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A state-of-the-art review of road tunnel subjected to blast loads

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Abstract: Road tunnels are critical components in road transportation networks. In their service life they may subject to explosion loads from terrorist bombing attacks, engineering blasting for construction and accidental explosions from transported flammable goods. These extreme loading conditions might not only lead to catastrophic damages to tunnel structures, severe casualties and economic losses, but also have immeasurable social impacts. Therefore, it is imperative for engineers, researchers and policy regulators to understand the performance of road tunnels under explosion loads towards a reliable blast-resistant design of tunnel structures. This paper presents a state-of-the-art review of dynamic response, damage assessment and damage mitigation of tunnels under blast loads. The common road tunnels, various explosion scenarios, and the corresponding blast wave characteristics are reviewed first. Then the dynamic response and damage characteristics of tunnel structures under blast loads including the analysis methods of tunnel response, types of tunnel response and key factors influencing tunnel response are reviewed and discussed. The assessment criteria of tunnel damage and the damage mitigation measures for tunnels against blast loads are also reviewed. Finally, concluding remarks and several key research areas for future work are presented.

Keyword: Road tunnel, explosion, blast response, damage assessment, damage mitigation

1. Introduction

Road tunnels, either buried, underground, under river or even subsea tunnels, are usually constructed as an important part of modern highway network to shorten the travel time within or between cities, reduce transportation costs, and improve traffic capacity (Cui, et al., 2015, Wang, et al., 2020). Based on open reports and literature, **Figure 1** (a) and (b) summarize the total number and mileage of road tunnels, respectively. By 2019, China has built 19067 road tunnels with the total mileage of 18966.6 km (MTPRC, 2020). With the foreseeable growth of transportation demand, road tunnels will be more intensively constructed worldwide and play increasingly vital roles in the transportation systems by virtue of its great advantage in overcoming physical barrier and minimizing local environment impact (Bassan, 2015).

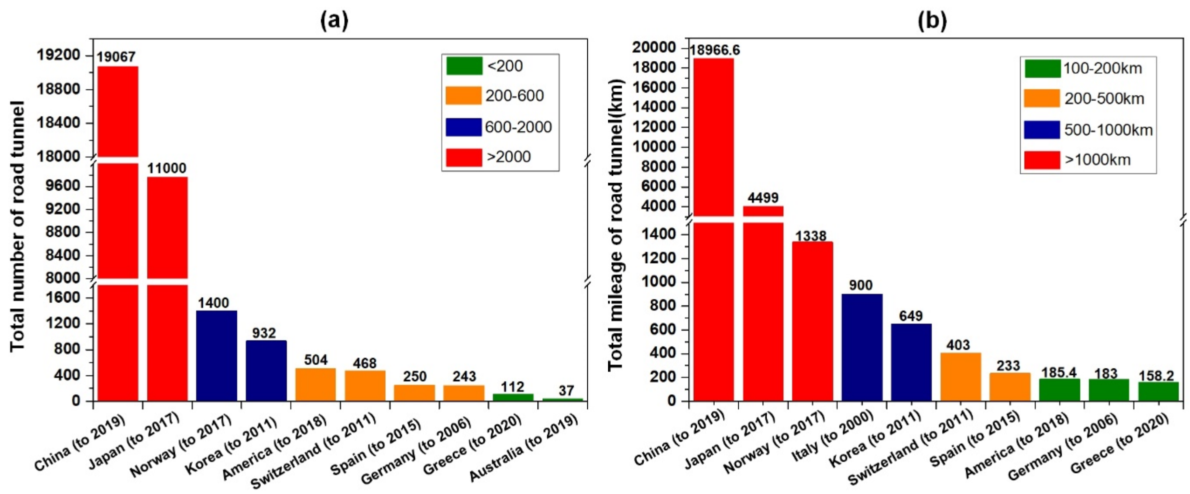
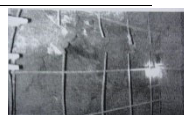


Figure 1. The total number and mileage of road tunnels. (a) the number of road tunnels, and (b) the mileage of road tunnels.

Road tunnels described as "traffic throats" or "choke points" are usually buried in various media (e.g. rock, soil and water) and are therefore in enclosed environment to connect open-air highway at both ends (TCRP86/NCHRP525, 2006). Some unexpected damage to a road tunnel can significantly and adversely affect or even disrupt the surrounding transportation network linked by the road tunnel. Hence, the safety issue of road tunnels has drawn more and more attentions from the local authorities to federal governments (Roberts, et al., 2003). During service life, road tunnels might be subjected to terrorist attacks, accidental explosions such as the explosion of transported flammable goods, or the blasting due to adjacent construction excavations, which might result in severe casualties, irreversible damage to tunnel structures and facilities. As reported by Masellis, et al. (1997), a tank-truck carrying 2500 litres of liquid petroleum gas (LPG) was hit by a coach car in a tunnel along the Palermo-Punta Raisi motorway (Italy) in March 1996, leading to a boiling liquid expanding vapour explosion (BLEVE) that caused 5 deaths, 34 injuries and severe damage to tunnel structures. It was also reported by Ingason and Li (2017) that a rear-end collision accident involving two methanol tankers occurred inside the Yanhou tunnel of China in 2014, inducing an explosion of a liquid methoxymethane tanker inside the tunnel 100 m from the entry portal. The explosion led to 52 casualties and destroyed 42 vehicles inside the tunnel. Some major accidental explosion accidents including BLEVE, Vapour Cloud Explosion (VCE) and high explosive (HE) blasting attacks from terrorists inside or in the vicinity of tunnels are listed in **Table 1**. Although it is seen in **Table 1** that the majority of terrorist attacks occurred in subway tunnels, many key road tunnels for the connections of adjacent important economic regions are also tempting attack targets, since the disruption of the road tunnels can hinder fluent cargo transportation and economic flows for a long time.

Table 1. Tunnel explosion incidents

Explosion type	Year	Name of Tunnel	Country	Cause	Consequence: Casualties	Consequence: Tunnel damage	Accident scene
Boiling Liquid Expanding Vapor Explosion (BLEVE)	1982 (Bangash and Bangash, 2005)	Salang tunnel	Afghanistan	Fuel truck explosion	1000-3000 deaths	Severe tunnel damage	 From (1) below
	1996 (Masellis, et al., 1997)	Palermo -Punta Raisi tunnel	Italy	LPG truck hit	5 deaths, 30 injuries	Severe tunnel damage	
	1999 (Auboyer, et al., 2007)	The Tauern tunnel	Austria	Fuel truck explosion	12 deaths, 48 injuries	Severe tunnel damage	
	2007 (McDaniel, 2017)	Newhall Pass Tunnel	United States	Car collision	2 deaths, 10 injuries	Severe tunnel damage (small explosion may occur)	
	2007 (Dix, 2012)	Burnley tunnel	Australia	Vehicle collision	3 deaths	Local tunnel damage	
	2011 (Lai, et al., 2016)	Qidaoliang tunnel	China	Truck tanker explosion	4 deaths, 1 injuries	Severe tunnel damage, local collapse	
	2012 (From (2) below)	Dimuan tunnel	China	Truck tanker explosion	5 deaths	Slight tunnel damage	
	2014 (Li, 2018)	Yanhou tunnel	China	Methanol vehicle collision	40 deaths, 12 injuries	Severe tunnel damage	
	2015 (From (3) below)	Skatestraum tunnel	Norway	Fuel truck trailer crashing into wall	-	Severe tunnel damage	
Vapor Cloud Explosion (VCE)	1993 (Nagao, et al., 1997)	Road tunnel in Tokyo	Japan	Methane leak from surrounding	4 deaths	NA	NA

	2005 (He, et al., 2019)	Dongjiashan tunnel	China	Methane leak from surrounding	44 deaths, 11 injuries	Severe tunnel deformation	
	2015 (He, et al., 2019)	Wuluolu tunnel	China	Methane leak from surrounding	7 deaths, 19 injuries	Severe tunnel collapse	
	2017 (He, et al., 2019)	Qishanyan tunnel	China	Methane leak from surrounding	12 deaths, 12 injuries	Severe tunnel collapse	
Highly-explosive Explosion (HE)	2005 (From (4) below)	London subway tunnel	British	Bomb attack	52 deaths, 700 injuries	Severe tunnel damage	
	2010 (Li, 2018)	Moscow metro Tunnel	Russia	Bomb attack	41 deaths, 120 injuries	Severe tunnel damage	
	2011 (From (5) below)	Minsk Metro tunnel	Belarus	Bomb attack	12 deaths, over 200 injuries	Severe tunnel damage	
	2012 (From (6) below)	Yanru tunnel	China	Highly-explosive explosion	20 deaths, 2 injuries	Severe tunnel damage	
	2012 (Yan, et al., 2019)	Lvliang tunnel	China	Highly-explosive explosion	8 deaths, 5 injuries	Severe tunnel damage	

Note: website (1):https://devastatingdisasters.com/salang-tunnel-fire-1982/;
(2):http://hunan.sina.com.cn/news/b/2012-10-07/081019665.html;
(3):https://www.youtube.com/watch?v=vqt-cC3Y4OU;
(4):https://www.mylondon.news/news/nostalgia/gallery/pictures-look-back-77-london-18555867;
(5):https://www.youtube.com/watch?v=KWE2aGdpNuo;
(6): http://www.china.com.cn/news///node_7153238.htm

The blast-resistant capacity of reinforced concrete (RC) lining structures of road tunnels is of great significance to prevent road tunnels from the fatal damage under intensive explosion loads. However, the existing design guidelines or manuals of road tunnels, as listed in **Table 2**, barely consider the effect of explosion loads on structural response despite intensive damages to many tunnels as partially listed in Table 1. Some design guides such as UFC 3-340-02 (US Department of

Defense, 2008) and ASCE/SEI 59-11 (ASCE, 2011) provide design guidelines and recommendations for the blast resistance of RC structures for buildings and bridges. It should be noted that the response of RC tunnel structures subjected to blast loads is more complex owing to the interaction between the buried tunnel structure and its surrounding media (Weidlinger and Hinman, 1988). So far, designers and engineers of road tunnels still lack necessary guideline to estimate the vulnerability of tunnel structures under explosion loads although some research works have been carried out and results reported in literature. This paper presents a comprehensive review of the existing literature on the dynamic response, damage assessment and damage mitigation of tunnels subjected to explosion loads, which will help researchers and tunnel engineers to better understand the current research status and understanding of the dynamic behaviours of road tunnels subjected to explosion loads.

Table 2.Design guidelines and manuals of road tunnels.

Guideline	Country	Agency	Remarks
Design Criteria for Bridges and Other Structures. Part C: Tunnels (DTMR, 2020)	Australia	Department of Transport and Main Roads	Static loads, fire and heat loads, traffic loads, etc.
Guide to Road Tunnels. Part 2: Planning, Design and Commissioning (Austroads, 2019)	Australia and New Zealand	Austroads	Static loads, fire and heat loads, traffic loads, seismic loads, etc.
Specifications for Design of Highway Tunnels Section 1 Civil Engineering (MTPRC, 2018)	China	Ministry of Transport of the People's Republic of China	Static loads, structural loads, heat loads, frost heave forces, seismic loads, etc.
Technical Standard for Structure Design of Road Tunnel (JRA, 2003)	Japan	Japan Road Association	Static loads, traffic loads, seismic loads, etc.
Guideline for Design of Road Tunnel (RDA and JICA, 2018)	Japan	Japan International Cooperation Agency	Static loads, seismic loads, traffic loads, etc.
(Manual 021) Road Tunnels (NPRA, 2004)	Norway	Norwegian Public Road Administration	Static loads, wind loads, fire loads, frost loads, etc.
Design Manual for Roads and Bridges, Part 9, Section 2 of Volume 2, Design of Road Tunnels (UKHA, 2000)	United Kingdom	UK Highways Agency	Static loads, traffic loads, fire loads, etc.
Tunnel lining design guide (BTSICE, 2004)	United Kingdom	The British Tunnelling Society and The Institution of Civil Engineers	Static loads, seismic loads, fire loads, temporary construction loads, etc.
FHWA Road Tunnel Design Guidelines (USDTFHA, 2004)	United States	U.S. Department of Transportation Federal Highway Administration	Static loads, construction load, seismic load, fire loads, etc.

Technical Manual for Design and Construction of Road Tunnels-Civil Elements (USDTFHA, 2009)	United States	U.S. Department of Transportation Federal Highway Administration	Static loads, traffic loads, seismic loads, wind loads, ice loads, etc.

This review paper summarizes the current research status and recent advances on the road tunnels subjected to explosion loads. The structure of this paper is organized as follows: Firstly, the common road tunnels, various explosion scenarios, and the corresponding blast wave characteristics are reviewed in Section 2 and 3. Next, dynamic response and damage of tunnel subjected to blast loads involving the analysis methods of tunnel response, types of tunnel responses, and key factors influencing tunnel responses are included in Section 4. Then, the assessment criteria of tunnel damage are summarized in Section 5, followed by damage mitigation measures for tunnels against blast loads in Section 6. At last, concluding remarks and several necessary key research areas for future work are presented in Section 7.

2. Overview of common road tunnels

A typical road tunnel consists of the main body tube and the portal of tunnel. **Figure 2** shows three typical cross sections of the main body tube. Their advantages, disadvantages and applicable geological conditions are summarized in **Table 3**. In the longitudinal direction, the portals at both ends of the road tunnel might extend outward a certain distance from the buried medium and expose to free air, while the main body tube of the road tunnel is usually buried in different media, i.e., rock mass, soil and water. Accordingly, road tunnels could be divided into three categories, i.e., tunnels in rock mass, tunnels in soil and tunnels under water. Meanwhile, the road tunnels under water can be further divided into two categories, i.e., tunnels in water (tunnels submerged or floated in water or the bottom of water) and tunnels below water (tunnels buried in soil or rock mass under water). It should be noted that one tunnel might run across different buried media. As reported in Shirlaw, et al. (2000) and Zhao, et al. (2007), both Kranji tunnel and the tunnel along North East line in Singapore run across rock mass and soil along their respective routes.

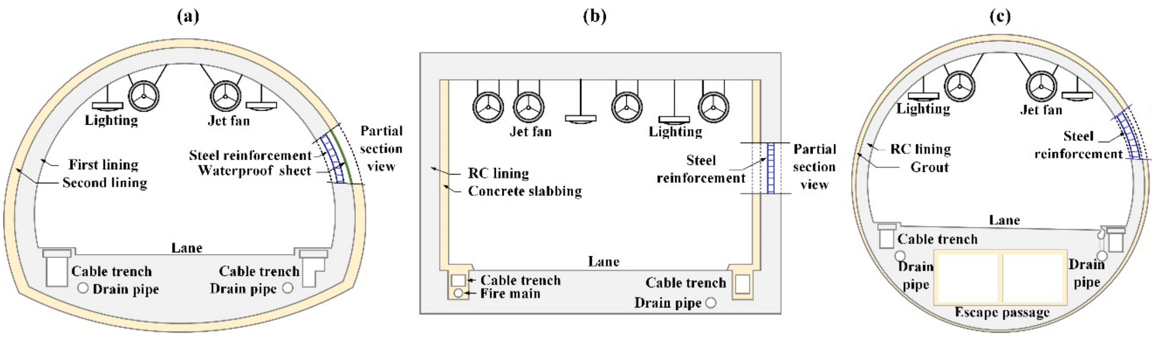


Figure 2. Typical cross sections of road tunnel with (a) arched shape, (b) rectangular shape, and (c) circular shape.

