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BLAST RESPONSE OF UNDERGROUND STRUCTURES SUBJECTED TO EXTERNAL EXPLOSION – A REVIEW

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ABSTRACT

Recent experiences believe that the complex underground structures response in a different manner when subjected to blast explosion compared to the aboveground structures. The underground structures have experienced significant structural and non-structural damages due to blast explosion. The blast response of underground structures depends on various uncertainties parameters such as weight of the explosion charge, distance from the blasting source, properties of the surrounding soil, structural type and geometric. In this study, a review of various numerical approaches adopted in investigating the behaviour and response of underground structures when subjected to external blast loads is presented. In particular, the efficiency of numerical techniques in predicting the dynamic blast response of underground structures is critically discussed. The review includes a comparison of the adopted methodology and the influence of uncertainties parameters (e.g. structural typology, soil condition, explosive charge) on modifying the predicted damage of the structures. Furthermore, the advantages and effectiveness of the numerical method in predicting the blast response of such structures are included.

1.0 INTRODUCTION

In these modern times of space scarcity, underground tunnels are chosen as a vital component of an urban transportation and utilities network. High demand for these multi-functional structures is increasing due to the fast population growth and limited aboveground spaces, especially in urban areas. The popularity of multi-functional underground facilities such as subway tunnel stations, military shelters, and utility tunnels are undeniable as in Figure 1.

Underground structures are classified as complex critical structures which require detailed analysis and design procedures. Tunnels, for instance, are constructed as part of transportation and utility infrastructure in urban environments. Considering their importance to the economy and public safety, any instability to the tunnels will be highly detrimental to the performance of the network. Indeed, the underground structural project is many times more expensive than a surface project, which required superior consideration before and after construction stages take place. In such cases, any potential risk to the structure should be registered, and an appropriate management plan must be implemented to control the associated risk.

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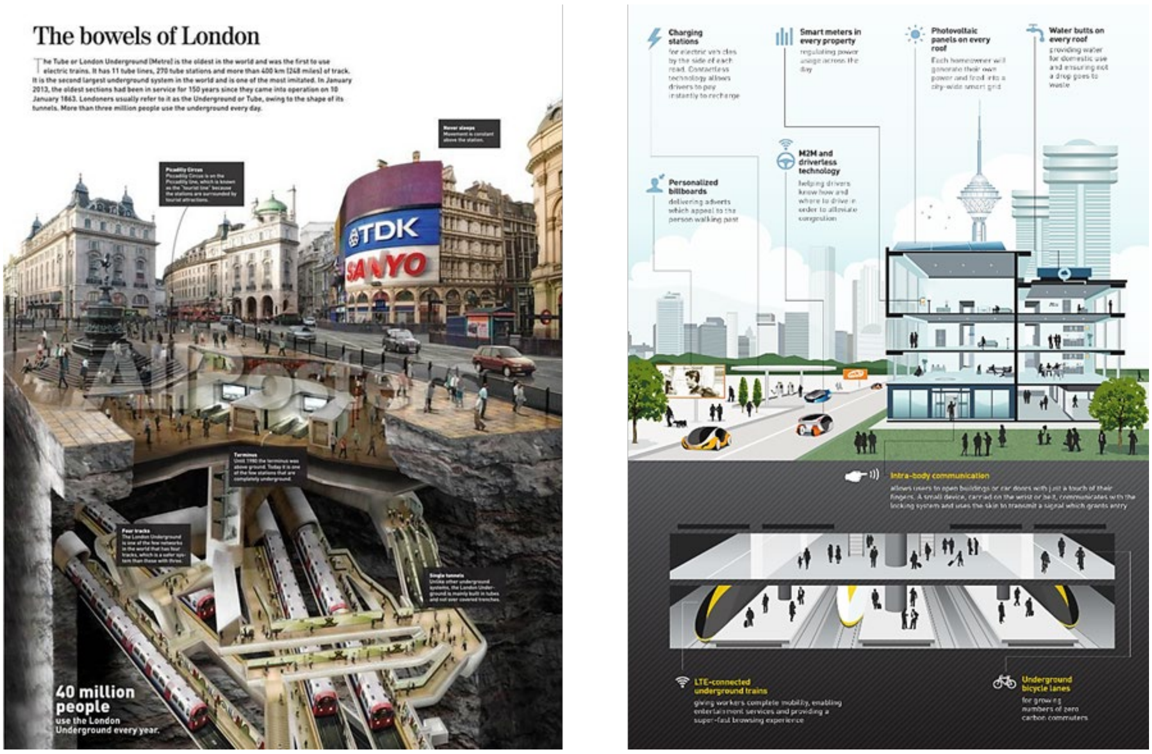

