation is applied on the boundary of the covered infrastructure and the building above

Accordingly, one may expect that the resistance to collapse of the structure by (high) fire intensities can be increased by approximately 240 / 30 = 8 times when a fire-resisting layer is used, which is a strong reduction. If the fire is not extinguished in case of a 300 MW fire within half an hour, the probability of collapse of the building above is estimated to be 0.9 (see [1]). However, it cannot be assumed that the probability of collapse of the building above infrastructure will decrease by a factor 8, if the resistance of the structure increases with a factor 8. Nonetheless, the effect of the fire-resisting layer, assuming the strong resistance effect of 8 times and the high temperature withstanding properties of the layer, both can be determined. The reduction effects for the probability that the structure of the building above the infrastructure collapses, is estimated to be approximately a factor 10 lower. This means that the probability of collapse of the structure in case of a 300 MW fire occurring on the infrastructure is approximately equal to 10^{-2}. Likewise, the probabilities of collapse of the building above can be assumed for a fire of 20 MW and a 5 MW fire: these are 10^{-3} and 10^{-4} respectively. It should be noted that in case of a fire spread to the building above, these probabilities are higher, because the fire intensity can be much higher than the mentioned 300 MW.

Other measures against fires could be the implementation of:
- an additional (concrete) layer between the building and the infrastructure;
- ventilation in the covered infrastructure;
- sprinkler system;
- emergency exits.

Likewise, the effectiveness of these measures can be determined, more details can be found in [1].

2.2 Measures against peak overpressure

Structural measures against peak overpressure are almost never feasible nor practicable. These measures are both structurally and practically almost impossible to realise, because the theoretical dimensions of such measures are enormous. For that reason, the investments in such measures are extremely high, even higher than the total project budget [1]. Calculations [4] show that when packing in the infrastructure in a steel tube to prevent the effects of a detonation towards the building above, the thickness of that profile should be at least 71 mm, costing € 121,800,000.= per kilometre, which is of course absurd and not thus practicable. Measures against explosions can be taken against a maximum value of $(2.5 - 5.0) \cdot 10^2$ kPa (≅ 2.5 - 5.0 bar). Besides, there is hardly any scientific knowledge or evidence about the practical functioning and applicability of measures, like a clap roof, energy absorbing measures or water mitigation measures in multiple use of space projects. Only 1:1 scale experiments can predict their feasibility. Berg & Weerheijm [5] provide some measures in tunnels against explosions, which are particularly focused on the vessel rather than the tunnel structure. The most obvious way to prevent a gas explosion is to ignite the gas before a flammable premixture of some size has built up [5]. A fire is easier to control than a gas explosion. Water deluge by a high flow rate sprinkler system cannot prevent a gas explosion but may substantially reduce the pressure effects of an already developing gas explosion. The water deluge should be immediately activated by a flammable gas detection system over the full tunnel length. A promising new development for gas explosion suppression is the micromist device. This technique seems to be able to introduce a sufficient amount of ultrafine water droplets to be able to inert the mixture and to cool the flame. Extinguishing a fire without stopping a source of flammable gas enables a gas explosion scenario. A source of flammable gas after the quenching of a fire may also consist of liquids and solids that evaporate and pyrolise as a consequence of their high temperatures. An effective measure against the blast of a BLEVE could be to prevent the explosive rupture of a pressure vessel by cooling the vessel with sprinklers, such that the internal vapour pressure of the liquefied gas does not increase beyond a critical limit. The blast of a BLEVE is strongly reduced if the structure of the pressure vessel is designed in such a way that it cannot instantaneously fall apart. If the outflow of liquefied gas is spread over just a time span of about one second, the subsequent blast effects are minor [6].

The separation of transport of hazardous materials and the urban activities is perhaps the most attractive solution. Considering the explosion scenario and its large consequences for the vicinity, it can be desired to separate functions of urban development and transport of hazardous materials that cause the explosion scenario, because one should realise that these functions cannot be combined together [1]. Still, one needs to deliberate the costs and the benefits of measures to separate them. Only then, a rational and a justified choice can be made.