Table 3. Summary of typical three cross sections of tunnel

Cross section	**Advantage**	**Disadvantage**	**Applicable geological conditions**	**Ref.**
Rectangular	High utilization rate of inner space as traffic tunnel	Poor self-stability and weak resistance to surrounding pressure	Shallow soil layer with low static pressures	(AASHTO, 2012, USDTFHA, 2009)
Circular	Good self-stability, low ground settlement	Low utilization rate of inner space as traffic tunnel	Shallow buried soil near dense buildings, deep buried soil and rock mass with high overlying and side pressures	
Arched	Moderate self-stability with moderate inner utilization rate	Low resistance to high side pressures of tunnel surroundings	Deep buried soil and rock mass with high overlying pressures and moderate or low side pressures	

According to the design manuals of road tunnel in **Table 2**, road tunnels in different media, i.e., rock mass, soil and water are usually excavated by using their respective favourite excavation methods and thus different cross section shapes are formed. The details are showed in **Figure 3**(a) and (b). As shown in **Figure 3**(c), three lining types, i.e. segmental lining, composite lining and monolithic lining are correspondingly selected for road tunnels depending on the used excavation methods. The segmental lining consists of single segment and connecting joints between segments, where the single segment is composed of RC material. The composite lining mainly comprises the first lining and the secondary lining, where the first lining is usually composed of shotcrete with anchors and rebar nets, and the second lining normally consists of RC material. Meanwhile, the monolithic lining is composed of RC materials. In urban or suburb areas, due to the limitation of underground space, the neighbour tunnel, multi-cell tunnel and branching-out tunnel are commonly seen (see **Figure 3**(d)). For the neighbour tunnel, based on the relative positions of two tunnels, they can be categorised into three types, i.e., parallel tunnels at different levels, parallel tunnels at the same level and diagonal tunnels at different levels (see **Figure 3**(e)).

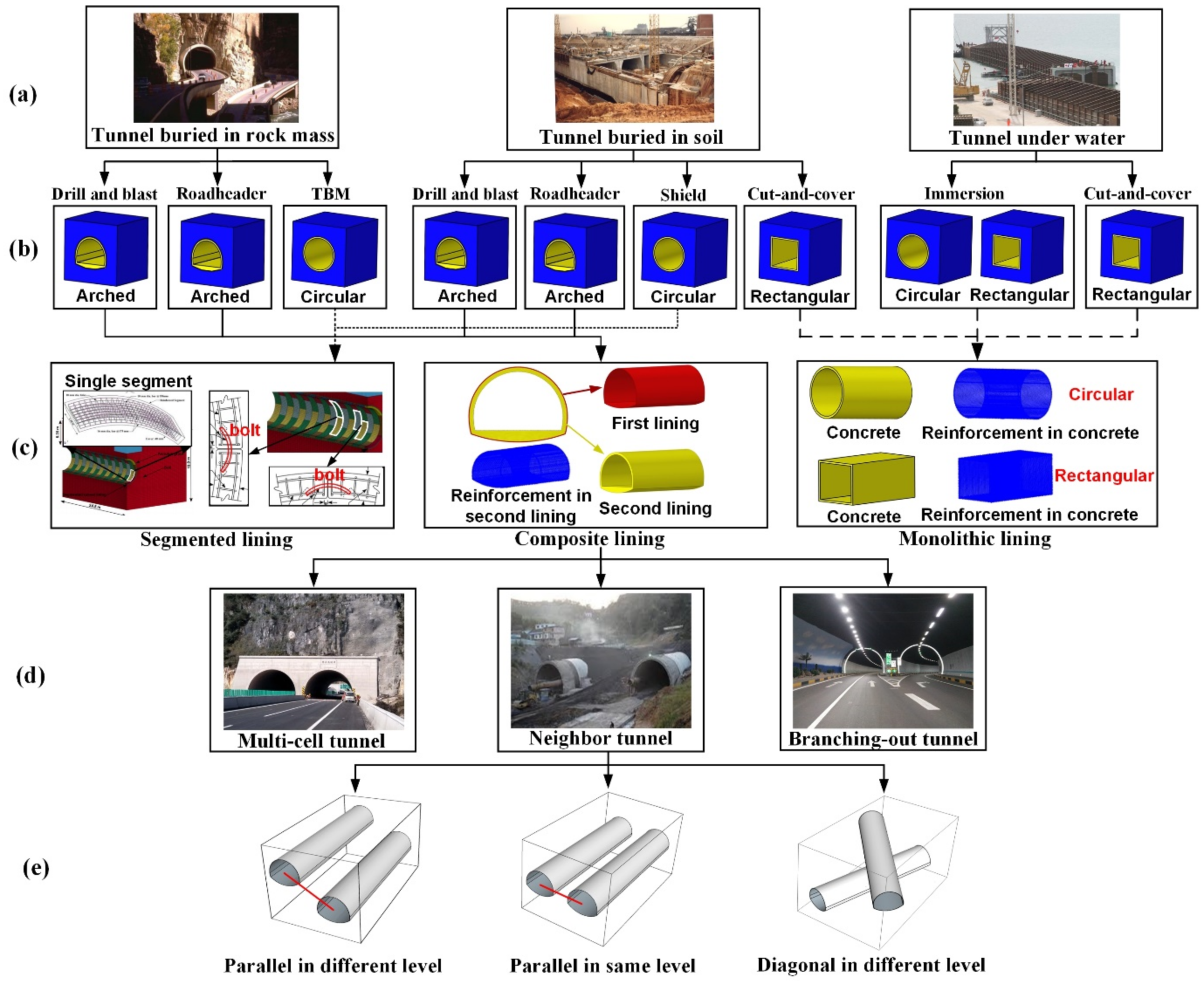


Figure 3. Summary of common road tunnels. (a) road tunnels buried in different media (Photos from USDTFHA (2009)), (b) excavation methods and cross-section shapes of road tunnels, (c) lining forms of road tunnels, (d) special forms of tunnel layouts, and (e) different layout forms for neighbour tunnels

3. Overview of possible explosion threats to tunnels

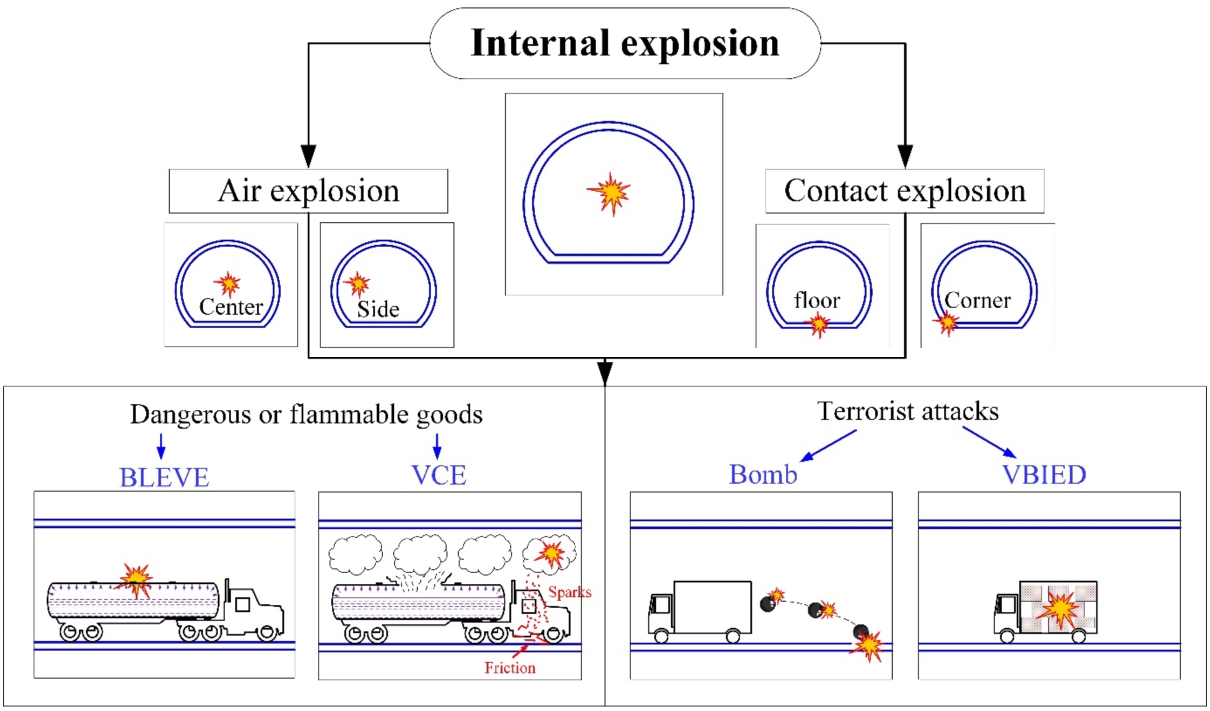
3.1. Explosion threat categories

The explosion threats to road tunnels during operation mainly result from three different sources, i.e., accidental explosions of flammable materials (e.g. flammable gas and volatile pressurized liquid) during transportation, terrorism or military bombing and construction blasting from adjacent site. Since these explosions may occur inside or in the vicinity of road tunnels, the explosions can be divided into two categories, i.e. internal and external explosions (see **Figure 4**) depending on the explosion locations.

As shown in **Figure 4**(a), the internal explosions can be further divided into internal air explosion (i.e. explosion in the air space of road tunnels) and internal contact explosion (i.e. close-in explosion on the wall or surface of road tunnels). Compared to the engineering blasting, the explosion of flammable materials and terrorist attacks are more likely to cause internal explosions. For instance, if a tanker truck carrying flammable materials (e.g., Liquefied Natural Gas (LNG) and Liquefied Petroleum Gas (LPG)) collides with another vehicle, or hits tunnel wall, the internal explosions of boiling liquid expanding vapour explosion (BLEVE) and vapour cloud explosion (VCE) are very likely to be triggered. In addition, with the rising terrorism activities, road tunnels are also confronted with the potential threats from improvised explosive devices such as the vehicle-borne improvised explosive devices (VBIEDs) and the suitcase bombs.

As shown in **Figure 4**(b), the external explosions can be subdivided into external surface explosions (i.e., explosions on the ground near road tunnels) and external buried explosions (i.e. explosions in buried media near road tunnels). In city, terrorist attacks are more likely to occur on or near the ground surface of tunnels, thereby being deemed as the external surface explosions of shallow urban road tunnel. Meanwhile, road tunnels may face the threats of hostile military attacks, where most missiles could penetrate the ground and explode below ground surface to result in external buried explosions. In addition, the engineering blasting, such as the demolition blasting of adjacent building, or the blasting excavations of urban foundation pit and underground chamber near existing road tunnels, might act as external surface explosion or buried explosion that can potentially threaten road tunnels.

(a)



(b)

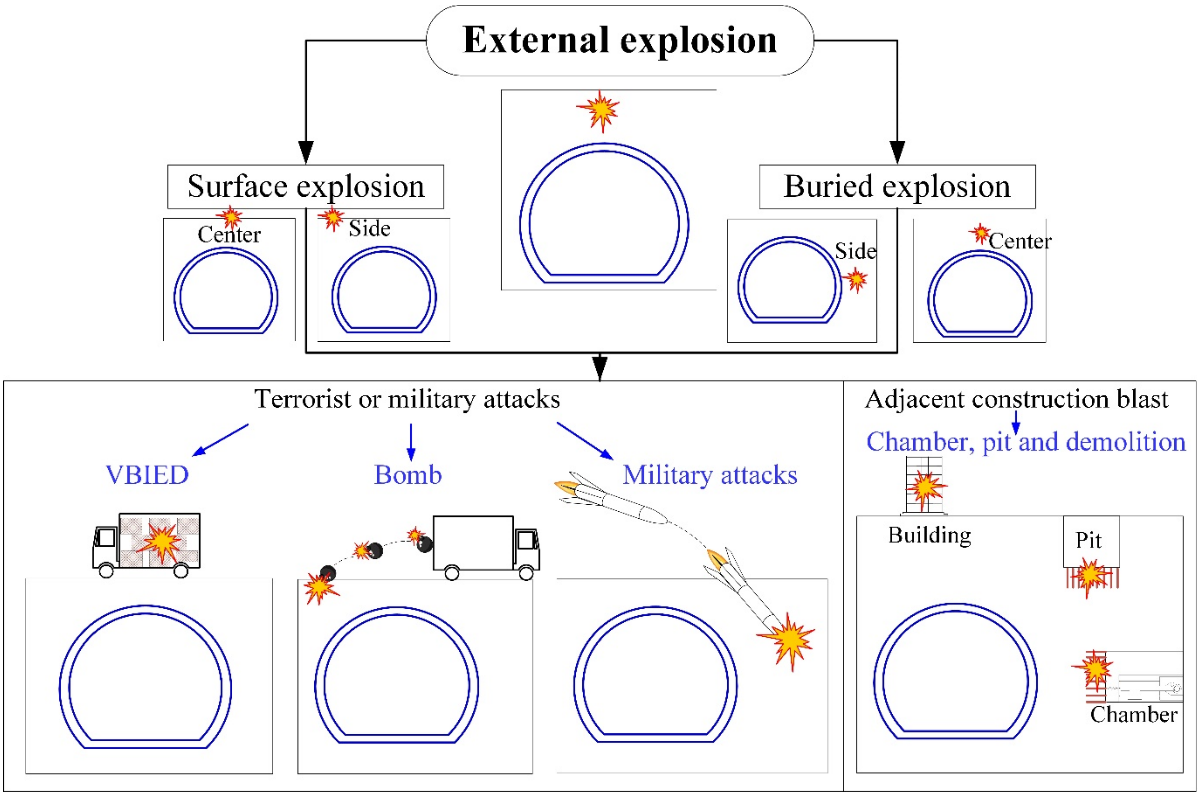


Figure 4. Types of explosions threaten road tunnels. (a) internal explosion, and (b) external explosion.

