A Quantitative Introduction of Physical Safety Measures for Realising Buildings above Roads and Railway Tracks

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Abstract

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 propose effects of safety measures for multiple use of space projects for critical scenarios i.e. fires, explosions, release of toxic substances and mechanical accidents.

1. Introduction

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. 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 (Suddle, (2003)):

(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).

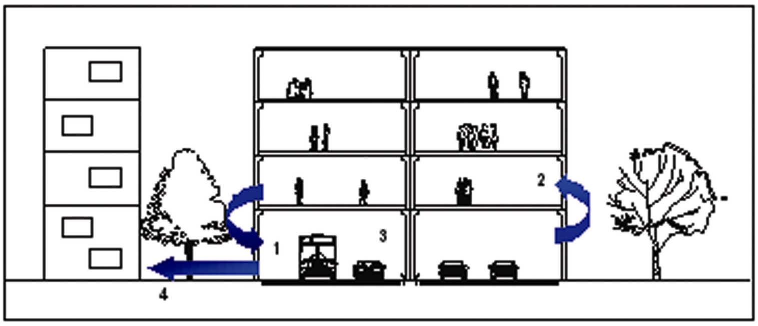

Figure 1. The four risk interactions in multiple use of space projects.

This paper will give a quantitative overview of physical safety measures. 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 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.

2. Measures against heat radiation

2.1 Fire protection

As far as safeguarding the structure is concerned, great uncertainty prevails with respect to the choice of the proper protective measures (see Both, (2001) & PROMAT, (2001)). This is exacerbated by the fact that fire protection measures have to be 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 (see also Tan, (1997)). The most important part of the RWS-curve is the gradient during the first 10 minutes (see e.g. Both, (2001)). The temperature rises so rapidly, that the structure has no opportunities to adapt. Moisture in the concrete becomes steam and causes high pore pressures and as a result, spalling of the concrete. This spalling follows each other rapidly and if the reinforcement is heated, it looses its strength and the construction and the building above may collapse. Although the probability of the RWS-curve is low, it occurred once, one likes to prevent this by protecting the construction by a *fire-resisting layer*, which has the property to reduce the gradient and give the construction time to adapt. This protecting layer must not collapse during the fire (VCR, (2002)). 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.

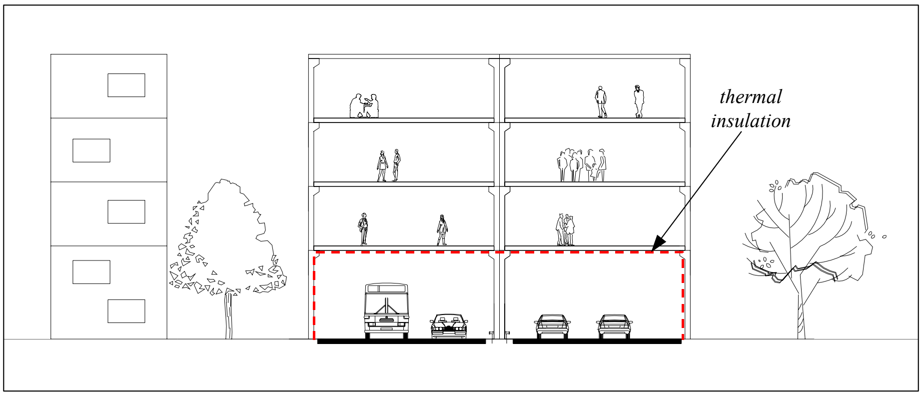

Figure 2. Thermal insulation is applied on the boundary of the covered infrastructure and the building above.

The effect of thermal insulation depends on both the scenario occurring in the building or at the infrastructure and the quality of thermal insulation. The thermal insulation covers various methods to protect the concrete. According to PROMAT, (2001) the main fire protecting measures of thermal insulation are concrete covering, sprayed covering and board linings. Depending on the type of fire exposure expected, the combination of some fire protecting measures (mostly board linings) can offer a fire protecting performance up to 240 minutes (adapted from PROMAT, (2001)), instead of the standard 30 minutes without applying a fire-resistant layer. In addition, the layers have to be resistant to aggressive environmental conditions such as vehicle fumes, spray water and thawing salt. It is also discussed by PROMAT (2001) that a good quality thermal insulation can withstand temperatures of 1,350°C up to 1,700°C and heat radiations of 100 kWm^{-2}.