2.3 Measures against toxic gasses

In order to make air - possibly polluted with toxic released gasses - impenetrable towards the building above and the vicinity, one must realise air proof buildings. This measure can be applied in particular for the building above the infrastructure rather than the vicinity, because the buildings in the vicinity are usually already established. For most already established buildings in the vicinity, it is not clear that they are airproof untill a certain level. Most buildings are usually not designed to be 100% airproof. In The Netherlands the air volume flow, also called the q_{v10} ratio, deduced from the ratio of pressure and volume flow characteristic in case of a pressure difference of 10 Pa, is a significant parameter that reflects the air permeability of buildings. The q_{v10} ratio is the number of litres outside air penetrating in the building per second. Normal buildings are designed on base of a q_{v10} ratio of 80 ls^{-1} [6]. Yet, one can yield profit from the air permeability. If one can realise buildings with a q_{v10} ratio of 8 ls^{-1}, one may decrease the effects of toxic gasses with a factor 10. In order to achieve a q_{v10} ratio of 8, one has to implement large concrete façade elements rather than permeable façade elements. Besides, the gaps between these elements should be carefully sealed up. This measure is in particular applicable for buildings above the infrastructure and this measure is against toxic gasses remaining a short time on one occasion (for a full overview see [6]). In some incidents with release of toxic gasses, the gasses remain for a long time period on one certain location, such as hydrosulphide (H_2S). By this, the probability of fatalities in open air due to intoxication increase considerably. In addition to the previous measure, one can realise 100% airproof buildings, in which an additional (internal) ventilation system is required. Such a system is used in submarines or chemical and biological laboratories. If a building is 100% airproof - i.e. no outside air, possibly toxically polluted, can penetrate the building - an internal circulation of fresh air in the rooms of that building is required. One may achieve this by means of a ventilation system in which the air is refreshed and filtered for instance once a day. The effect of airproof buildings with additional ventilation is enormous, because the combination of airproof building and a ventilation system almost eliminates fatalities through intoxication. Therefore, the effect of implementing the measure in question is estimated to save 99% of the people in the building.

In case of an accident with toxic materials one may use the gasmasks in buildings. By this, the released gas is not able to contribute to the number of victims. Gasmasks are meant to enhance respiratory protection against chemical gasses, etc. The effect of gasmasks is theoretically estimated on a risk reduction of 90%, in which it is assumed that there is a good working detection and warning system. Besides, it is also assumed that the people are trained in such situations. More details can be found at http://www.ukgasmask.co.uk/.

2.4 Measures against collisions against the building structure

If a vehicle on the infrastructure collides with a column of the building above the infrastructure, this building may collapse, causing a large number of fatalities in the building. In order to reduce the consequences of mechanical accidents on infrastructure hitting the bearing structure of the building above, one can implement a crash barrier (in case of roads), derailment control (in case of railway tracks), a concrete wall instead of columns or even over-designed columns, combined with independent bearing structures for both building above the covered infrastructure and the covered infrastructure itself. One may also implement an alternative bearing structure in the building, by which the probability of collapse decreases. One may consider to omit columns on the footprint of the infrastructure. The main advantage of omitting columns on the infrastructure, is that the probability of a collision of a train with the main structure of the building will decrease, let say with a factor 10. The reduction of damage depends on the traffic type and can be determined exactly. A crash barrier is more effective for car collisions than for collisions with trucks. Therefore the reduction of probabilities is ranked in accordance with the traffic type (see table 1). One applies this measure in the design stage of a project.

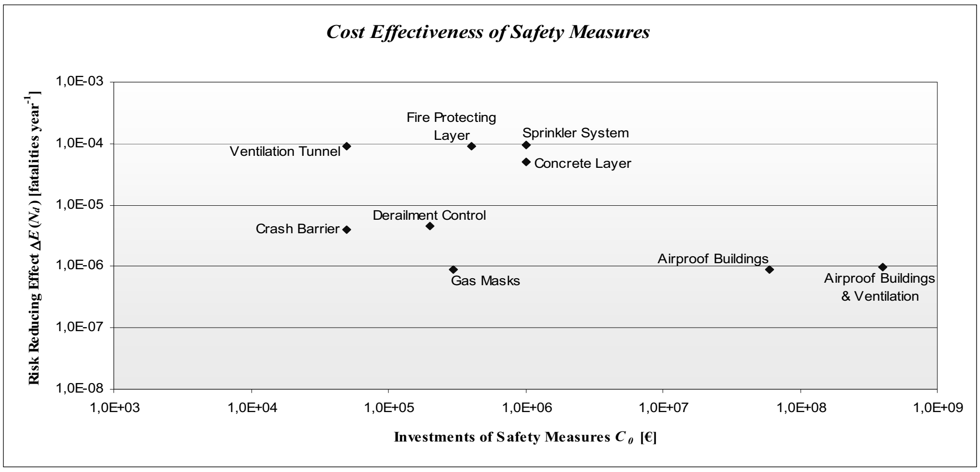
Table 1: The assumed reduction of probabilities and the traffic type [1]