3.2. Characteristics of explosion pressure and blast wave around tunnels

Terrorist bombing, military attacks and engineering blasting are mostly associated with high explosives, whereas gas explosions are resulted from gaseous material with slower chemical reaction than that of high explosives. Therefore, compared to high explosives, the blast waves generated by gas explosions are different (Birk, 2017). As shown in **Figure 5**, the high explosive generates much steeper blast wave than gas explosion. The pressure of high explosive instantaneously increases to the peak incident pressure P_i (as seen in **Figure 5** (a)), while the blast waves of gas explosions (as seen in **Figure 5** (b) and (c)) gradually increase to the maximum pressure P_i. In order to further illustrate the difference between high explosive explosion and gas explosion, the characteristics of the BLEVE loading in **Figure 5**(b) and its TNT equivalent loading characteristics are compared in **Table 4**. Gas explosions usually generate blast waves with lower peak overpressures but longer duration and higher impulses than those of high explosive explosion with the same TNT equivalency (Hao, et al., 2016). Compared to high explosive explosion, the lower peak pressure and slower rising time of gas explosion can reduce the instantaneous shear stress in tunnel structures and the risk of crushing damage on tunnel structures, while the longer duration and higher impulsive are prone to induce severe bending deformation and thus increase the risk of tensile damage.

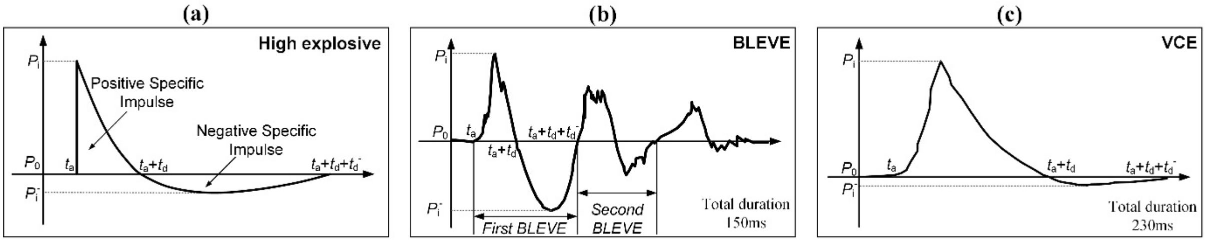


Figure 5. Typical blast loads from (a) high explosive (US Department of Defense, 2008), (b) BLEVE (Birk, et al., 2007), and (c) VCE (CCPS, 2010), respectively. P_0 represents the ambient pressure. P_i, and P_i^-, represent the maximum positive and negative peaks of incident pressure, respectively. t_a, t_d, and t_d^- represent the arrival time of incident wave, the positive duration of wave, and the negative duration of wave, respectively.

Table 4. The blast loading characteristics of gas explosion and high explosive explosion

Explosion type	**Peak pressure**	**Rising time**	**Positive duration**	**Negative duration**	**Total duration**
Gas explosion	About 9 kPa	About 12 ms (First BLEVE)	About 38 ms (First and second BLEVE)	About 45 ms (First and second BLEVE)	About 83 ms (First and second BLEVE)
High explosive explosion	About 14 kPa	Almost instantaneous	About 10 ms	About 28 ms	About 38 ms

Note: TNT equivalent loading characteristics are obtained based on UFC 3-340-02 (US Department of Defense, 2008)

The blast loads acting on tunnel structures could be generated in different media such as air, soil, and water, etc. The characteristics of blast loads in different media are different. Taking the high explosive as an example, the blast load in air domain has the profile as shown in **Figure 5**(a) (US Department of Defense, 2008), while the blast loads in water consist of shock front followed by a series of pressure pulses which are caused by subsequent oscillations of bubbles (Wang, et al., 2020), as shown in **Figure 6**(a). The blast load in the solid medium (soil or rock mass) could rise quickly near the explosion source, similar to the blast load in air (Vivek and Sitharam, 2018). However, as the shock front propagates in the solid media, it rapidly attenuates to a lower intensity stress wave with a gradual decrease in peak pressure (Vivek and Sitharam, 2017). A typical pressure time history of blast load with a non-instantaneous rise in solid medium can be found in Lu, et al. (2005), as shown in **Figure 6**(b).

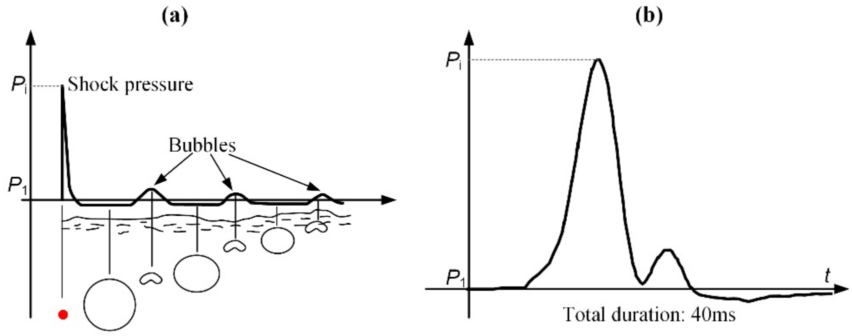
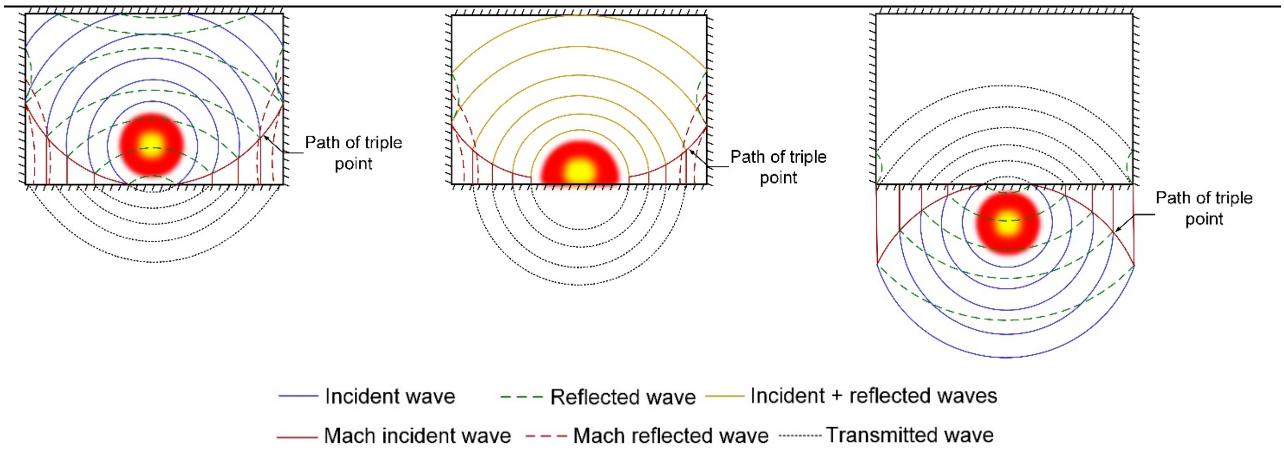


Figure 6. Blast pressure-time histories in (a) water (Swisdak Jr, 1978), and (b) solid medium (Lu, et al., 2005). P_i is the positive peak pressure, P_1 is the ambient pressure.

When the explosion occurs inside or outside the tunnel, the reflected and transmitted blast waves interact each other. A rectangular tunnel is taken as an example to illustrate the behaviours of blast waves inside and around the tunnel under internal and external explosions, as shown in **Table 5**. For the scenario of internal air explosion, when initial blast incident waves encounter the closest tunnel wall, the reflected and transmitted blast waves are formed simultaneously. The reflected blast waves continue to propagate in the tunnel, and the transmitted blast waves continue to propagate outwards in the medium around tunnel. When the reflected blast waves reach the other sides of tunnel wall, the reflected waves re-reflect again, thereby resulting in multiple pressure peaks inside the tunnel. In addition, Mach fronts could be also formed at the closest tunnel wall due to the interaction of the initial blast waves with the reflected blast waves. As Mach waves continue to propagate along the tunnel wall and to impinge other tunnel walls, the reflected Mach waves may be formed. For the scenario of internal contact explosion, the generated Mach waves are similar with the Mach waves of internal air explosion. However, unlike the internal air explosion, the reflected waves from the internal contact explosion merge with the incident waves at the point of detonation source to form single waves with hemispherical shape, which yields higher blast pressure and impulse. For the scenario of external explosion, when the initial blast waves arrive at the closest tunnel wall, most blast waves are reflected into surrounding medium and only a small portion of blast waves are transmitted into the inner tunnel. Although the transmitted waves continue to propagate and reflect in tunnel, the damage of the transmitted wave to tunnel could be negligible due to the low loading intensity.

Table 5. Blast wave propagation inside and in the vicinity of tunnels

Internal air explosion	Internal contact explosion	External explosion



4. Response and damage of tunnel subjected to explosion load

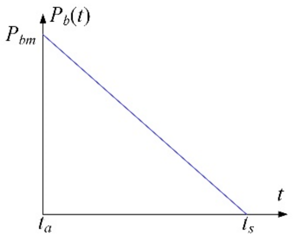
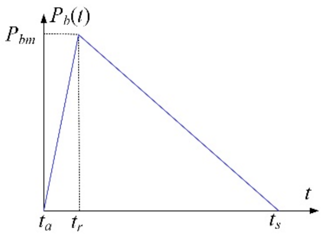
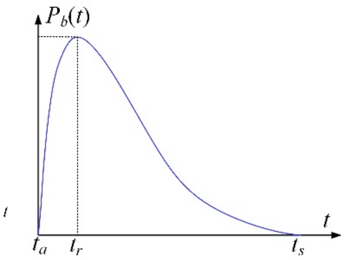
4.1 Analysis methods of tunnel response under explosion

Analysis methods of tunnel responses under explosions can be divided into three categories, i.e., theoretical methods, experimental methods, and numerical methods, as described below.

4.1.1 Theoretical methods

Three analytical methods based on Fourier transform (Li and Li, 2018, Li, et al., 2018, 2020, Tao, et al., 2019), Laplace transform (Gao, et al., 2013, Senjuntichai and Rajapakse, 1993), and modal superposition (Chen, et al., 2013a, 2013b, Ma, et al., 2010) to investigate the tunnel response under blast loads could be found in the literature. Two forms of blast loads, i.e., simplified triangular loads (e.g., right and non-right) and equivalent exponential loads were commonly used in the analytical methods. Their expressions are given in **Table 6**. The governing formulae, advantages, and shortcomings of three analytical methods are summarized in **Table 7**. The first analytical method based on the Fourier transform technique could convert the steady-state response of tunnels under harmonic waves into the transient response of tunnels subjected to blast loads by using Fourier transform and its inversion. The second analytical method based on the Laplace transform first calculates the transient response of tunnel in Laplace domain. The solution in Laplace domain is then converted into time domain by the inverse Laplace transform. In the existing studies, the Fourier transform technique was commonly used to solve the transient response of unlined tunnel (i.e., without the lining-surroundings interaction) against external explosions, while the Laplace transform was often employed to analyze the dynamic response of lined tunnel (i.e., with lining-surroundings interaction) subjected to internal explosions. In fact, both Fourier transform and Laplace transform techniques can be applied to study the dynamic response of tunnels subjected to internal explosion and external explosion scenarios with or without lining-surroundings interaction. The challenges are that the direct inversions of Fourier transform and Laplace transform are usually difficult or sometimes not available owing to complex integral paths and possible singularity during inversion. Accordingly, the algorithms such as the Trapezoidal Approximation technique (Li, et al., 2018) for Fourier transform and the Durbin's formula (Gao, et al., 2013) for Fourier transform and the Durbin's formula (Gao, et al., 2013) for Laplace transform are developed to numerically solve the inversions in order to obtain approximate results. Unlike the above two methods, the analytical method based on modal superposition does not require the difficult inversion procedure and solves the transient response of tunnel against explosions with the superposition of various modal response results. However, high-order modal results of tunnel structural response are usually neglected in this analytical method for fast and easy calculation. Hence, the accuracy of this analytical solution is also limited.

Table 6. The most used blast loading types in analytical methods of dynamic response of tunnel

Blast loading types	Graphs	Equations	Ref.
Simplified right triangular load		$P_b(t)=\begin{cases}0 & ,t<t_a \\ \dfrac{t_s-t}{t_s-t_a}P_{bm} & ,t_a\le t<t_s \\ 0 & ,t_s\le t\end{cases}$	(Ma, et al., 2010)
Simplified non-right triangular load		$P_b(t)=\begin{cases}0 & ,t<t_a \\ \dfrac{t}{t_r-t_a}P_{bm} & ,t_a\le t<t_r \\ \dfrac{t_s-t}{t_s-t_r}P_{bm} & ,t_r\le t<t_s \\ 0 & ,t_s\le t\end{cases}$	(Li, et al., 2018)
Equivalent exponential load		$P_b(t)=\begin{cases}0 & t<t_a \\ e^{\frac{\alpha}{\beta}\mathrm{acrtan}\left(\frac{\beta}{\alpha}\right)}\sqrt{1+\left(\frac{\beta}{\alpha}\right)^2}\cdot e^{-\alpha t}\sin\beta t & \alpha\ge 0\ ,\ t_a\le t<t_r \\ e^{\frac{\alpha}{\beta}\left(\mathrm{acrtan}\left(\frac{\beta}{\alpha}\right)+\pi\right)}\sqrt{1+\left(\frac{\beta}{\alpha}\right)^2}\cdot e^{-\alpha t}\sin\beta t & \alpha\le 0\ ,t_r\le t<t_s \\ 0 & t_s\le t\end{cases}$	(Tao, et al., 2019)

Note: $P_b(t)$ represents the blast loading time history, P_{bm} is the peak pressure of the blast loading, t_a, t_r and t_s are the arrival time, the rising time and total time of the blast loading, respectively. Where β is equal to π/t_s, α is determined by $\beta\cot\beta t_r$.

Table 7. Summary of three analytical methods

Method	Key governing formulae	Advantage	Disadvantage
Based on Fourier transform	$g(H_i,t)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty}\chi(H_i,\omega)F(\omega)e^{-i\omega t}d\omega$ $g(H_i,t)$: The transient response of tunnel $\chi(H_i,\omega)$: The steady-state response of tunnel with a specific frequency ω $F(\omega)$: Transformed Fourier form of blast load	Bridging the gap between the steady-state and transient response	Complex integral paths, difficult direct inversion of Fourier transform
Based on Laplace transform	$\frac{\partial^2\overline{\varphi}}{\partial r^2}+\frac{1}{r}\frac{\partial\overline{\varphi}}{\partial r}=\frac{s^2}{c^2}\overline{\varphi}$ s: Transform parameter c: Propagation speed of blast wave in medium r: Travel distance of blast wave in medium $\overline{\varphi}$: Laplace transform of potential function φ of displacement	Using transform function to reduce the difficulty of solving differential equation	Difficult or sometimes not available for direct inversion of Laplace transform
Based on modal superposition	$w(x,t)=\sum_{n=1}^{+\infty}W_n(x)q_n(t)$ $w(x, t)$: The transient response of tunnel $W_n(x)$: The n^{th} mode shape $q_n(t)$: The n^{th} generalized modal coordinate	Not requiring complex inversion	Simple linear superimposition, usually only superimposing several low-order modal results

The intensities of shock and stress waves induced by close-in explosions usually far exceed the strength of tunnel structures, causing plastic response of tunnel structures. However, the above three analytical methods for the tunnel response under blast loads are based on the theory of elastic wave. Hence, the analytical solutions derived by the elastic wave theory are not suitable for the response analysis of tunnel structures subjected to close-in explosions. Moreover, both tunnel and buried media material need be homogeneous and isotropic in the analytical methods, whereas the concrete and surrounding media around tunnel are actually heterogeneous. Hence, the aforementioned analytical solutions do not necessarily give accurate predictions of blast response of tunnel.