Accordingly, one may expect that the resistance of collapsing of the structure by (high) fire intensities can be minimised by approximately 240/30 = 8 times when a fire-resisting layer is used, which is a strong reduction. If the fire was not extinguished in case of a 300 MW fire within a half an hour, the probability of collapse of the building above was estimated on 0.9. However, it cannot automatically be assumed that the probability of collapse of the building above infrastructure will decrease by a factor 8, when the resistant of the structure increase with a factor 8. Nonetheless, the effect of the fire-resisting layer, assuming that both the strong resistance effect of 8 times and the large withstand of high temperatures of the layer, can be determined; it is estimated that the reduction effects for the probability of structure collapses is approximately a factor 10 lower, which means that the probability of structure collapses in case of a 300 MW fire is approximately equal to 10^{-2}. Likewise, the probabilities of collapse of the building above can be determined of a 20 MW and a 5 MW fire. These are 10^{-3} and 10^{-4} respectively.

The investments of using thermal insulation vary between € 10 / m^2 for spalling from a maximum fire of 5 MW and € 100 / m^2 for spalling from a maximum fire of 300 MW (VCR, (2002)), which also depends on the concrete quality and the cover. If fire resistant plates are implemented in precast of concrete, then the cost will be approximately € 50 / m^2. Furthermore, it is important to note that maintenance of such a measure is essential for the durable effect of that measure.

Although applying thermal insulation is an outstanding measure for the people present in the building above and in the vicinity, no effect of this measure will be gained for people present in the covered infrastructure.

2.2 Additional (concrete) layer

One may use an additional layer for protecting the building above against fire occurring on the infrastructure beneath and visa versa. In order to prevent the spread of fire from the infrastructure to the building above, the layer should be enough massive. If the height of the concrete layer is set to be 1 meter and it is assumed that a fire on the infrastructure is burning for one hour, the temperature increase in the building will be 84°C. The effect of this measure is almost the same as the effect of the fire resistant layer. However, the fire resistance is now achieved from the massive floor. The disadvantage of this measure is that the massive floor may disrupt the view.

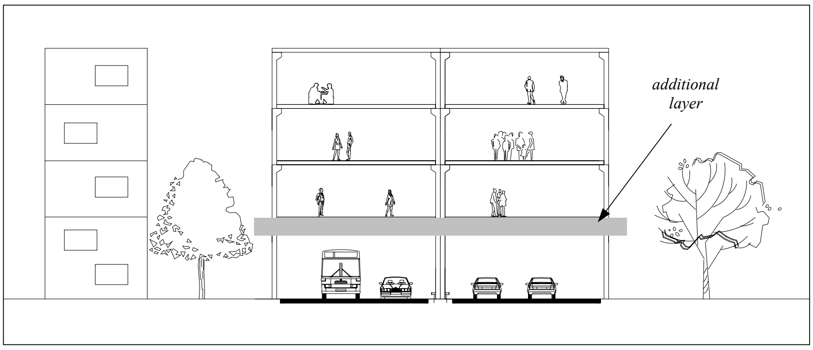

Figure 3. An additional layer between the covered infrastructure and the building above.

The risk reduction effect of this measure is less than the effect of a fire-resisting layer, because the additional layer does not protect the walls of the covered infrastructure. Therefore, it is assumed that the probability of collapse of the building above the infrastructure due to the additional concrete layer is a factor 5. This means that the probability of collapse of the building above the infrastructure given a fire of 300 MW fire is approximately equal to $5 \cdot 10^{-2}$. Likewise, the probabilities of collapse of the building above can be determined of a 20 MW and a 5 MW fire. These are $5 \cdot 10^{-3}$ and $5 \cdot 10^{-4}$ respectively.

The costs of implementing such measure - including labour costs - are in the order of magnitude of € 500 / m^3 concrete, thus € 500 / m^2 concrete (COBOUW, (2003)), because almost no extra investments have to be taken into account (Suddle, (2001[A])). This measure effects the risk dimensions (1), (2) and (4).

2.3 Sprinkler System

Sprinkler systems both in buildings and in the infrastructure beneath could be effective, in case of fire occurrence. The sprinkler system - consists of water pipe system - sprays directly water on the fire when detected. Although a complex detection system for fire occurrence is strongly required, the probability of spreading fire from the building to the infrastructure below and visa versa can be decreased. Sprinkler systems are highly regarded by fire protection professionals in buildings and fire departments because of their long successful history. Nonetheless, there is little experience with using sprinklers in tunnels or infrastructure covered by buildings. Arends, (2003) presented (dis)advantages for the evaluation of a sprinkler system in tunnels.