Figure 1. Multifunction underground facilities [1–2]

Recent experience proved that underground structures damage severely due to blast explosion (*i.e.* internal and external) from the either accidental or intentional event (*i.e.* terrorist attack) [3–15]. The escalating terrorism threats as summaries in Table 1 contributes to severe catastrophic events, which cause thousands of deaths, large-scale damages, and economic losses. The reported considerable damage has riveted the world attention on the effect of this extreme load to structural components. Therefore, numerous research have performed a critical in-depth study to understand and investigate the response of the structures under the impact of blast loads.

To investigate the blast response of underground structures, it is necessary to determine the parameter that has a reasonable influence on blast-induced vibration. In this study, a review of various numerical approaches adopted in investigating the response of underground structures when subjected to external blast loads is presented. In particular, the efficiency of numerical techniques in predicting the dynamic blast response of underground structures is critically discussed. The review includes a comparison of the adopted methodology and the influence of uncertainties parameters (e.g. structural typology, soil condition, explosive charge) on modifying the predicted damage of the structures. On the hand, the advantages and effectiveness of the numerical method in predicting the blast response of such structures are included. This effort, in turn, is beneficial in providing new information for protecting THE critical underground structures as well as improving public awareness and preparedness towards unpredictable extreme hazards.

Table 1. Escalation of underground explosion and damages

Occurrences	Location	Types of Damages / Losses
March 2010	Lubyanka station and Park Kultury station, Moscow, Russia	Killing at least 37 people and wounding more than 65 people
July 2005	London's Underground trains, United Kingdom	The attacks killed 52 people and 700 people injured
March 2004	Madrid's commuter train system, Spain	Killed 191 people and wounded 1,800 (10 explosions took place on-board of four trains)
February 2004	Avtozavodskaya subway station Moscow, Russia	A bomber killed 41 people, and approximately 120 people were injured
February 2003	Daegu Metropolitan Subway, South Korea	Killed approximately 200 people and 147 people injured
February 2001	Belorusskaya station, Moscow,	Approximately 15 people including 2 children

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Occurrences	Location	Types of Damages / Losses
	Russia	injured in the rush-hour bomb blast
June 2000	New York's subway, Brooklyn, New York City	About 66 people injured, whereby 3 victims were in critical condition
March 2000	Tokyo subway, Japan	About 4 killed and more than 40 injured in the rush-hour collision between two trains
October 1995	Baku's metro station, Azerbaijan	Nearly 300 people are killed and at least 250 injured
August 1995	Toronto Subway, Ontario, Canada	Killed 3 people when a packed commuter train collides with a stationary train
July 1995	Paris Metro system, France	More than 6 killed or injured in a bomb blast
July 1995	Saint-Michel Station, Paris, France	Killed eight people and injured over 200
March 1995	Tokyo subway, Japan	Twelve killed and thousands injured in a gas attack
July 1994	Azerbaijan, Baku's metro station	Killed 13 people and injured 42 people
August 1991	New York City subway, New York	Five people killed and more than 200 injured
November 1987	Kings Cross station, London, United Kingdom	Thirty-one killed and dozens injured when an escalator fire engulfs the ticket hall at Kings' Cross station
February 1975	Moorgate station, London, United Kingdom	Approximately 43 people dead and injured
August 1903	Couronnes station, Paris, France	About 100 people died at Couronnes station

2.0 BLAST LOADING

In particular, blast loading is divided into two types: internal loading and external loading. It can be estimated based on the location of the explosive charge is being placed [16–17]. The blast loadings can be found in the form of solid, liquid or gas explosive (*i.e.* nuclear weapon or conventional high-explosive bomb). Alternatively, the distribution of blast energy also can be estimated based on the types of explosions. *An external blast* or also known as an unconfined explosion can be divided into three categories: (i) free airburst, (ii) airburst, and (iii) surface burst. The significant difference of these burst explosion is the location of the detonation charge. *Free airburst* explosion refers to an open-air blast, which causes a wave that spreads from the source of detonation to the structure without any wave amplification.

Meanwhile, the *airburst* explosion occurs when an explosion is located above the targeted structure at a given distance and height. Thus, the initial blast wave increases due to the reflection of the ground before it contacts the structure. The height limitations of these explosions are two to three times the height of a one-story or two-storey structure [16]. However, the *surface burst* explosion occurs when the detonation is situated near or on the ground, whereby the initial pressure increases immediately because of refraction on the ground. In addition, subsurface burst also is categorised as an external explosion, whereby the explosive charge is in shallow depth which is between the ground surface to top level of tunnel crown.