4.1.2 Experimental methods

Experimental methods including field and laboratory tests are another approaches to investigate the dynamic response and damage of tunnel structural elements under explosion loads. The experimental tests can be classified into two categories based on the model size, i.e., the full-scale tests and the scaled-down tests. **Table 8** summarizes some typical experimental tests of the tunnel responses under blast loads. Test methods, test instruments in experiments, and their corresponding advantages and disadvantages are summarized in **Table 9**.

For internal explosions in tunnel, limited full-scale tests have been conducted to investigate the behaviour of tunnels subjected to explosion loads. One representative internal full-scale explosion test conducted by Zhao, et al. (2016) investigated the dynamic response and damage of a segmental lining tunnel under an internal high explosive explosion, as listed in **Table 8**. The test investigated the response of tunnel lining under the eccentric detonation via the full-scale test. Apart from this study, some other full-scale internal explosion experiments such as blasting induced vibration tests inside tunnel (Ansell, 1999, Deng, et al., 2020) and internal explosion tests of ammunition storage tunnel (Joachim, 1990, Zhou, 2011) were also reported in open literatures. Unlike the scarcity of internal explosion scenarios, many full-scale external explosion experiments have been carried out by surface pit blasting (Duan, et al., 2018, Jiang and Zhou, 2012, Shin, et al., 2011) and underground cavern blasting (Liang, et al., 2012, Xia, et al., 2013, Zhao, et al., 2015) near tunnels to investigate the dynamic response of tunnel against external explosion loads.

Compared to full-scale tests, more scaled-down tests were conducted over the past decades to investigate the response of tunnels under different explosion scenarios. These scaled-down tests are divided into two categories depending on whether the centrifuge device was utilized or not. On one hand, many scaled-down tests have been conducted without using the centrifuge device. Blast loads were generated by using high explosives (Chen, et al., 2014, 2015, Krone, 2018, Xie, et al., 2014, Zhou, et al., 2020), ignited flammable materials (Groethe, et al., 2007, Meng, et al., 2020a, 2020b) or blast simulating generators (Kiger, et al., 1989, Smith, et al., 1986, Tener, 1964) to investigate the blast response of the scaled-down tunnels. Typical interaction processes between blast shock waves and tunnel linings without and with reinforcement are shown in **Figure 7**(a) and (b), respectively. The scaled-down tunnels in **Figure 7** were placed on the ground and the influence of tunnel-surroundings was not taken into consideration. The tunnel-surrounding interactions were not considered in some other studies of scaled-down tunnel explosion tests either (Groethe, et al., 2007, Kristiansen, 2019, Prochazka and Jandeková, 2020). The above scale-down tests under the normal gravity are defective since the structural dead loads (i.e. gravity loads) are not scaled down (Townsend, et al., 1987).

On the other hand, the centrifuge testing is a better way to solve the problem of gravity similarity. A series of scaled-down centrifuge tests were conducted in the past to investigate the response of tunnels under explosions (De, et al., 2013, 2016, 2017, Koneshwaran, et al., 2015a, Liu and Nezili, 2016, Soheyli, et al., 2016, Townsend, et al., 1987), some of which have been listed in **Table 8**. However, these studies using the centrifuge mostly focused on investigating dynamic response of tunnel with metal lining rather than RC lining to blast loads. In addition, it is worth pointing out that the size of centrifuge model is small, which may not be able to predict the local damage and response of tunnel structures. Meanwhile, complex tunnel structure involving structure joints, and secondary structures, etc., cannot be considered in the centrifuge test due to its small size.

It is worth pointing out that most of the previous experimental tests were conducted by using high explosives. Very limited studies have investigated tunnel response under gas explosions. Meanwhile, the existing explosion experiments were mainly conducted in solid media. Experiment study on the response of tunnel in water has not been reported in open literature. In order to gain more comprehensive knowledge on the behaviour of tunnel, more tests including full-scale tests should be conducted under different explosion sources and in different buried media.

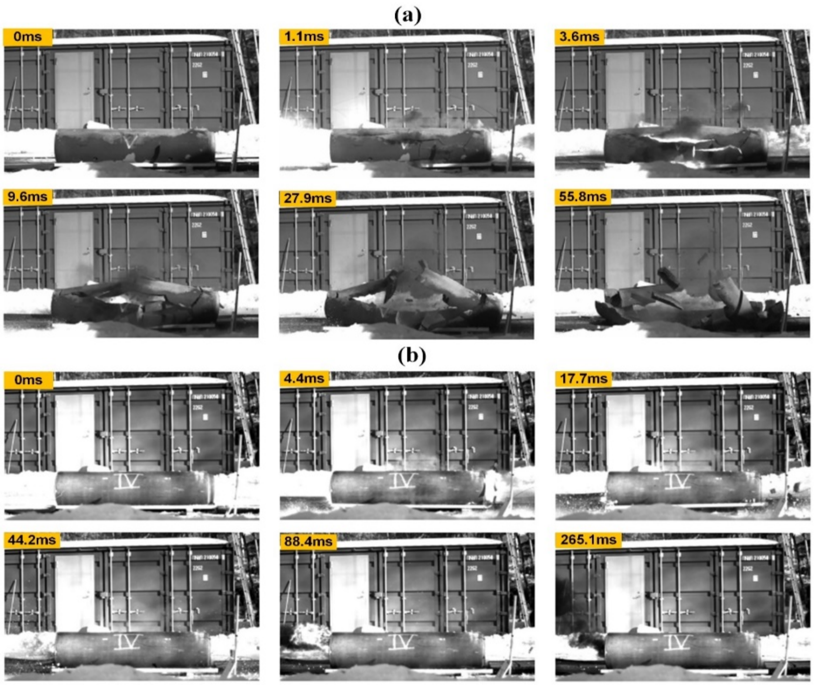
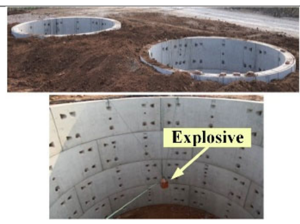
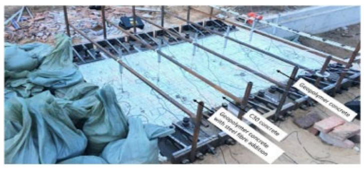
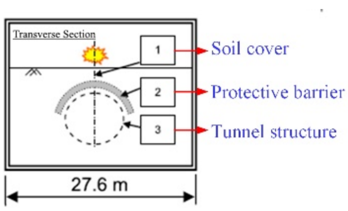


Figure 7. Damage process of (a) a plain concrete tunnel, and (b) a reinforced concrete (RC) tunnel under internally centric explosions with 100g C4 charge (Krone, 2018).

Table 8. Experimental tests of tunnels subjected to explosion loads

Experimental test	**Explosion type**	**Description of tunnel**	**Ref.**	**Experiment scene**
Full-scale test	High explosive	5.5m inner diameter with the lining thickness of 0.4m and the axial length of 1.2m	(Zhao, et al., 2016)	

Scaled-down test	Without centrifuge	High explosive	2.9m inner span, 1.15m side wall height, the side wall lining thickness of 150mm, the floor lining thickness of 100mm, the axial length of 10m	(Chen, et al., 2014, Xie, et al., 2014)	
		BLEVE	A 78.5-m-long circular tunnel with a cross-sectional area of 3.74m^2.	(Groethe, et al., 2007)	
		High explosive	The tunnel length of 5 m, 0.5m and 1m inner diameters in two case. The lining thickness of 0.09m for both cases	(Prochazka and Jandeková, 2020)	
		High explosive	The inside span of 1.5m, the lining thickness of 120 mm in all sides	(Zhou, et al., 2020)	
		VCE (Methane -air)	The tunnel cross section of 1.6m*0.6m, the lining thickness of 0.1m, the longitudinal length of 20m, 9.5% methane concentration condition.	(Meng, et al., 2020a, Meng, et al., 2020b)	
	Centrifuge test	High explosive	5.5 m outer diameter, 0.133 m lining thickness, 53m length of tunnel, copper as the material of tunnel structure (model scale = 1/70 prototype scale)	(De, et al., 2013, De, et al., 2016, Koneshwaran, et al., 2015a)	

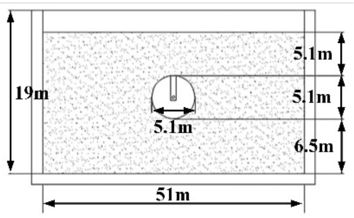
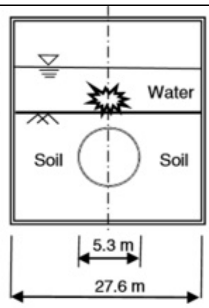
	High explosive	5.1m outer diameter and 8.25cm wall thickness, 25m length of tunnel, aluminum as the lining material (model scale = 1/50 prototype scale)	(Liu and Nezili, 2016)	
	High explosive	5.5 m outer diameter of tunnel, 0.133 m lining thickness, 53m length of tunnel, copper as the material of tunnel structure (model scale = 1/70 prototype scale)	(De, et al., 2017)	

Table 9. Summary of current methods and instruments adopted for tunnel explosion tests

Test types	Test methods	Instruments	Advantages	Disadvantages
Full scale test	Field test	Explosive instruments	Directly measuring blast load, showing structural response and local damage	Costly, high risk, and time-consuming
Scaled-down tests without centrifuge	Field test	Explosive instruments	Reduced cost, directly measuring blast loading and showing structural response and local damage	Moderate risk, no scaled-down gravity load and material properties
	Laboratory test with explosive			
	Laboratory test without explosive	Blast simulating generator	Safe operation, no explosive required, cost-effectiveness	Not applicable for the internal explosion of tunnel
Scaled-down tests with centrifuge	Laboratory test	Centrifuge machine, explosive instruments	Considering gravity similarity	Small model size, not considering complex tunnel structure, not predicting the local structural damage

4.1.3 Numerical methods

Due to the difficulty of experimental tests and the limits of theoretical methods, numerical method becomes a popular alternative for the analysis of tunnel structures subjected to explosion load. With the advances of computer power and computational mechanics in recent decades, numerous numerical tools have been developed (Hao, et al., 2016). Numerical simulations can not only predict blast load generation, wave transmission, wave-structure interaction and tunnel response, but also provide supplement data for the physical testing (Hao, et al., 2016). However, it should be noted that a high-fidelity numerical model should be verified by reliable experimental data before it can be confidently used to predict the dynamic responses of tunnel structures under blast loads.

In the open literature, the commonly used numerical methods to investigate dynamic response of tunnel structures subjected to blast loads are based primarily on the traditional Lagrangian method (Buonsanti and Leonardi, 2013, Liang, et al., 2012, Mishra, et al., 2020, Mishra, et al., 2020), the coupled Eulerian-Lagrangian (CEL) method (Koneshwaran, 2014, Mandal, et al., 2020, Mussa, et al., 2017, Tiwari, et al., 2016), the boundary element method (BEM) (Shakeri, et al., 2020, Stamos and Beskos, 1995), the hybrid smoothed particle hydrodynamics (SPH)-finite element method (FEM) (Koneshwaran, et al., 2013, 2015b, 2015c, Wang, et al., 2005), the discrete element method (DEM) (Deng, et al., 2014, Xia, et al., 2013), the hybrid FEM-DEM (Mitelman and Elmo, 2014, 2016), and the coupled Godunov-variational difference method (VDM) (Feldgun, et al., 2008, 2013a, 2013b, 2014), etc. Their advantages and disadvantages are summarized in **Table 10**. These numerical methods have embedded in some numerical software, such as LS-DYNA, AUTODYNA, ABAQUS, and UEDC, etc, whose characteristics, advantages and disadvantages are summarized in **Table 11**.

Table 10. Summary of numerical methods for dynamic response of tunnel subjected to blast loads

Category	Advantage	Disadvantage
Lagrangian method	Fast calculation; Suited to treat inhomogeneous, anisotropic materials with nonlinear behaviour	Prone to experience severe mesh distortion and computational overflow; Requiring artificial boundary in infinite or semi-infinite models such as non-reflection boundary
CEL	Considering the interaction between blast wave and structure; Effectively reducing mesh distortion	Strongly relying on the element size; Computationally time-consuming; Blurry material interface in Eulerian element
BEM	Not requiring artificial boundaries; Reducing calculated dimensionality in infinite or semi-infinite domains compared to FEM	Not suited to inhomogeneous, anisotropic materials (e.g., concrete, rock) with nonlinear behavior
SPH-FEM	Not requiring mesh for SPH; Suited to extreme distortion situation; Not requiring material track	Computationally time-consuming
DEM	Allowing finite detachments and rotations of discrete blocks of tunnel structure; Enable to model fragment of tunnel under blast loads	Computationally time-consuming; Not realistically predicting the crack initiation and propagation of tunnel owing to the pre-defined discretization models
Hybrid FEM-DEM	Allowing realistic simulation of brittle fracture-driven processes of tunnel and a full consideration of failure kinematics	Computationally time-consuming due to re-meshing procedures
Coupled Godunov-VDM	Addressing large deformations and buckling of the tunnel lining	Not suited to model fragment of tunnel lining

Table 11. Summary of commonly used software packages for dynamic response of tunnel subjected to blast loads

Software	Characteristics	Function	Advantage	Disadvantage
ANSYS/ LS-DYNA	Explicit algorithm for explosion analysis, based on finite element method	Simulating explosive detonation and its interaction with tunnel; Modelling the nonlinear tunnel response	Abundant material models for concrete and reinforcement; Multiple ways to simulate blast wave propagations	Less geotechnical material model; computational costly with refined mesh
ANSYS/ AUTODYN	Explicit algorithm for explosion analysis, based on finite difference method	Simulating explosive detonation with afterburning effect; Modelling blast wave interaction with tunnel; Modelling the nonlinear tunnel response	Allowing modelling detonation with high grid resolution without increasing computational cost; Being good at multi-physics coupling problem	Less geotechnical material model
ABAQUS	Explicit algorithm for explosion analysis, based on finite element method	Simulating blast wave interaction with tunnel by CEL method; Modelling the nonlinear tunnel response	Multiple available soil and rock material models; Stable calculating ability	Less concrete model; computational costly with refined mesh
UEDC	Based on block discrete element method	Modelling discontinuous block media such as joint rock	Modelling the energy dissipation during the fracture process and the kinetic energy of each discrete block	Computational costly; Not simulating real crack process

Most of these numerical methods can intuitively show the propagation of blast wave and its interaction with lining structures. For instance, Yang, et al. (2018) used the CEL method to investigate the whole process of shock wave propagation and its interaction with a multi-cell rectangular tunnel in an external explosion scenario, as shown in **Figure 8**. Meanwhile, Li, et al. (2018) investigated the detailed propagation process of shock wave inside the tunnel for an internal explosion by the CEL method, as shown in **Figure 9**. These numerical methods are mostly conducted to investigate dynamic response of tunnel subjected to high explosive explosions, in which the explosion loads are obtained by using conventional weapons effects program (CONWEP) and computational fluid dynamics (CFD) method, etc. It should be noted that the above-mentioned high-explosive-based numerical methods may not give accurate prediction of explosion loads from gas explosions, especially when the standoff distance is short (Li and Hao, 2020, 2021). Two studies (Molenaar, et al., 2009, Vervuurt, et al., 2007) using multiple energy method and one study (Wang, et al., 2021) based on simplified overpressure-time history of gas deflagration numerically investigated the dynamic response of tunnel subjected to internal gas explosions. The multiple energy method and the simplified method were developed to predict explosion load from gas explosion at ground surface or in free air, ignoring the multiple interactions between blast waves and lining. In addition, in the case of gas explosion, the damage of tunnel could be caused by the coupling effect of explosion and fire if the material involved is flammable. In open literature, only two studies (Buonsanti and Leonardi, 2013, Colombo, et al., 2015) investigated the dynamic response of tunnels against the combination of pre-explosion fire and followed explosion. No study in open literature has investigated the influence of pre-explosion followed by fire on the dynamic response of tunnel.