Generally speaking, it can be stated that there is little scientific data and experience with sprinklers in tunnels (see e.g. DARTS, (2002)). Though there are indications that the sprinkler system can be useful to reduce the aggravation of some scenarios. It may prevent a BLEVE resulting in a collapse of the tunnel (RWS, (2002)) and thus the building above; it can reduce effects of small fires, particularly when additives are used and it can gain time for the emergency crews to enter the tunnel. There are some signs that the sprinkler system may endanger people in the direct vicinity of the huge fire (Arends, (2003)). Another serious issue suggested by DTFHA, (2000) is the detection system needed for a sprinkler system. On one hand the reaction time must be very short, thus preferably automatic (RWS, (2002)). On the other hand, people close to the fire must have the opportunity to flee before the system gets activated. This means that both the detection and the sprinkler system must be very accurate. At the moment, none of the detection systems can comply with these demands.

Although there are only few data (sometimes contradicting) on sprinkler systems, more (field) research is needed. In this paper, the risk reducing effects of the sprinkler system are estimated in a simplified approach as follows. The sprinkler system can prevent a BLEVE, but cannot prevent an instantaneous explosion. Besides, for some fire types like pool fires by burning petrol, the sprinkler system may spread the fire to a large area. Since little is known about the mitigating effects of sprinklers for tunnel fires, this effect is not taken into account (in fact: some authors argue that the use of sprinklers in case of an accident can increase the risks since large amounts of smoke will be developed, (see e.g. Jonkman *et al.*, (2003)). Hence, a sprinkler system can prevent 90% of the BLEVE ’s (Arends (2003)). It was assumed that in case of a BLEVE the probability of building collapse above is equal to 0.9. From this point, the probability of collapse of the building above the infrastructure will be reduced by 90%. Another assumption concerning the material damage is made for this research. It is assumed that material damage in case of implementing a sprinkler system is 50% of the original situation.

The costs of a sprinkler system are estimated by Jonkman *et al.*, (2003), to be approximately € 10^7 / km tunnel. The estimation of these costs is predominantly based on experience data.

3. Measures against peak overpressure

3.1 Explosion resistant covering of infrastructure

According to Baker *et al*., (1983), there are two main types of explosions, namely a deflagration and a detonation, which may occur on the covered infrastructure. Considering the deflagration, the positive phase of the gas explosion is relatively long and the peak overpressure varies between 10 - 800 kPa (≅ 0.1 to 8.0 bar). While the characteristics of a detonation are that the positive phase of the gas explosion is relative short and the peak overpressure may reach a magnitude in the order of $2 \cdot 10^3$ kPa (≅ 20 bar). Without countermeasures, a gas explosion occurring in the covered infrastructure may cause demolition or severe damage of the building above. The design of countermeasures depends on the considered explosion type and thus on the loads on the structure. Nonetheless, one may consider structural countermeasures that reduce the effects of an explosion towards the building above. There are two main techniques to realise this. First, one may implement *explosion resistant structures* towards infrastructure or the building above, see e.g. the research about "optimal control of adaptive building structures under blast loading" done by Adeli & Saleh, (1998). Such structures will hardly be damaged and will be maintained after an explosion. The second option is to realise part of light structures designed to give up, also called the *explosion reduction measures*.

Considering the explosion resistant measure, one may imagine that such structures will consist of large dimensions. A very interesting measure against peak overpressure is packing the road and rail infrastructure in a steel tube with a diameter of e.g. 7.0 m and 12.8 m respectively. This will allow a profile of free space for double track traffic in that tube, which should be only used for transport of hazardous materials. The effect of such a tunnel is very large, because the effects of an explosion will merely be enclosed in the tunnel. Such a tunnel may prevent the following consequences of peak overpressure caused by a gas explosion. If the tunnel is constructed and designed appropriate, one may realise such tunnels particularly in densely populated urban areas where the problem of external safety occurs. However, some aspects should be carefully considered. First, the thickness of the tunnel-tube is large, which is difficult to realise. It depends of course on both the diameter and the occurring scenario in the tunnel. Secondly, large concentration of shock waves at both ends of the tube should extensively be analysed.