Traffic Type	Reduction probability crash barrier	Reduction probability derailment control
Car	0.90	-
Bus	0.30	-
Trucks	0.10	-
Trains	-	0.9

3. COST-EFFECTIVENESS OF SAFETY MEASURES

The risk reducing effect per measure have to be compared with the investments in that measure, because of efficiency considerations. In this regard, the cost effectiveness of the safety measures of this chapter is determined for a case study. Although both the effects and investments of measures are unique to each multiple use of space project, depending on several circumstances, some measures can be generalised and their risk reducing effect and cost can be determined, leading to particular basic and technical solutions in such projects. Note that influencing the local circumstances, the cost-effectiveness of safety measures can be inconsistent with the presented results. Moreover, some measures can only be implemented in combination with other measures, rather than implementing individual measures. The thesis of Suddle [1] presents basic probabilities and consequences of scenarios, partly derived from Wiersma *et al.* [6]. Subsequently, the risk reduction per safety measure is determined. Finally, the human risk (decrease) $\Delta E(N_d)$ is compared with the investments C_0 of safety measures, as presented in figure 3. This figure should not be used as ”the exact cost-effectiveness diagram” for all multiple use of space projects, but as indicator of cost-electiveness of safety measures. For other cases, these results may differ entirely. If we consider figure 3 in a broader sense, some interesting remarks can be made. From figure 3 it becomes evident that measures against toxic gasses are possible, but not cost effectively. Safety measures like fire resistant lining, ventilation in the covered infrastructure and sprinkler systems are very cost effective. From a risk point of view, it is therefore efficient to implement measures without making large investments C_0 resulting in a large risk reducing effect $\Delta E(N_d)$. As a result, measures against fire protection and collisions on the infrastructure are strongly proposed to be implemented in multiple use of space projects. Measures against toxic gasses can be taken, however, these are not cost effective, except gas masks: their risk reducing effect is too marginal in comparison with their relatively large investments. The main reason for this is that although a large number of human lives can be saved, the probability of the release of a toxic gas is relatively small in comparison to other scenarios.

Figure 3: Cost Effectiveness of Safety Measures [1]



4. CONCLUSIONS

An overview of the previous sections shows that there are a large number of variations in implementing measures against some kind of scenario in multiple use of space projects. As a consequence, it is utmost important to consider the implementation of any measure in combination with other measures, e.g. measures from the safety chain, measures against other scenarios such as a fire protecting layer combined with derailment control or crash barriers, or ventilation in the covered infrastructure together with emergency exits. This paper also illustrates that safety measures against fires, release of toxic gasses and collisions against the main structure of the building above can be realised easily, while measures against explosions are both structurally and financially impossible to realise in practice. Some measures against peak overpressure can be taken to the development of a gas explosion or the vessel itself, e.g. the most obvious and simple way to prevent a gas explosion from developing is early ignition. However, it is questionable whether these mitigating measures will work. If these measures fail to work, a large number of fatalities can occur. Therefore, one should seriously consider that transported materials causing an explosion, such as LPG or ammonia, do not harmonise with urban development near or above such a transport route. Furthermore, measures against toxic gasses are less cost effective than measures against fire. Therefore, separation of the transport of toxic gasses through urban development is optional as well. This can accomplish urban development surrounding the infrastructure with less risk. One should deliberate the investments of these measures with their probability or risk reducing effect. From this point of view, measures against fire or collisions should be taken during the design stage of such projects.

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