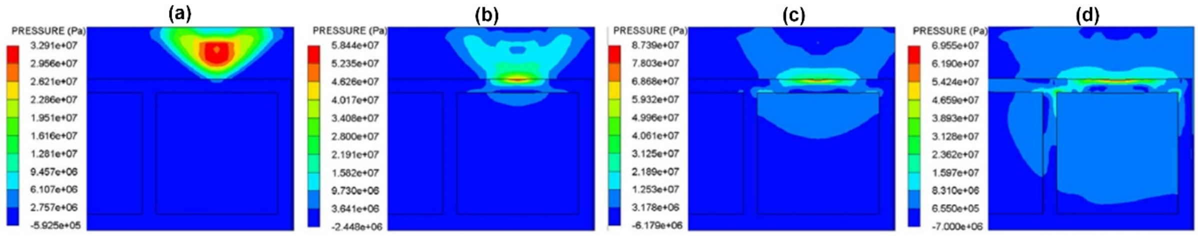


Figure 8. Propagation of surface explosion pressure waves at (a) 2ms, (b) 3ms, (c) 4ms, and (d) 5ms, respectively (Yang, et al., 2018).

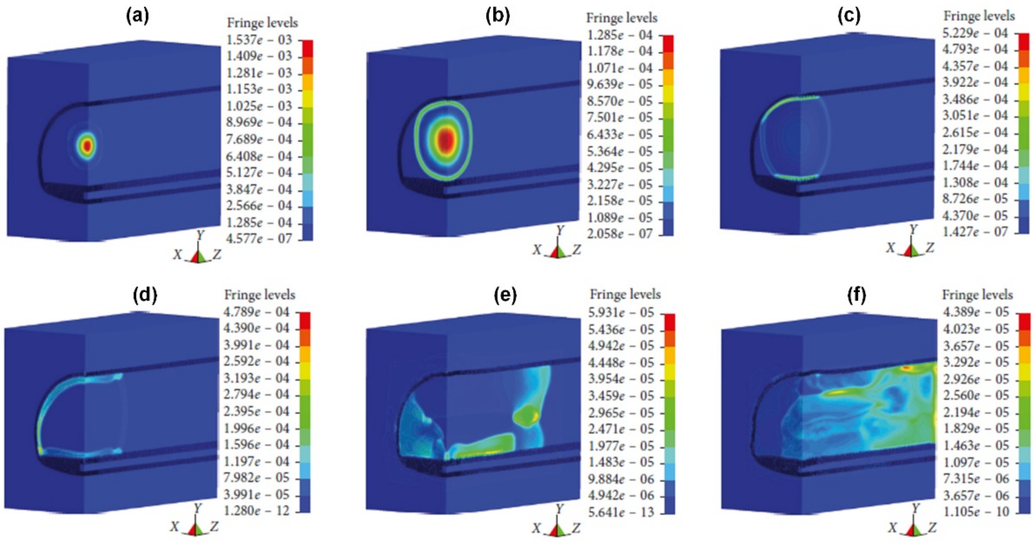


Figure 9. Propagation of blast shock wave inside a tunnel at (a) 0.5ms, (b) 0.98ms, (c) 1.3ms, (d) 2.2ms, (e) 7ms, and (f) 12ms. The units are 10^2 GPa (Li, et al., 2018).

4.2 Forms of damage and response of tunnels under explosions

In addition to the above-reviewed analysis methods, the forms of damage and response of tunnels under blast loads are reviewed and classified in this section. The damage and response forms can be mainly classified as crushing and spalling of tunnel linings, cracks of tunnel linings, deformation and collapse of tunnel lining, bending and tensile failures of reinforcements, and damage of tunnel surroundings, which are reviewed in details in this section.

4.2.1 Crushing and spalling of tunnel linings

The tunnel lining may suffer both crushing and spalling damages under external explosions, while the tunnel is prone to experience crushing subjected to internal explosions. Under the external explosion load, the crushing usually appears on the outer surface of the tunnel lining, where the superposition of the incident wave and reflected wave at the interface of lining and surroundings intensifies the compressive stress waves. The spalling damage occurs on the inner surface of the lining under external explosion, which is due to the tensile action of stress wave in the tunnel lining. The typical crushing and spalling damages of tunnel lining under external blast loads is shown in **Figure 10**(a) and (b). Under internal explosions, the crushing can occur at both the inner surface and the outer surface of lining. Due to the intensification of reflected compressive waves on the inner surface of lining, the crushing of inner surface first occurs and continuously propagates outwards in the tunnel. Meanwhile, when the transmitted stress waves reach the interface of lining-surroundings, the compressive stress waves reflect again due to the difference of wave impedance between surroundings and the lining. The reflected waves further intensify the stress waves, which might lead to the crushing at the outer surface of tunnel lining. The combined effect of the inner and the outer crushing of tunnel lining may breach the tunnel lining.

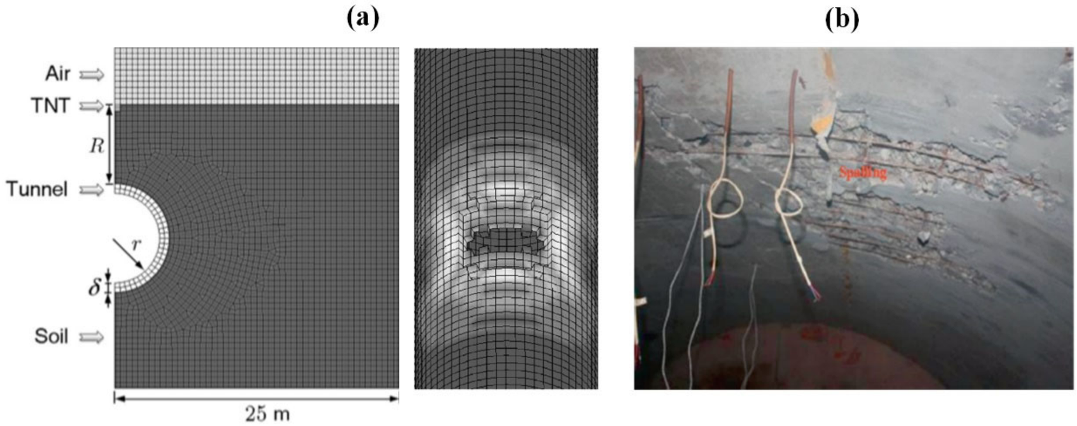


Figure 10. The crushing and spalling damage of tunnel lining under external blast loading. (a) the crushing damage of tunnel lining (Mobaraki and Vaghefi, 2016), and (b) the spalling damage of tunnel lining (Chen, et al., 2015).

4.2.2 Cracks of tunnel linings

The cracks of tunnel linings usually appear outside the spalling and crushing zones or collapse zones (Chen, et al., 2014, Li, et al., 2018, Yang, et al., 2019), or on the tunnel lining near detonation under low-intensity blast loading (Koneshwaran, et al., 2015b, Krone, 2018, Zhao, et al., 2016), or on the whole section of tunnel lining along the longitudinal direction (Stolz and Ruiz-Ripoll, 2015, Zhou, et al., 2020). Under external explosions, the presence of these cracks are mainly attributed to the overall bending deformation of tunnel lining and the reflected tensile damage. As reported by

Zhou, et al. (2020), due to the downward bending deformation of the tunnel roof, three longitudinal cracks along the mid-span of whole roof were observed in the external surface explosion experiment, as shown in **Figure 11**(a). In addition to the crack damage induced by the bending deformation, Chen, et al. (2014) observed that due to the reflected tensile damage, oblique cracks and ring cracks around spalling areas on the inner surface of an arch tunnel lining were formed after a series of external explosions (see **Figure 11**(b)). Under the internal explosion, the cracks of tunnel lining are usually formed due to the radial expansion deformation of tunnel lining with the increased hoop tensile stress of tunnel lining. As reported by Krone (2018), due to the radial expansion of tunnel lining under internal explosion, the ring cracks appeared on the tunnel lining near detonation, and the longitudinal cracks on tunnel lining were observed outside the ring cracks, as shown in **Figure 12**(a). In the numerical study, Kristoffersen, et al. (2019) also observed the crack damage on the circular and rectangular submerged float tunnels under an internal eccentric explosion with 500 kg TNT charge, as shown in **Figure 12**(b). In addition, the cracking behaviours of tunnel with segmental linings under internal explosion were experimentally investigated by Zhao, et al. (2016). They found that the joints between segments were more prone to be cracked due to stress concentration at the connection of joints.

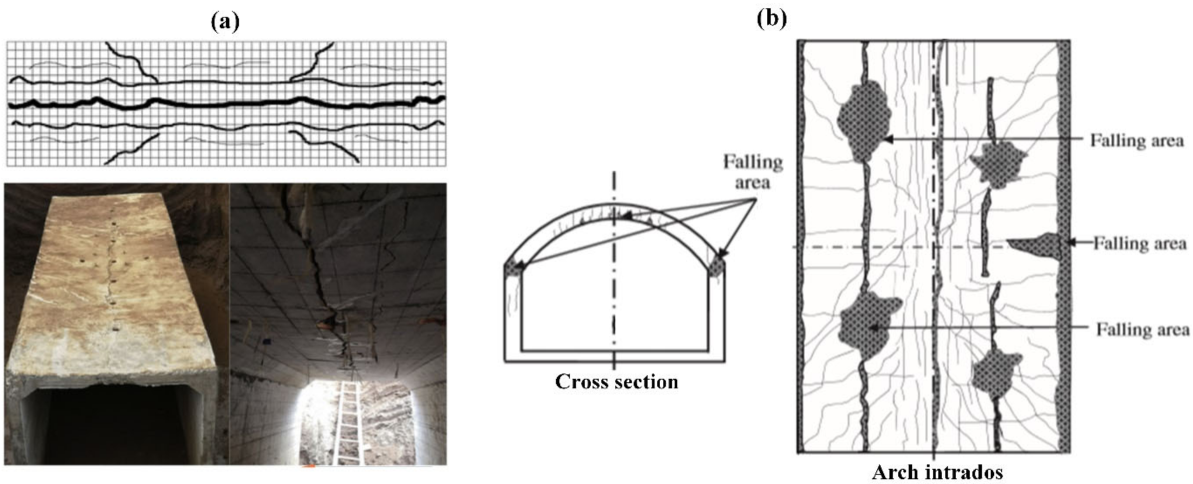


Figure 11. The crack damage of linings with (a) rectangular tunnel subjected to external explosion load (Zhou, et al., 2020), and (b) arch tunnel subjected to external explosion load (Chen, et al., 2014).

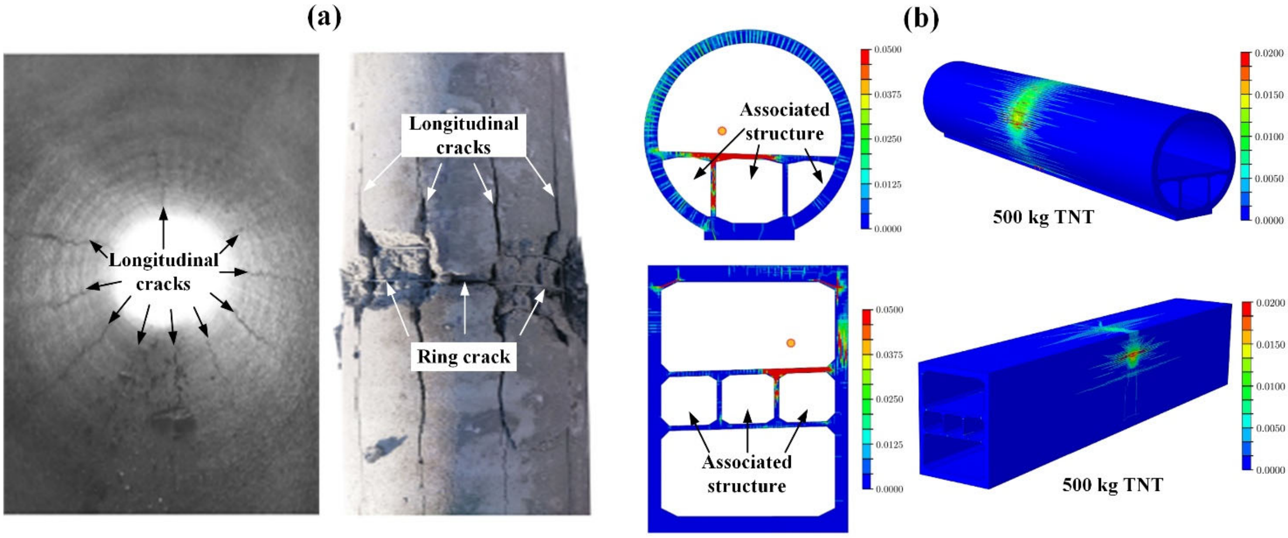


Figure 12. The crack damages of (a) a circular tunnel lining under an internal centric explosion (Krone, 2018), and (b) circular and rectangular submerged float tunnels under an internal eccentric explosion (Kristoffersen, et al., 2019).