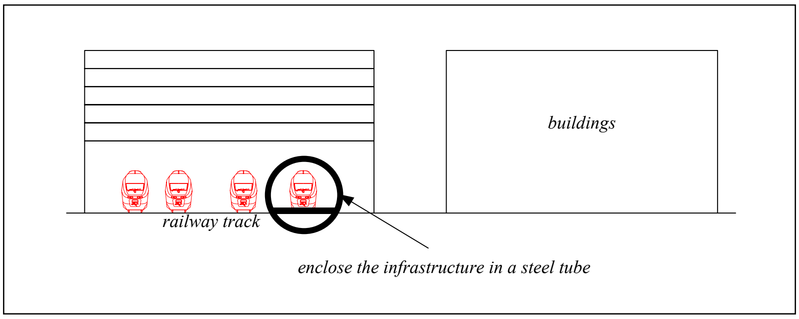

Figure 4. Enclosing the infrastructure in a steel tube.

In order to determine the thickness of the tunnel-tube, some basic calculations have been made using the literature AFESC, (1989) Baker *et al.,* (1983), NASA, (1975) and Biggs, (1964). It appeared that the thickness of the tunnel-tube is approximately 20 mm (diameter of 7.0 m) and 36 mm (diameter of 12.8 m) for a cloud explosion with the length of a cloud of 100 m and a peak overpressure of 10^3 kPa (≅ 10 bar) as mentioned by Berg *et al.*, (2001). If the detonation scenario is considered, the thickness of the tube will increase to 39 mm (diameter of 7.0 m) and 71 mm (diameter of 12.0 m). It also appeared that, given the peak overpressure of e.g. 10^3 kPa (≅ 10 bar), the dynamic effects of such a structure leads to a quasi-static design approach, because the ratio of the duration of the load and the response time of the structure (T_L/T_N) is large. Therefore, the design of that structure is based on a quasi-static approach including a DLF (Dynamic Load Factor) of 2, which has been discussed by both Biggs, (1964) and Baker *et al*., (1983). Furthermore, an assumption has been made that the steel will deform plastically instead of linear elastic behaviour of steel. As a consequence, welding the profile of the tunnel should be carefully considered (Rolloos *et al.*, (1996)).

The price of steel is normally about € 4 / kg, including realising costs (COBOUW, (2003)). It is assumed that these cost increases by a factor 2.5, in case of a large thickness of the tube. So, the price of steel is approximately € 10 / kg. From this, the total costs of the steel tunnel can be estimated, which are $10 \cdot \pi \cdot 0.020 \cdot 7 \cdot 7{,}800 \cdot 10^3$ = € 34,306,000 / km steel tube for roads to € 61,751,000 / km steel tube for double railways. If the design is based on the detonation scenario, the costs will be much higher (see Table I). The costs are remarkably high; they range in the order magnitude of a shield driven tunnel. In addition to this, if the traffic has to be lead in the tube, the costs of the realisation to lead the traffic in the tube by fly-overs and traffic junctions and interchanges should also be taken into account. If one needs to realise traffic junction on a different height level of the infrastructure on both ends, one has to make investments of € 75,000,000 / junction. Furthermore, this measure should not be implemented solely as well; additional fire resistant layer is required.

Table I: Thickness and the investments of profiles by different peak overpressures.

Peak overpressure	Radius *r* = 7.0m		Radius *r* = 12.0m	
	Thickness profile	Investments profile (km^{-1})	Thickness profile	Investments profile (km^{-1})
$1 \cdot 10^3$ kPa (≅ 10 bar)	20 mm	€ 34,306,000	39 mm	€ 66,900,000
$2 \cdot 10^3$ kPa (≅ 20 bar)	36 mm	€ 61,751,000	71 mm	€ 121,800,000

Considering the fact that the explosion is mostly enclosed into the tube, the probability that the building above or besides the infrastructure will collapse will be a factor 100 smaller, because of residual risks from heat radiation and external blast effects. It is clear that this measure is applicable for external safety variants, i.e. people present in the building above the infrastructure (risk dimension (1), (2), (4)), except the buildings or people present on the ends of the covered infrastructure. From this point, both ends of the covered infrastructure should be carefully analysed because a gas explosion in the covered infrastructure may cause damage to the building above or near the ends as well, because there is a large concentration of shock waves at both ends. Therefore, the building above the tube should be designed to resist the blast load or it should be realised with a large setback, otherwise the shock waves may damage the building above after all (see Figure 5). Furthermore, this measure is also applicable for other scenarios like release of toxic gasses and mechanical traffic accidents towards the building above. Note that the internal safety decreases in the tube (risk dimension (3)).