In general, the burial depth is measured from the ground surface up to the crown of the tunnel lining and is ranging from shallow to moderate burial depth. Figure 2 describes the three different burial depth of the tunnel, namely, shallow, medium or deep. The figure shows tunnel buried with H depth of soil is considered as a shallow tunnel when the ratio of burial depth (C) to the diameter of the tunnel (D) is less than 2 (*i.e.* C/D ≤ 2). In contrast, the tunnels buried at the ratio C/D more than 2 (*i.e.* C/D ≥ 2) are referred to moderate or deep tunnels.

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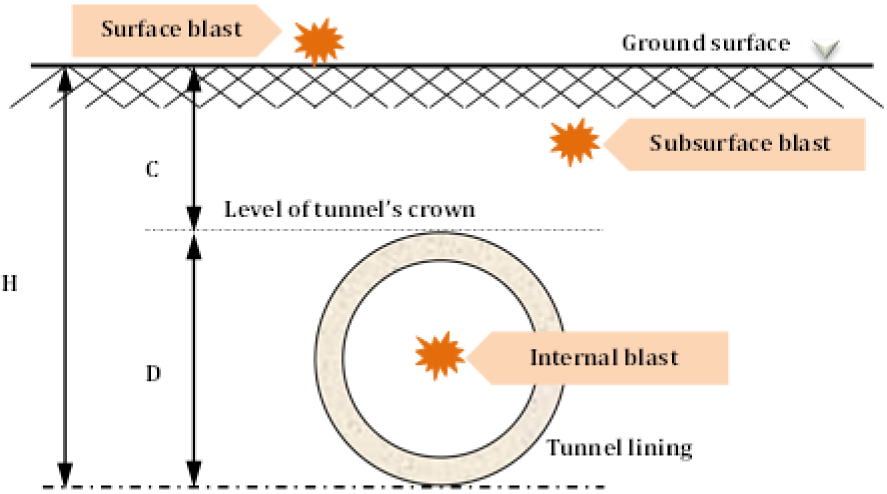

Figure 2. Location of explosive charge and burial depth

Meanwhile, an *internal blast load* is a confined explosion, whereby, the explosion is placed inside the structure which subsequently produces exceptionally high peak pressures and initial wavefronts. This type of blast is divided into three categories: (i) fully vented, (ii) partially confined, and (iii) fully confined. The initial wave of a *fully vented explosion* is vented to the atmosphere forming a shock wave which propagates away from the structures which having one or more openings [17]. Second, a *partially confined explosion* occurs when the explosion produced within an element of the structure with limited size openings and frangible surfaces. For this type of explosion, the initial wave of detonation vented to the atmosphere and produced a long duration of shock pressures. Meanwhile, for a *fully confined explosion*, the internal blast loads consist of unvented shock loads and produced the most prolonged period of shock pressures. The magnitude of shock pressures usually small and only affect the facilities located outside the containment structure [17]. Table 2 summarised the blast loading categories with the pressure loads for two different types of charge confinement.

Table 2. Blast loading categories [16–17]

Charge Confinement	Categories	Pressure loads
External / Unconfined	Free airburst	Unreflected
	Airburst	Reflected
	Surface or Subsurface burst	Reflected
Internal / Confined	Fully vented	– Internal shock – Leakage
	Partially confined	– Internal shock – Internal gas – Leakage
	Fully confined	– Internal shock – Internal gas

Besides, for underground structures, there is one additional type of internal explosion can be taken into consideration, namely, *deep underground burst*. The blast effects are magnified because it detonated within an enclosed space and resulted in large-scale damages of underground structures. No air burst is produced; however, the energy forming the cavity around the bursting point and appears in the form of a ground shock wave [19].

Furthermore, the impact of an explosion also influences the types and weight of explosive charge used. Each explosive device has a different intensity of explosion depending on their mass-specific energy, the detonation velocity, the detonation pressure and other related factors. As illustrated by Ngo *et al.* [20], it can be seen that the blast explosion will decrease in strength and speed depending on the location or distance of the blast to the structure as the blast waves propagate in Fig 3. Currently, the TNT (Trinitrotoluene) equivalent unit is adopted to estimate the charge mass of explosive. The specific energy of different types of explosive and their conversion factors to TNT equivalent units is presented in Table 3.