It is worth noting that associated structures of two tunnels in **Figure 12**(b) were also seriously damaged by the internal explosion. Due to the lack of surrounding support, the associated structures of tunnel, e.g. escape and smoke passages are more vulnerable to blast loads than main structure (i.e. lining) of tunnel. The damage of associated structures could significantly interrupt the transportation functionality of road tunnels, and even induce severe casualties. However, very limited studies have investigated the response of associated structures under blast loads, which is deemed necessary for further study.

4.2.3 Deformation and collapse of tunnel linings

With the presence of cracks, tunnel linings might experience large deformation or collapse. Under external explosion, the tunnel lining directly facing blast loadings is usually deformed towards the inner of tunnel (Slawson, 1984). When tunnels suffer intensive external blast loads, the collapse of tunnel lining could occur. It was reported by Kiger, et al. (1989) and Smith, et al. (1986) that the tunnel-like arches buried in soil collapsed under intensive surface explosion. **Figure 13**(a)-(c) show the deformation and collapse after removing the buried soil. When two penetrating cracks along the haunches or roof corners of tunnel lining at both sides are formed, the tunnel lining deforms or collapses. Moreover, for segmental lining, the deformation patterns of radial dislocations between adjacent segments and longitudinal dislocations between adjacent lining rings might occur under external explosions (Koneshwaran, 2014, 2015b). Under internal explosions, the tunnel linings normally expand radially outward if the intensive incident pressure can overcome the blocking action of tunnel surroundings (Han, et al., 2016, Li, et al., 2018). Other types of deformation patterns could occur under eccentric internal explosion. For instance, when internal explosion occurs near bottom lining, Zhao, et al. (2016) observed an elliptical deformation of a circular tunnel lining, i.e., the expansion of the upper and lower tunnel lining and the inward deformation of two side linings. When a multi-cell tunnel is subjected to an internal explosion, the mid-lining wall might experience deformation and collapse due to the lack of surrounding support, as shown in **Figure 14**. Currently, very limited studies have investigated the damage of mid-lining of multi-cell tunnel under internal explosion.

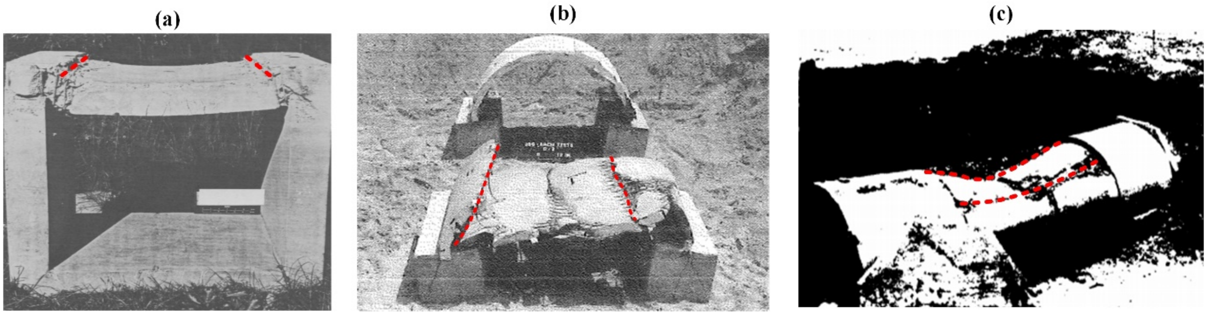


Figure 13. The collapse of tunnel linings under external explosion. (a) permanent deformation of tunnel-like box roof (Slawson, 1984), (b) collapse of tunnel-like arch structure (Kiger, et al., 1989), and (c) vault collapse of tunnel-like arch structure (Smith, et al., 1986).

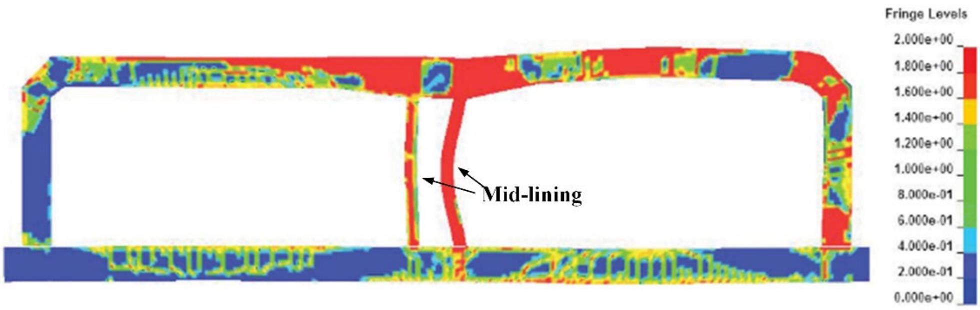


Figure 14. The deformation and damage of a rectangular tunnel lining under internal explosion (Molenaar, et al., 2009).

4.2.4 Bending and tensile failure of reinforcement

The bending and tensile failure of reinforcement in tunnel lining was often observed under external explosion. Chen, et al. (2015) reported that the arch roof of a tunnel-like structure experienced severe bending damage of the longitudinal and hoop reinforcements under a series of external explosions, especially at the conjunction of roof and sidewall, as shown in **Figure 15**(a). Meanwhile, with the presence of longitudinal structural cracks on tunnel lining, hoop steel bars across the longitudinal cracks were stretched to fracture, as shown in **Figure 15**(b). It was also reported by Smith, et al. (1986) that under surface explosions the lining structure experienced catastrophic collapse, along with bending and tensile failures of reinforcement. However, there is no report on bending and tensile failure of lining reinforcement when subjected to internal explosion.

Figure 15. The bending and tensile failures of reinforcement (Chen, et al., 2015). (a) bending failure, and (b) tensile failure.

4.2.5 Deformation and damage of tunnel surroundings

The deformations of tunnel surroundings involve the deformation around tunnel and the ground heave. Under internal blast loads, the deformation around a shallow buried tunnel first occurs and then the ground deformation above tunnel is possible with the propagation of blast-induced stress waves. As reported by Tiwari, et al. (2018), an obvious ground heave above a circular curved tunnel was simulated under an internal explosion, as shown in **Figure 16**. The large ground deformation might potentially damage surface structures (e.g. the multi-storey buildings) near the tunnel. Therefore, the stability of buildings near the tunnel subjected to explosion loads need be evaluated.

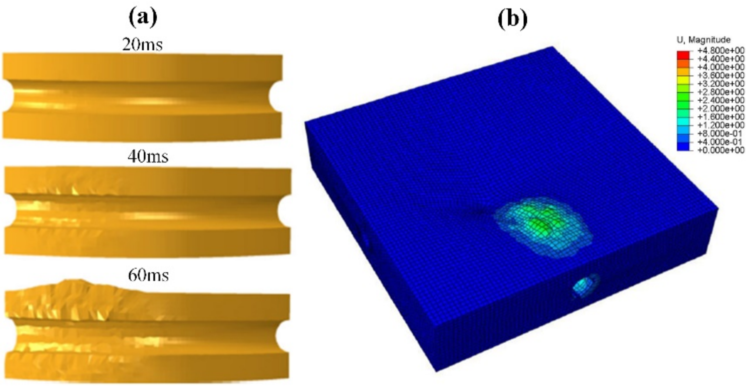


Figure 16. The ground heave above a curved tunnel under internal blast loading (Tiwari, et al., 2018). (a) the deformation process of tunnel surroundings, and (b) the aerial view of the ground heave (The unit of *U* is m).

In addition to the deformation, tunnel surroundings might be subjected to the blast induced damage and collapse under high-intensity explosion loadings. In some existing studies (Deng, et al., 2014, Hao and Wu, 2001, Mitelman and Elmo, 2014, 2016, Wu and Hao, 2006), the damage and collapse of the surroundings of tunnel or tunnel-like structure without the lining supports were investigated under internal and external explosions. For example, Hao and Wu (2001) numerically investigated the damage zones of surroundings of a tunnel-like rock chamber under the internal blast loadings with different loading densities. As expected, more damage was generated in the rock mass with the increasing loading density. Mitelman and Elmo (2014) investigated the collapses of surroundings for unlined tunnels under external explosions. It was observed that the main collapse zones occurred above the tunnel roof, which had closer distance to the external explosion centre than other tunnel parts. Although the surroundings of road tunnels are usually supported by the lining structure, very limited studies on the collapse of tunnel surroundings with the support of lining under internal and external explosions have been conducted.

4.3 Influence factors of tunnel response subjected explosion loads

Dynamic response and damage levels of tunnels subjected to blast loads are affected by various factors. In this section, the key factors influencing the tunnel response and damage are presented.

4.3.1 Equivalent charge weight

The equivalent charge weight is one of decisive factors affecting the peak pressure acting on tunnel structures and the damage of tunnel structures. In the previous studies, the effect of charge weight on the tunnel response was investigated with respect to various parameters including displacement (Dhamne, et al., 2018, Koneshwaran, et al., 2015c, Yang, et al., 2018), pressure (Choi, et al., 2006, Han, et al., 2016, Yang, et al., 2010), stress (Parviz, et al., 2017, Prasanna and Boominathan, 2014), strain (Kristoffersen, et al., 2019, Liu, 2012), acceleration (Soheyli, et al., 2016) and velocity (Lu, et al., 2016, Mussa, et al., 2018). It is noted that the equivalent conversion from gas explosive to high explosive might not give accurate predictions of the overpressure from gas explosions, especially for the overpressure of near-field explosions, which might cause the inaccurate predictions of the tunnel response and damage.

4.3.2 Standoff distance

The standoff distance between tunnel structure and explosive as a critical factor has been widely investigated. Under the internal blast loading, standoff distance can be varied by changing the size of tunnel cross section with the determined explosive location (Choi, et al., 2006). By increasing the size of tunnel cross section, the loading density defined as the ratio of explosive weight to internal space decreases given the same explosive weight, which results in the decreased explosion load acting on the tunnel structures. Under external blast loading, the standoff distance varies by changing the location of tunnel with the determined explosive location (Mobaraki and Vaghefi, 2015, Yang, et al., 2018, Yang, et al., 2010), or changing the location of explosive with the determined tunnel location (Yang, et al., 2019, Yankelevsky, et al., 2012) for single tunnel, and changing the spacing between tunnels for neighbouring tunnels (Mo, et al., 2013, Prasanna and Boominathan, 2014). With the increased standoff distance between the tunnel and the charge, the intensity of external blast pressure acting on the tunnel structures reduces and hence structural damage decreases.

4.3.3 Burial depth of tunnel

Varying burial depth of tunnel results in various confinement levels to tunnel structures. For the relatively shallow buried tunnel, increasing confinement levels with the increased burial depth of tunnel suppress the deformation and vibration response of tunnel subjected to explosions, which is beneficial to reduce the damage of tunnel. As reported by Yu, et al. (2015), with the burial depth increased from 6m to 12m, the effective plastic strain at the vault of the circular tunnel decreased under the internal explosion. However, for the relatively deep buried tunnel, the increase of confinement levels by increasing the burial depth usually results in more strain energy accumulated around the tunnel due to the increased in-situ stress. The release of higher strain energy with blast load as a trigger is adverse to the stability of tunnel. As reported by Li, et al. (2018), the damage of tunnel with the burial depth over 500m was more severe than that at the burial depth of 500m. It is noted that no existing study has provided the specific depth ranges for shallow and deep buried tunnels. The depth ranges of shallow and deep buried tunnels might vary with different geological conditions. The influence of burial depth with respect to different geological conditions on the dynamic response of tunnel subjected to blast loads should be investigated and the depth ranges for shallow and deep tunnels can be specified in the future study.

4.3.4 Charge position

Charge position could be changed in the same cross-section plane of tunnel or along the longitudinal direction of tunnel. Tiwari, et al. (2015) investigated the effect of variation of charge position along the longitudinal direction of a curved tunnel on the dynamic response of tunnel under internal explosion. The results indicated that when the explosive was placed in the longitudinal centre of tunnel as compared to that at the quarter of tunnel along the longitudinal direction, larger deformation of lining and surroundings was observed due to longer venting time of explosive cloud. In the same cross-section plane of tunnel, the charge position could vary both inside (Colombo, et al., 2016, Feldgun, et al., 2014, Yu, et al., 2015) and outside (Koneshwaran, et al., 2015d) tunnel. For instance, for the charge inside tunnel, a study conducted by Feldgun, et al. (2014) investigated the pressure distributions on the walls of a rectangular tunnel under centric explosion and eccentric explosion near floor. The results indicated that the maximum peak pressure on tunnel lining under the eccentric explosion was higher than that under the centric explosion. Overall, the tunnel was safer under the centric explosion. In actual operating road tunnel, explosions could happen at different locations on the tunnel floor. However, no study has been conducted on the influence of internal explosions at different locations of tunnel floor on dynamic response of tunnel. With regard to the charge position outside the tunnel in the same cross-section plane, Koneshwaran, et al. (2015d) investigated the influence of varying charge position on the ground surface, where two same charges were located on the ground directly and obliquely over the tunnel with the same standoff distance. The results showed that the tunnel directly below the charge was more vulnerable to the surface explosion than the tunnel obliquely below the charge. It should be noted that the tunnels with rectangular or arched cross sectional shapes subjected to external explosions at various locations and standoff distances have not been studied yet.

4.3.5 Shapes of tunnel

Tunnel has different shapes in the cross section and the longitudinal directions. Varying the shape of cross section influences many other factors, such as the interaction area between surroundings-structure, the cross sectional curvature, the cross sectional dimension, the standoff distance and the tunnel aspect ratio, which may affect the load-carrying capacity of tunnel. Mobaraki and Vaghefi (2015) found that as compared to the tunnels with circular, box and arched cross sections, the semi-ellipse tunnel had the least damage under the same external explosion due to its maximum contact zone between the soil and tunnel in the study, thereby increasing the stability of the semi-ellipse tunnel. However, the contribution of other influencing factors to the stability of the tunnel, especially the difference in cross-sectional dimensions and aspect ratios, was not considered in this study. When the standoff distance from the centre of external explosion to tunnel wall is kept the same, the smaller cross section dimension is usually more beneficial to the blast resistance of tunnel (Wu, et al., 2011). If the cross-sectional dimensions of the tunnel are similar, the greater the aspect ratio (the ratio of height to span) of the tunnel is, the more sensitive the dynamic response of tunnel to blast loads would be (Dhamne, et al., 2018, Wu, et al., 2011). When the cross sectional dimensions and aspect ratios of tunnels are similar and the standoff distance from explosion centre to the tunnel wall is kept the same, the circular tunnels have better resistance against external explosions than others (Mandal, et al., 2020). It is because the curvature of circular tunnel results in less reflected pressure on the tunnel structures (Gebbeken and Döge, 2010). Under internal explosion, some studies (Goel, et al., 2020, Prasanna and Boominathan, 2020) concluded the curvature of circular tunnel could cause more even distribution of blast load on the tunnel structure than box tunnel with similar height and span, thereby having a better blast resistance. However, a numerical study conducted by Yu, et al. (2015)_found that the maximum plastic strains on the lining of the circular tunnel subjected to an internal centric explosion were higher than those of the square-shaped tunnel with similar cross sectional dimension.