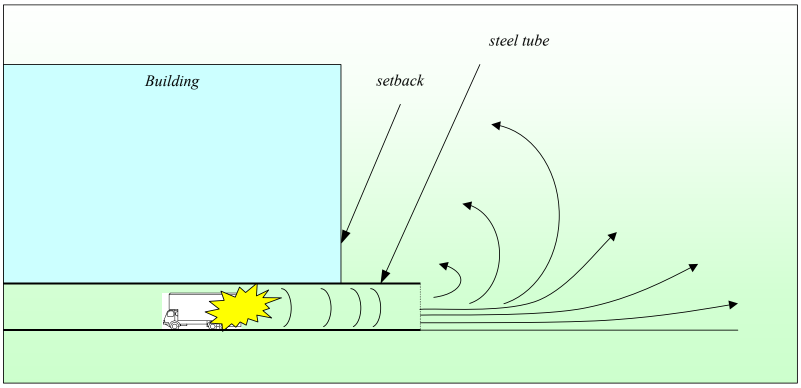

Figure 5. Damage may occur on both ends of a covered infrastructure.

One may realise an explosion resistant covering of infrastructure of concrete. However, some remarks can be quoted presenting that such a covering in concrete may fail. An extensive research has been presented by Veen & Blaauwendraad, (1983) on a dynamic elasto-plastic model for reinforced concrete members. In this study, a gas explosion in a tunnel is investigated. The study of Veen & Blaauwendraad, (1983) clearly shows that the dynamic response analysis of the tunnel roof, where the permissible value of $p_{max} = 2.5 - 5.0 \cdot 10^2$ kPa ($\cong 2.5 - 5.0$ bar) is found, results in shear failure. The tunnel in that study was a immersed-tube tunnel installed under a 2 m thick soil cover, a 10 m depth of water with a span of 15 m and resulted in a the roof which was 1,2 m thick. A tunnel without 2 m thick soil cover and 10 m depth of water, results in a 1.5 m thick roof with a permissible value of $p_{max} = 2.0 \cdot 10^2$ kPa ($\cong$ 2.0 bar). Hence, it can be concluded that without explosion reduction measures a rectangular shape of the covered infrastructure with regard to explosions is almost not feasible. Accordingly, cylindrical or spherical structures or structures with a form of an arc or a dome are much more effective to explosions, because the load distribution is much better than a rectangular structure in case of gas explosions. The structural design for spherical structures is treated by Biggs, (1964). However, considering the large peak overpressures, the effect will not be that much. Without countermeasures to reduce the explosion load a reinforced concrete structure will hardly be feasible.

3.2 Clap Roof

Another manner to minimise the effects of an explosion towards the building above may be realising part of light structures particularly designed to give up, also called explosion reduction measures. One of such light structures might be a clap roof in combination with strong sidewalls. The roof should be much weaker and lighter than the sidewalls, because only then the roof will directly be launched after an explosion. In this way, one may implement an air or a pressure release valve between the building and the infrastructure. This valve is not a real valve, but it can be a form of a light concrete layer or another light structure/plates (see Figure 6) that should be damaged or even collapse in case of an explosion as quickly as possible. This measure is most effective when the reaction time of the clap roof to open is much smaller than the pressure rise time. The condition is hard to meet and the feasibility depends on the type and severity of the explosion.

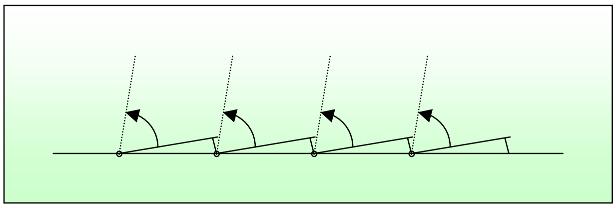

Figure 6. A clap roof with an ultra light structure; the plates will be sucked out in case of a gas explosion.

The clap roof should be carefully considered in the design. It should be noticed that an additional problems or scenarios might occur; suppose that the clap roof collapses in case of a pressure built up, the pressure piling in the layer of above the infrastructure building should be considered rigorously. On top of that, the released gas may form together a reactive mixture combustion gas in the building above, which may react as a second gas explosion. The building above may collapse after all. Hence, the second layer of the building above the infrastructure should be explosion resistant and sufficient openings in the sidewalls are necessary to release pressure outside the building (see Figure 7).

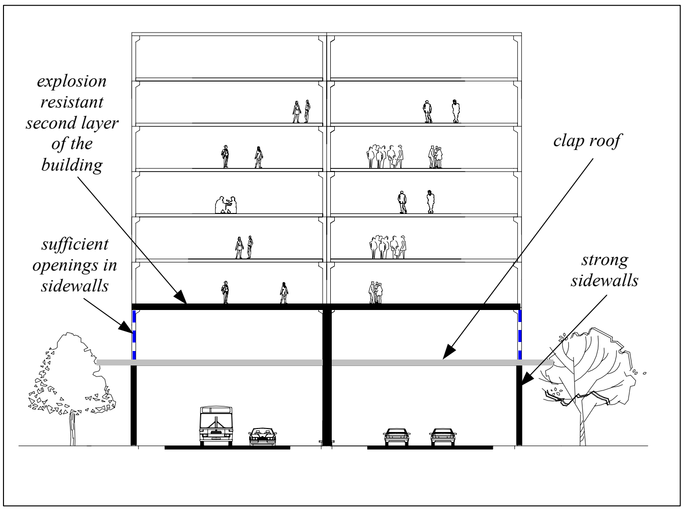

Figure 7. A clap roof between the covered infrastructure and the building above in combination with strong sidewalls and an explosion resistant second layer of the building.

Another point of discussion is that one has to consider the speed and thus the impulse caused by those launched fragments, which may lead to damage or collapse of the building above. In other words, the clap roof should be designed in virtue of pressure release, in order to minimise the pressure effects on the building above. Furthermore, it is important that there is enough space between the clap roof and the lowest story of the building and the weight of the clap roof is enough, because otherwise the clap roof may cause a domino effect on floors of the building as well and damaging the building. Combinations of extensive calculations, simulations and field research are needed to determine the optimal height of the non explosion resistant variant of the clap roof. The effect of the clap roof in case of an explosion is that the effect probabilities for the vicinity and the building above will not be improved in a large manner, than without implementing that measure, because the functioning of this measure is disputable. So, the probability in case of an explosion will be a factor 2 times less than in the begin situation.

The costs of implementing a clap roof are relatively low, let say in the order magnitude of € 200 / m^2 and investments for extra concrete (COBOUW, (2003)), because almost no extra investments have to be made (Suddle, (2001[A])). This measure effects the risk dimensions (1), (2) and (4) of chapter 1 regarding the peak overpressure.

3.3 Energy-absorbing measures

Other part of structures designed to give up, are energy-absorbing measures in covered infrastructure. One of the first field experiments regarding energy-absorbing measures in tunnels were carried out by RWS/OBB, (1982). This tunnel model was built at Beveren and was 27 m long with a square inner section of 1,80 x 1,80 m. RWS/OBB, (1982) discusses an overview of the investigations on energy-absorbing constructions in tunnels. Further, this report discusses same financial aspects and indicates in what direction supplementary investigations can be made. Although there is a huge lack of knowledge regarding energy absorbing measures, one should investigate the possibilities of such measures.

Other measure about which less is known can be *water mitigation* as an effective measure against explosions. The main advantage of such measures is that in case of an explosion, missile effects are eliminated, because water drops will be the missiles. However, there is hardly scientific knowledge for implementing such measures. The knowledge hereabout is obtained from experiments on small scale rather than 1:1 scale.

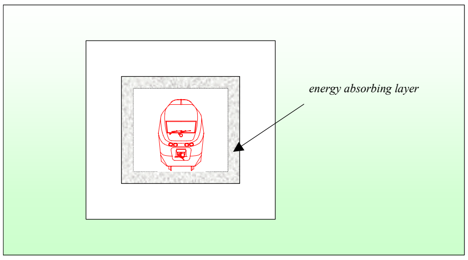

Figure 9. Energy absorbing layer in tunnels (section tunnel).

4. Measures against toxic loads

4.1 Covering the infrastructure with use of a water curtain or a barrier on both ends

Measures against toxic loads can be implemented to different areas; the building above the infrastructure, the infrastructure itself and the vicinity. The group risk caused by toxic loads, is the result of many buildings in a wide vicinity of infrastructure not having the proper measures so that people present in those buildings can easily be the victim due to intoxication.