Further work should be conducted to reveal the effects of different shapes of cross section with similar cross-sectional dimension on the response of tunnel subjected to internal explosions.

Very limited studies have been conducted with respect to the influence of the longitudinal shape of tunnel on the dynamic response of tunnel to blast loads. One study conducted by Tiwari, et al. (2018)_investigated the influence of radii of tunnel curvature in the longitudinal direction on the response of tunnel. Two curved tunnels with the curvature radii of 30m and 70m were subjected to the same internal explosion. The soil around tunnel and the ground directly above the tunnel with the tunnel curvature radius of 30m experienced larger deformation than those with the curvature radius of 70m (see **Figure 17**). It is because the smaller curvature radius (30m) is apt to contain blast wave inside tunnel and induce more reflections of blast wave inside tunnel. Besides the curved tunnel, the sloped tunnel has been constructed whilst the influence of slope of the tunnel on the blast response of tunnel has not been investigated.

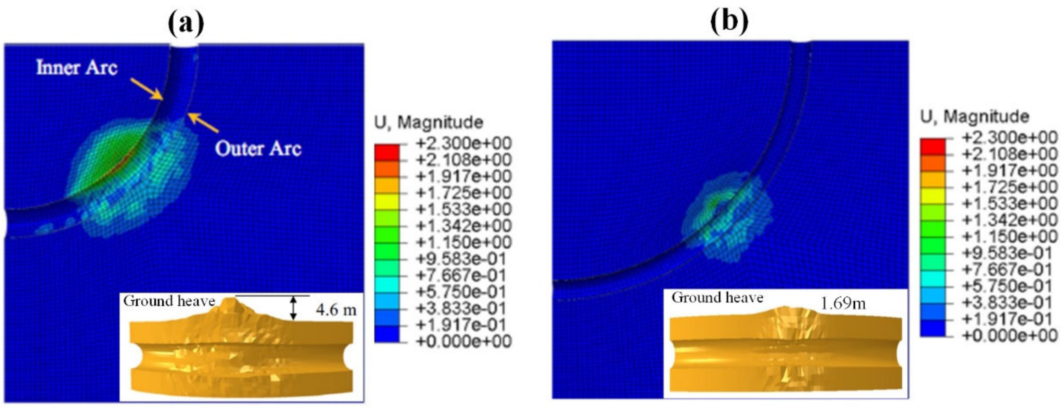


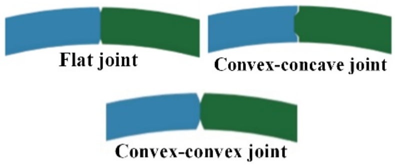
Figure 17. The deformation around tunnel and the ground heave above the tunnel with the curvature radius of (a) 30m, and (b) 70m (Unit of *U* is m) (Tiwari, et al., 2018).

4.3.6 Physical and mechanical properties of lining and surroundings

The existing studies regarding the influence of lining material properties on the response of tunnel focus on the influence of the lining stiffness (Han, 2014), the lining strength (Khan, et al., 2016), the lining damping (Han, 2014), the lining brittleness (Liu, 2012), the lining thickness (Mussa, et al., 2017, Prasanna and Boominathan, 2020, Tiwari, et al., 2017), the type of lining material (Chaudhary, et al., 2018, Colombo, et al., 2015, Parviz, et al., 2017), and joint types for segmental lining and the number of segments (Koneshwaran, 2014). **Table 12** summarizes their influences on the dynamic response of tunnel subjected to blast loads.

Table 12. The influence of lining properties on the dynamic response of tunnel subjected to blast loads

Factor	Effectiveness on the blast resistance of tunnel

Increase lining stiffness	Significantly enhance the resistance of lining to bending and deformation
Increase lining strength	Enhance the anti-damage ability of tunnel lining
Increase lining damping	Decrease the damage levels of tunnel due to stronger ability to absorb explosion energy
Decrease lining brittleness	Improve the vulnerability of lining against rupture
Increase lining thickness	Decrease the damage of tunnel due to the increased moment of inertia
High-performance lining material	Decrease damage levels of tunnel due to high strength, high stiffness and high energy absorbing ability of material
Joint type for segmental lining (Koneshwaran, 2014) 	(Convex-concave joint compared with flat joint) Reduce the drifting response of tunnel at joint due to the mechanical interlocking; (Convex- convex joint compared with flat joint) Reduce the crack levels at joint due to less friction areas between segments and more dependence on the joint bolt
Increase the number of segments	Reduce the cracks of lining under small blast loads due to the increased flexibility

The effects of tunnel surroundings including rock mass and soil on the dynamic response of tunnel under explosions have been comprehensively investigated by considering the water contents of surrounding medium (Al-Damluji, et al., 2010, Koneshwaran, et al., 2015d, Osinov, et al., 2019), strength (Tiwari, et al., 2016, 2017), stiffness (Liu, 2009, Verma, et al., 2017, Yang, et al., 2010), density of surrounding medium (Higgins, et al., 2013, Parviz, et al., 2017, Stolz and Ruiz-Ripoll, 2015), damping ratio (Dang, et al., 2018, Gui and Chien, 2006), wave impedance (Chen, et al., 2013a, 2013b), joint performance in tunnel surroundings (Deng, et al., 2014), and lateral pressure coefficients (Li, et al., 2018). **Table 13** summarizes their influences on the dynamic response of tunnel under explosions. It is found that very limited study has investigated the influence of the interface properties between lining and surroundings on the dynamic response of tunnel under explosions.

Table 13. The influence of surroundings properties on the dynamic response of tunnel subjected to blast loads

Factor	**Effectiveness on the blast resistance of tunnel**
Increase water content	Decrease the damage of tunnel under low blast pressure due to the reduction of the blast load acting on soil skeleton with the water sharing; Increase the damage of tunnel under intensive blast loads due to the water weakening on soil skeleton and the instant increase of undrained pore pressure
Increase stiffness of surroundings	Decrease the blast damage due to the increase of resistance of surroundings to deformation

Increase strength of surroundings	Reduce the damage of tunnel surroundings while not significantly reduce the response of tunnel lining
Increase density of surroundings	Reduce the damage of tunnel lining under internal explosion due to its enhanced support; Increase the damage of tunnel lining under external explosion due to more blast wave transferred to the tunnel
Higher damping of surrounding	Absorb more blast energy and thus reduce the damage of tunnel under external explosion
Lower wave impedance	Reduce the damage of tunnel under external explosion due to more attenuation of blast wave
Joint performance of tunnel surroundings	(Small joint dip angle, large joint stiffness and small joint spacing) Enhance the resistance of tunnel against blast loading
Increase lateral pressure coefficient	Increase strain energy stored around the tunnel and thus damage tunnel more severely with its release under blast loads

5. Assessment of tunnel damage under explosion

Damage assessment of tunnel under explosions is critical for the design of tunnel structure and subsequent retrofitting. By far, there are many available criteria for assessing and predicting the consequences of tunnel damage, i.e., the deflection or deflection-span ratio, peak particle velocity (PPV), crack grades, moment-force interaction diagram, pressure-impulse diagram, diagram of charge weight versus standoff distance, and the empirical equation of spall and breach. Depending on the spans of tunnels, these methods are readily used to evaluate the overall failure as well as the local damage of tunnel structures. The specific details of the methods are reviewed below.

5.1 Based on deflection or deflection-span ratio

The damage assessment based on deflection or deflection-span ratio is achieved by simplifying the tunnel structure into an equivalent elastic-perfect-plastic single degree of freedom (SDOF) model (Mussa, et al., 2017). Since the SDOF approach is based on the assumption that the first mode of the structure is the dominant response mode, various damage levels of tunnel structures corresponding to the maximum mid-span deflection of tunnel wall were suggested (Mussa, et al., 2018). **Table 14** gives the damage index related to the deflection, the deflection-span ratio, and the ratio of deflection to half-span. These damage criteria were proposed based on the assumption of global ductile response. Therefore, it is not applicable to apply the criteria for the cases of shear response and localized concrete crushing and spalling response (Hao, 2015). In other words, the damage criterion is suitable for the damage assessment of tunnel structures where the flexural mode is dominant.

Table 14. The damage criteria related to deflection for tunnel structure under blast loading

Ref.	Criterion index	Damage levels/damage index			
		Slight damage	Moderate damage	Severe damage	Collapse
(Mussa, et al., 2017)	Deflection	<20mm	20-40mm	40-80mm	>80mm
(Yang, et al., 2019)	Deflection-span ratio	<1/200	1/200-1/100	1/100-1/50	>1/50
(Ma, et al., 2008, 2010)	Deflection to half-span ratio	2.5%	6.0%	12.5%	-

5.2 Based on peak particle velocity

The damage assessment of tunnel based on peak particle velocity (PPV) could be divided into two categories. The first category only gives a damage threshold of PPV, which is usually determined by establishing empirical relationships between effective stress/strain and PPV (Jiang and Zhou, 2012, Liang, et al., 2012, Liu, et al., 2019, Mobaraki and Vaghefi, 2015), in which the PPV is proportional to the energy of blast shock wave and structural stress/strain. When the effective stress or strain reaches allowable maximum limit of tunnel structure material, e.g, the maximum strength or failure strain of lining material, the corresponding PPV threshold is obtained by using the established empirical equation. The second category provides the PPV thresholds of different damage levels based on experimental or numerical observations. Some studies (Hendron, 1978, Li and Huang, 1994) suggested the PPV thresholds for different damage levels of the unlined tunnel. A comprehensive study of unlined tunnel damage was the US Army's Underground Explosion Tests (UET), as reported in Hendron (1978). In the study, the tunnel damage was classified into four damage zones along the longitudinal direction of tunnel, i.e. the intermittent failure zone with the PPV of 0.9 m/s-1.8 m/s, the local failure zone with the maximum PPV limit of 4 m/s, the general failure with the maximum PPV limit of 12 m/s, and the tight closure zone. However, the road tunnels are usually supported by lining. Only limited studies gave the PPV thresholds for different damage levels of the lined tunnel. Dowding (1984) reported that the damage levels of lined tunnel could be divided into four categories, i.e., cracking of lining with the PPV limit of 1m/s, displacement of cracks with the PPV limit of 1.3 m/s, local failure with the PPV limit of 7.4 m/s, and complete failure with the PPV limit of 40 m/s. In another study, Mussa, et al. (2018) determined the PPV thresholds for different damage levels of the tunnel lining with three different thicknesses by matching damage results to those based on the criterion of deflection-span ratio. It is noted that the damage criterion based on PPV is site-dependent, i.e., related to the specific properties of tunnel lining and surrounding materials.

It has been well known that the damage status of tunnel structures is not only related to the PPV but also the frequency of blast wave. The blast damage levels of tunnel could vary significantly under different main frequency bands of blast wave with the same PPV and tunnel condition. In other words, the tunnel response and damage depend not only on the blast wave amplitude, i.e., PPV, but also on its frequency contents. However, no study has considered the influence of blast wave frequency on the PPV-based damage criteria for tunnel structures.

5.3 Based on crack grades

The crack-grade-based damage assessment method is usually established by observing the cracks of tunnels after explosions. Major findings from two studies (Koneshwaran, et al., 2015d, Yang, et al., 2019) using different crack indexes to establish the damage criterion (one is based on penetrating cracks and the other depends on the crack width and number) are listed in **Table 15**. The damage category based on crack grades was obtained qualitatively instead of quantitatively, which means the assessment could be subjective.

Table 15 The damage levels of tunnel lining based on crack grades

Ref.	Damage level	Description
(Yang, et al., 2019)	Slight damage	No penetrating cracks, overall good performance of tunnel lining
	Moderate damage	Short penetrating cracks
	Severe damage	Penetrating cracks running through the whole lining wall
	Collapse	The coalescence of multiple penetrating cracks running through the whole lining wall
(Koneshwaran, et al., 2015d)	No damage	Some minor cracks in segments with maximum crack width < 0.3 mm, and no bolt failure
	Slight damage	A small number of cracks with maximum crack width > 0.3 mm, and a few bolts fail at the joints, but no significant drifting response
	Moderate damage	A large number of cracks with maximum crack width > 0.3 mm, a large number of failed bolts, and significant drifting or sliding of segments at joints, but remaining the functionality of tunnel
	Severe damage or collapse	Formation of full depth cracks, and a large number of bolt failures, resulting in a large drift between segments

5.4 Based on moment-force interaction diagram

The combination of axial forces and bending moments causing structure failure allows to determine the moment-force interaction curve (Rashiddel, et al., 2020). There are two methods to obtain the moment-force diagram for the damage assessment of tunnel structures in literature. The first method is to utilize the design codes of RC structure to calculate the moment- force diagram for tunnel lining. As reported, Yu, et al. (2014) adopted GB50010-2010 (MOHURD, 2011) code and Gui and Chien (2006) used ACI 318-99 (ACI, 1999) code to calculate the moment-force diagram of RC wall, which was used as the moment-force interaction diagram of tunnel lining. For instance, the critical moment-force equation of RC wall subjected to combined flexure and axial loads in ACI 318-99 is given as Eq. (1). It should be noted that the moment-force diagram calculated from these design codes does not consider the influences of the curvature of tunnel cross-section and the surroundings-structure interaction on the capacity of tunnel lining. The second method to obtain the moment-force diagram of tunnel lining was proposed by Colombo, et al. (2015, 2016). The moment-force interaction diagram was built by evaluating the diagrams of bending moment versus curvature of the tunnel cross-section for different axial forces and considering the peak of each curve in the diagram as the resistant moment for a given axial force. However, the interaction between lining and surroundings was not taken into account in establishing the moment-force interaction diagram. Further study should be conducted to develop the moment-force interaction diagram by considering the surroundings-lining interaction for road tunnel.

$$M_{ua} = M_c \times (1 - 5P_u l_c^2 / (0.75 * 48 E_c I_{cr}) \quad (1)$$

where M_c is the design moment strength of RC wall, M_{ua} and P_u are the moment and axial force acting on wall, respectively. l_c is the height of wall, E_c is the modulus of elasticity of concrete, and I_{cr} is the moment of inertia of wall section.