In general, covering the infrastructure for an as long as possible distance, i.e. outside urban contours, can be a logic measure to enclose the effects of a hazard with transport of toxic materials. Closing barriers or a water curtain is vital on both ends of the covering length. The effect of such a measure is great. If one can realise that the toxic substance stays inside the covered infrastructure, one may have an almost exclusion of victims in the building above (risk dimension 2) and the vicinity (risk dimension 4) due to an accident in which toxic substances are released. It should be noted that the covering length should be as large as possible. The estimation of the probability of being killed due to such an accident with implementation of the considered measure in the vicinity will decrease with a risk level 2 on a logarithmic scale, which means the probability with of being killed given that toxic gasses may be released will be 10^{-2}. However, many victims can occur for people in the covered infrastructure (risk dimension 3).

The costs of such a measure, based on the detection system in the covered infrastructure and the barrier or a water curtain, are difficult to estimate, since there is hardly an application of such a measure. Covering the infrastructure for a long distance is more a measure from an urbanistic point of view and thus these costs cannot be determined.

4.2 Airproof buildings

In order to make air - possibly polluted with toxic released gasses - impenetrable towards the building above and in the vicinity, one may 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 till a certain level. As a result, most buildings are 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 as discussed in NEN, (1989). The q_{v10} ratio is the number of litres outside air penetrated in the building per second, so it is measured by (dm^3s^{-1}). Normal buildings are designed on base of a q_{v10} ratio of 80 dm^3s^{-1} (Wiersma *et al.*, (2003)). Yet, one can yield profit from the air permeability. If one can realise buildings with a q_{v10} ratio of 8 dm^3s^{-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 watchfully 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 Wiersma *et al.*, (2003)). The prise of such a measure is about € 50 /m^2. This can usually be integrated during the design stage of the project (Wiersma *et al.*, (2003)).

4.3 Airproof buildings with additional ventilation

In with some incidents with toxic gasses, such as hydrosulphide, the gasses remain for a long time on one certain location. By this, the probability of people killed by intoxication may increase. In addition to the previous measure, one can realise 100% airproof buildings, in which an additional 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 fresh air can enter the building, a 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 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 disables casualties through intoxication. Therefore, the effect is estimated to be that implementing the measure in question will save 99% of the people in the building.

Though the measure reflects a large risk reduction, the measure has some crucial disadvantages. First, the measure is quite expensive. It is shown in Wiersma *et al.*, (2003) that the investments for this measure are at least € 2,500,000 / per building of 30 x 30 x 10 m^3. This means that when implementing this measure for more buildings, it would be a large investment. Besides, implementing this measure means that a large number of building surface will be lost, because the ventilation system requires much space.

4.4 Gasmasks

Gasmasks are meant to enhance respiratory protection against chemical gasses, etc. Gas masks for emergency services and civilian use costs about € 300 /each. 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 increase the number of victims. The effect of gasmasks is theoretically estimated on 90% risk reduction, in which it is assumed that there is a good working detection and warning system. Besides, it is assumed that the people are trained in such situations.

5. Measures against mechanical accidents

5.1 Measure against collisions

In case of a collision occurs on the infrastructure and the traffic hits a column of the building above, the building above the infrastructure may collapse, causing large number of people killed in the building. In order to reduce the consequences of mechanical accidents on infrastructure hitting the bearing structure of the building above, one could implement a crash barrier (in case of roads) or derailment control (in case of railway tracks). The reduction of damage depends on the traffic type. A crash barrier is much effective for car collisions than for collisions with trucks. Therefore the reduction of probabilities is ranked in accordance with the type of traffic (see Table II).

Table II: The reduction of probabilities and the traffic type.

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

One may apply this measure in the design stage of a project. The prise of a crash barrier, used on motorways, is approximately € 20,000 / km (info: Bouwdienst Rijswaterstaat, Utrecht). The price of derailment control depends on the extra concrete needed to realise this measure. If the extra concrete is 2.0 m^2 on each side, than the costs will be approximately in the magnitude of € 2,000,000/km.

5.2 Structure of the building

In order to implement independent bearing structures for both building above and the covered infrastructure, one may realise no columns in the space of the infrastructure. The main advantage of implementing no columns on the infrastructure is that the probability of a collision of a train towards the main structure of the building will decrease with one risk level (a factor 10).

6. Integral approach of safety measures

If the safety measures are integrally considered, the probability (of failure) or risk reducing effect per measure and the average probability of an event should be compared with investments of that measure. In this regard the cost effectiveness of measures regarding the probability of failure is done for a typical building with covering length, span and height of 100 m, 20 m and 50 m respectively. In Table III, basic probabilities of scenarios are derived from Wiersma *et al.*, (2003). Furthermore, the reduction of a safety measure and the final probability given by Rd_{fi} and P_{fi} respectively.