5.5 Based on pressure-impulse diagram

The pressure-impulse diagram can be used for the damage assessment of tunnel lining on the basis of pre-defined damage criteria, such as the deflection-span ratio (Ma, et al., 2008, 2010) and the moment-force interaction diagram (Colombo, et al., 2015). Based on the given damage criteria, a group of pressure and impulse applying onto tunnel lining at the ultimate limit state could be obtained for the critical pressure-impulse diagram. For instance, Ma, et al. (2008, 2010) generated the pressure-impulse diagrams for different damage modes of lining walls under blast loads based on the maximum shear and bending displacements, in which the governing equations of pressure-impulse diagram is given in Eq. (2). In addition, Colombo, et al. (2015) built up the pressure-impulse diagram of tunnel lining by using the moment-force interaction diagram, In that study, the moment-force interaction diagram neglected the interaction between tunnel structure and surroundings, which might undermine the accuracy of the established pressure-impulse diagram. Therefore, a reliable pressure-impulse diagram should be developed by considering surroundings-tunnel interaction in the future.

$$\begin{cases} S(P^*,\ I^*) = 1.1 \times \delta h \gamma_v \\ B(P^*,\ I^*) = 1.2 L \beta \end{cases} \tag{2}$$

where δ is material parameter varying from 0.6 to 0.866, h is the thickness of lining, γ_v is the critical shear strain, L is the half length of lining, and β is the ratio of mid-span deflection to half span. $S(P^*,\ I^*)$ and $B(P^*,\ I^*)$ are the implicit expressions with respect to normalized pressure and impulse for shear and bending, respectively.

5.6 Based on charge weight versus standoff distance

The damage assessment can also be performed by using charge weight and standoff distance based on some pre-defined damage criteria, such as the deflection-span ratio (Yang, et al., 2019), the crack grades (Koneshwaran, 2014, Koneshwaran, et al., 2015d), and the moment-force diagram (Colombo, et al., 2016), etc. According to the given damage criteria, the damage level of tunnel structures can be obtained corresponding to the given charge weight and standoff distance. Based on the obtained damage level under the specific charge weight and standoff distance, the boundary lines between different damage levels are fitted in the diagram of charge weight versus standoff distance. Threshold equations from Yang, et al. (2019) for different damage levels are given in Eq. (3). It is noted that in addition to the charge weight and standoff distance, there are some other factors as discussed in Section 4.3 influencing the damage levels of tunnel under blast loads. Therefore, this damage criterion should be cautiously used while other influencing factors might be involved.

$$R = \begin{cases} 3.27\ln(W) - 5.82 & \text{Slight damage} \\ 4.05\ln(W) - 10.80 & \text{Moderate damage} \quad (2\text{m} \le R \le 8m) \\ 4.14\ln(W) - 13.81 & \text{Severe damage} \end{cases} \tag{3}$$

where R is the standoff distance (m); W is the charge weight in TNT equivalence (kg).

5.7 Based on empirical equation of spall and breach

An empirical approach in UFC 3-340-02 (US Department of Defense, 2008), which was derived to calculate spalling and breaching in concrete slabs under blast loading, has been used to evaluate blast damage of tunnel lining by Bai, et al. (2018). The expressions of the empirical equation is given as

$$\frac{h}{R} = \begin{cases} \dfrac{1}{a_1 + b_1\psi^{2.5} + c_1\psi^{0.5}} & \text{Spall threshold} \\ \dfrac{1}{a_2 + b_2\psi + c_2\psi^2} & \text{Breach threshold} \end{cases} \tag{4}$$

where h is the damaged concrete thickness (ft); R is the standoff distance from slab to charge centre (ft), a_1, b_1, c_1 are constants equal to 20.02511, 0.01004, and 0.13613, respectively; and a_2, b_2, c_2 are equal to 0.028205, 144308, and 0.049265, respectively. Ψ is a spall parameter related to the concrete compressive strength, steel weight, and charge weight. The details can be referred to UFC 3-340-02 (US Department of Defense, 2008) and Bai, et al. (2018). Based on the empirical equation, the extent of spalling and breaching damage of tunnel lining could be determined under different charge weights. It should be noted that the empirical approach is established for free air or surface bursts. The multiple interactions between blast wave and tunnel structures are not considered. In addition, this method neglects the interaction between lining and surroundings.

6. Damage mitigation measures of tunnel under explosion

A range of mitigation measures against explosions has been developed, which could be classified into two categories, i.e., active and passive measures. The active mitigation measures reduce the destructive effects on tunnels by controlling the explosion source or activating appropriate systems to minimize blast pressure and impulse acting on tunnel structures. The passive mitigation measures mitigate blast damage to tunnel by installing protective layers, using high performance lining materials, and changing components of tunnels, etc.

6.1 Active mitigation measures

Tunnel structures usually face three main threats of explosion sources, i.e., terrorist attacks (i.e. high explosive), explosions of dangerous transported goods (i.e. VCE or BLEVE), and adjacent construction blasts (i.e. high explosive). The terrorist attacks are conducted intentionally by terrorists or hostile forces, while VCEs or BLEVEs accidentally occur in tunnels. The locations of such explosions vary and are difficult to be predicted. However, the threats of engineering blasting for construction near tunnels can be actively mitigated by controlling the explosion source. The designers of engineering blasting can adjust the blasting parameters to control blast pressure from explosion source, e.g., by using the millisecond delay technique (Qiu, 2014) and decoupling charge structures (Park and Jeon, 2010). The technique of millisecond delay could reduce blast pressures by controlling the delay times among a series of explosions. The decoupling charge structures could reduce the detonation pressures transmitting into soil or rock.

Apart from controlling the explosion source itself, suppression systems to reduce blast pressures in tunnel can be adopted to mitigate the damage of tunnel structures if the initiation of explosion is unavoidable (Shirbhate and Goel, 2020). A representative automatic suppression system is the high-speed, long-acting water deluge system, which has been used to mitigate the explosion threats in underground facilities (Chikhradze, et al., 2017). It is noted that an appropriate active suppression system must have a quick trigger, otherwise the shock wave that propagates rapidly in the tunnel cannot be suppressed in time. Although some active protection measures are currently available, their effectiveness and applicability are not necessarily assured since the explosions tend to be intensive and the blast waves propagate in sonic or supersonic velocities.

6.2 Passive mitigation measures

Compared to the active mitigation measures, the passive mitigation measures of tunnels against explosion loads have been more widely studied due to their adaptability to various explosion scenarios. Existing passive mitigation measures for tunnels can be divided into three categories, i.e., changing components of tunnel itself, installing protective measures, and using high performance materials. **Table 16** summarizes various mitigation and reinforcement measures for each category and their corresponding working mechanisms, and effectiveness and cost of specific measures.

Table 16. Summary of three passive measures.

Categories	Types	Specific measures	Mechanism	Effectiveness	Cost
Changing components of tunnel itself	Reinforcement	Anchoring	Improving strength of rock/soil surroundings	High	Moderate
		Grouting	Enhancing strength of soil surroundings	High	Moderate
		Increasing lining thickness and concrete grade	Enhancing strength and stiffness of lining	High	Moderate
	Mitigation	Providing ventilation channels	Releasing blast waves to outside of the tunnel	Moderate	High
		Using flexible joint bolts for segment lining	Increasing allowance of lining deformation.	Moderate	Moderate
Installing protective measures	Reinforcement	Applying CFRP sheet	Improving flexural rigidity and tensile capacity of tunnel lining	High	Moderate
	Mitigation	Applying polyurethane foam, expandable polystyrene (EPS) foam, wood, rubber, EPS-cement matrix, and protective steel sheets	Enhancing blast energy absorption	High	Moderate
Using high-performance materials	Reinforcement	Fiber-reinforced concrete	Improving the tensile and post-peak performance of lining.	High	High
	Mitigation	Sandwich structures	Enhancing blast energy-absorbing capability	High	High

The components of tunnel can be changed and enhanced by (1) installing some support measures such as anchoring (Deng, et al., 2014, Wu, et al., 2011) and grouting (Liu, 2009), (2) providing ventilation channels (Han, 2014, Tiwari, et al., 2015, Van den Berg and Weerheijm, 2006), (3) adjusting the parameters of the structure itself such as increasing the lining thickness (Tiwari, et al., 2015, 2018), improving the concrete grade of tunnel lining (Tiwari, et al., 2018), enhancing the steel reinforcement (Yang, et al., 2019), using the flexible joint bolts for the segment lining (Zhao, et al., 2016), and adding the flexible honeycomb between the segments (Koneshwaran, 2014). The anchoring could strengthen the inner connection of tunnel surroundings to improve the stability of tunnel surroundings, while the grouting can enhance the strength and stiffness of soil surroundings to significantly increase the blast-resistance of tunnel structures. Installing the ventilation channels can release the blast wave inside the tunnel to outside of the tunnel, thereby reducing the range and level of tunnel damage. The parameter-adjusting measures, such as increasing the thickness, concrete grade, and steel reinforcement of tunnel lining could enhance the strength and stiffness of structure, while other measures such as using flexible joint bolts for segment lining and adding flexible honeycomb between segments could increase the allowance of lining deformation against blast loading.

Installing protective layers on the surface or in the vicinity of tunnel is another effective mitigation measure. The polyurethane foam (De, et al., 2016, Koneshwaran, 2014), the expandable polystyrene (EPS) foam (Qiu, 2014), the wood (Qiu, 2014), the rubber (Qiu, 2014), the EPS-cement matrix (Zhao, et al., 2015), and the protective steel sheets (Cichocki, 1999) have been studied as the sacrificial cladding or energy absorbing layer of tunnels. These materials installed on the surface or in the vicinity of the tunnel could absorb blasting energy due to their high damping and compressibility (Stolz, et al., 2010), which considerably reduces the intensity of blast loading acting on the tunnel structure behind the protective layers. In addition to absorbing energy, the protective layers adhered or wrapped on the tunnel lining using CFRP (Chen, et al., 2015, Xie, et al., 2014, Yang, et al., 2019) can improve the flexural rigidity and loading capacity of tunnel lining, and suppress the formation of structural cracks and the rotation of lining walls (Chen, et al., 2015, Xie, et al., 2014, Yang, et al., 2019). It is worth noting that optimizing the thickness of protective layer is imperative for the protective design of tunnel lining. A suitable thickness of protective layer can achieve good blast resistance, beyond which the increase in thickness does not result in the incremental benefit.

In addition, high performance lining material can be used to replace traditional RC lining material to improve the blast resistance of tunnels. Existing studies have experimentally and numerically investigated the performance of tunnel linings made of advanced materials or structures, such as the reinforced cement concrete (RCC) (Chaudhary, et al., 2018), the basalt fiber reinforced polymer (BFRP) concrete (Zhou, et al., 2020), the steel fiber reinforced concrete (SFRC) (Chakrabortya, et al., 2014, Chaudhary, et al., 2018), the high-performance fibre-reinforced cementitious composite (HPFRCC) with the core of SFRC (Colombo, et al., 2014, 2015, 2016), the steel fibre reinforced geopolymer concrete (SFRGC) (Meng, et al., 2020a, 2020b), the steel-dytherm foam-steel (SDS) panel (Chakrabortya, et al., 2014, Chaudhary, et al., 2018), the steel polyurethane foam-steel (SPS) panel (Chakrabortya, et al., 2014, Chaudhary, et al., 2018), and the steel-aluminium cenosphere syntactic foam-steel (SAS) (Chaudhary, et al., 2018). It should be noted that although the high performance materials have been intensively studied, their engineering application as lining material is very limited due to the cost and immature construction technology. Therefore, the cost-effectiveness and simplicity of these mitigation measures can be further investigated for engineering practice.

7. Future perspectives and conclusion

This study presents a state-of-the-art review on the dynamic response, damage assessment and damage mitigation of tunnel subjected to blast loads. Most relevant literatures regarding blast response of tunnels have been reviewed to better understand the behaviors of road tunnels under blast loads. Firstly, the common road tunnels, various explosion scenarios to tunnels, and the corresponding blast wave characteristics around tunnel are reviewed. Next, the dynamic response and damage of tunnel under blast loads, with respect to analysis methods of tunnel response, types of tunnel response, and key factors influencing tunnel response are included. Then, the assessment criteria of tunnel damage are summarized followed by the damage mitigation measures for tunnels against blast loads. The main findings are summarized as follows.

(1) The existing theoretical methods to predict response of tunnel are not accurate enough due to its elastic response assumption. Most of the existing experimental tests and numerical studies focused on the tunnel response under high explosive explosions. Very limited studies investigated dynamic response of tunnel under gas explosions and no study investigated dynamic response of tunnel caused by the coupling effect of gas explosion and followed fire, which are deemed necessary for further study.

(2) The existing experiments were carried out for tunnels in solid medium, while no published experimental study on the response of tunnel in water has been conducted. In the previous numerical studies on the dynamic response of tunnel in water, the effect of oscillations of water bubbles on tunnel damage was not considered, leading to conservative estimation of the tunnel damage. Hence, more studies are required to investigate dynamic response of tunnel in different buried media under various types of explosions.

(3) Road tunnels could have different damage modes under different explosion conditions, i.e., the spalling and crushing of lining, cracks of lining, deformation and collapse of lining, bending and tensile failure of reinforcement, and deformation and damage of tunnel surroundings. Most of the existing studies focused on the blast damage to main structure (i.e., the lining) and surroundings. Only

limited studies investigated the blast damage to tunnel associated (i.e., secondary) structure, such as the escape passage, the smoke channel, and the mid-wall of multi-cell tunnel. It should be noted the associated structures of tunnel are more vulnerable to blast loads due to the lack of support from surroundings. Hence, it is essential to investigate the dynamic response of the associated structures and their influence on the damage behaviors of tunnels under blast loading in the future.

(4) The explosions occurring in the shallow buried road tunnel could induce ground vibrations due to the intensive blast-induced stress wave, which might endanger adjacent buildings. Hence, the performance and safety of buildings subjected to the tunnel explosion induced ground vibration need be investigated for further study.

(5) Various influencing factors on the blast response of tunnel have been investigated. However, some factors such as charge position insider and outside tunnel, tunnel cross sectional geometry and dimension, depth ranges of shallow tunnel and deep tunnel, different slopes of tunnel, and interface properties between lining and surroundings, have not been well investigated and are recommended for further study.

(6) Various assessment methods of blast damage of tunnel have been proposed while these methods have various limitations in assessing and quantifying blast damage of tunnel. Hence, there remains a need for further study to develop reliable assessment methods to address these drawbacks in the existing methods.

(7) A range of mitigation measures against blast damage of tunnel have been investigated. However, most of the mitigation measures are still at the early research stage and have not be put into engineering practice due to the high-cost and immature construction technology. There remains a need for efficient, low-cost and easy-to-install mitigation measures for tunnels against blast loads.

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