From this table it becomes evident that measures like installing a sprinkler system or a steel tube are not cost effective. Safety measures like a fire resistant lining are much cost efficient. From a risk point of view, it is, therefore, efficient to implement measures with small investments resulting in a large probability or risk reducing effect. As a result, measures against fire protection and collisions in the infrastructure are strongly proposed to implement in multiple use of space projects.

Table III: The cost effectiveness of measures regarding the probability of failure.

Safety measures	**Fire protect. layer**		**Concrete layer**		**Sprinkler system**		**Steel Tube**		**Clap Roof**		**Airproof buildings**		**Airproof buildings & ventilation**		**Derailment control**	
Scenario i	Rd_{fi}	P_{fi}	Rd_{fi}	P_{fi}	Rd_{fi}	P_{fi}	Rd_{fi}	P_{fi}	Rd_{fi}	P_{fi}	Rd_{fi}	P_{fi}	Rd_{fi}	P_{fi}	Rd_{fi}	P_{fi}
1. Traffic collisions towards building P(scenario) = 10^{-7}	-	-	-	-	-	-	0.1	10^{-8}	-	-	-	-	-	-	0.1	10^{-8}
2. Fires P(scenario) = 10^{-6}	0.1	10^{-7}	0.5	$5\cdot10^{-7}$	0.1	10^{-7}	-	-	-	-	-	-	-	-	-	-
3. Leak of toxic substances P(scenario) = 10^{-9}	-	-	-	-	-	-	0.01	10^{-11}	-	-	0.1	10^{-10}	0.01	10^{-11}	-	-
4. Explosions P(scenario) = 10^{-8}	-	-	-	-	0.1	10^{-9}	0.01	10^{-8}	.5	$5\cdot10^{-7}$	-	-	-	-	-	-
Total P_f after measure	10^{-7}		$5\cdot10^{-7}$		10^{-7}		$2\cdot10^{-8}$		10^{-8}		10^{-10}		10^{-11}		10^{-8}	
Costs measure [€]	$4\cdot10^{5}$		10^{6}		10^{6}		10^{7}		$2\cdot10^{3}$		$6\cdot10^{5}$		$4\cdot10^{6}$		$2\cdot10^{5}$	
Risk interaction	(1), (2), (4)		(1), (2), (4)		(1), (2), (3), (4)		(1), (2), (4)		(2), (4)		(2), (4)		(2), (4)		(2), (4)	

An overview of the previous sections clearly shows that there are a large number of variations to implement measures against all kind of scenarios in multiple use of space projects. Yet, implementing individual or single measures is mostly expensive and less effective. Therefore, it is persuasively proposed that most safety measures should never be implemented individually, because the most individual measures are beneficial to one scenario, while for other scenarios they may have an opposite effect. As a consequence, it is utmost important to consider that the implementation of any measures should be in a combination with other measures e.g. measures from the safety chain or measures against other scenarios or e.g. measures fire protecting layer combined with measures like derailment control.

This paper also showed that safety measures against fires, release of toxic gasses and mechanical accidents against the main structure of the building above are easily realisable, while measures against explosions are more difficult to implement and to realise. So, one may concentrate on measure which unable to cause an explosion. Measures against explosions can be applied i.e., steel tube which can also be called the ”cannon barrel”. Implementing this measure is perhaps a progressive approach, since this measure enables the activities and accidents occurring on the infrastructure in the tube. By this, one may realise either buildings above or next to the infrastructure. However, the investments in such a measure are higher than investments in realising a shield driven tunnel. Although implementing the steel tube could be the basic solution for the external safety discussion in The Netherlands, the measure is too expensive and almost practically not realisable to implement and should be compared with e.g. rerouting the transport of hazardous materials through urban areas. Furthermore, the tube variant will mostly not harmonise with urban development. It should be noted that the explosion scenario belongs to the category of critical risks: low probability and high consequence. The outcome of the judgement of the cost effectiveness strongly depends on the kind of building, infrastructure and number of people involved in the accident. In the current paper a system is considered to illustrate the approach and tendencies in (cost) effectiveness of safety measures.

Considering the previous, it can be concluded that multiple use of space projects cannot be realised without safety measures. However, one should deliberate the investments of these measures with their probability or risk reducing effect. From this point, measures against fire on or collisions should be at least taken during the design stage of such projects.

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