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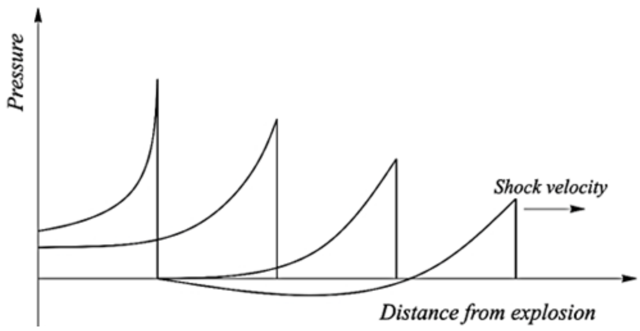

Figure 3. Variation of blast pressure with distance [20]

Table 3. Specific energy of explosives and TNT equivalent [16]

Types of explosives	Specific energy (Q_x / kJ/kg)	TNT equivalent (Q_x / Q_{TNT})
Compound B (60% RDX, 40% TNT)	5190	1.148
RDX (Ciklonit)	5360	1.185
HMX	5680	1.256
Nitroglycerin (liquid)	6700	1.481
TNT	4520	1.000
Explosive gelatin (91% nitroglycerin, 7.9% nitrocellulose, 0.9% antracid, 0.2% water)	4520	1.000
60% Nitroglycerin dynamite	2710	0.600
Semtex	5660	1.250
C4	6057	1.340

3.0 BLAST RESPONSE OF UNDERGROUND STRUCTURES UNDER AN EXTERNAL EXPLOSION

Blast explosion refers to a short-term loading which causes a rapid and intense action to a targeted structure subsequently contribute to induce severe local structural damages. In this section, several investigations on the response and performance of underground structures under blast explosion were discussed and highlighted. As mentioned in the previous chapter, a blast explosion can be group into two; external and internal. Several studies have been conducted in evaluating performance and response of underground structures for a different type of blast. In this section, the review is divided into three subsections depending on the location of explosive charge and types of target structures involved. The previous numerical research is compared and critically discussed based on the adopted numerical method, explosive type, structural type, and properties of surrounding soil and other related parameters.

3.1 Protective Structures Under Conventional Weapons

The impact of conventional weapons on military underground protective structures has received special attention from previous researches [21–25]. Conventional weapons refer to a type of weapon that can damages due to kinetic or incendiary or explosive energy (*e.g.* armoured fighting vehicles, combat aircraft, artillery and warships), but exclude weapons of mass destruction (*e.g.* nuclear, biological, and chemical weapons). Typically, any armament used in crimes, conflicts or wars is also categorised as conventional weapons. The example of such weapons is small arms, defensive shields and light weapons, bombs, shells, rockets, missiles.

Pioneer researchers, Weidlinger and Hinman [22], have started their study by presenting detailed procedure for analysing underground protective structures, *i.e.* military shelter subject to conventional weapons effects. A box-shaped reinforced concrete structure located below the ground surface was modelled and was subjected to three generic positions of the explosive source and the stand-off distance, R_o as illustrated in Figure 4. The researchers proposed the decoupled single degree of freedom (SDOF) formulation for analysing the impact of blast load, taking into consideration the complex structure-medium (*i.e.* soil) interaction (SMI) effects. The decoupled SDOF formulation was validated with the finite element (FE) analysis performed using the nonlinear FE Code, *i.e.* FLEX. The proposed SDOF formulation,

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which usually adopted for analysing the aboveground structure, has proven as an efficient method for optimisation studies, concept evaluations and preliminary designs. However, for underground structures, the researchers highlighted the challenges of modelling the underground structures using the proposed method due to the presence of the surrounding soil. Due to that, the decoupling concept is applied to SDOF models to obtain both elastic-plastic deformation response and rigid body response.

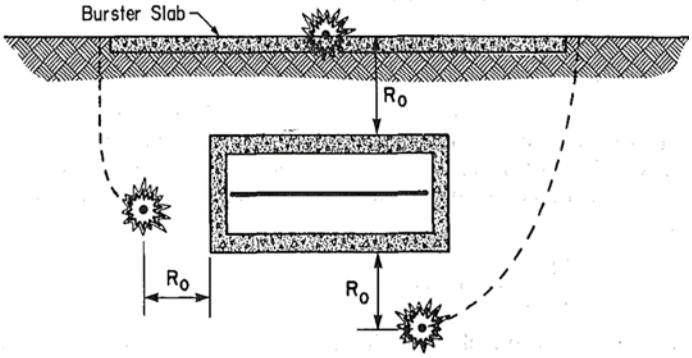
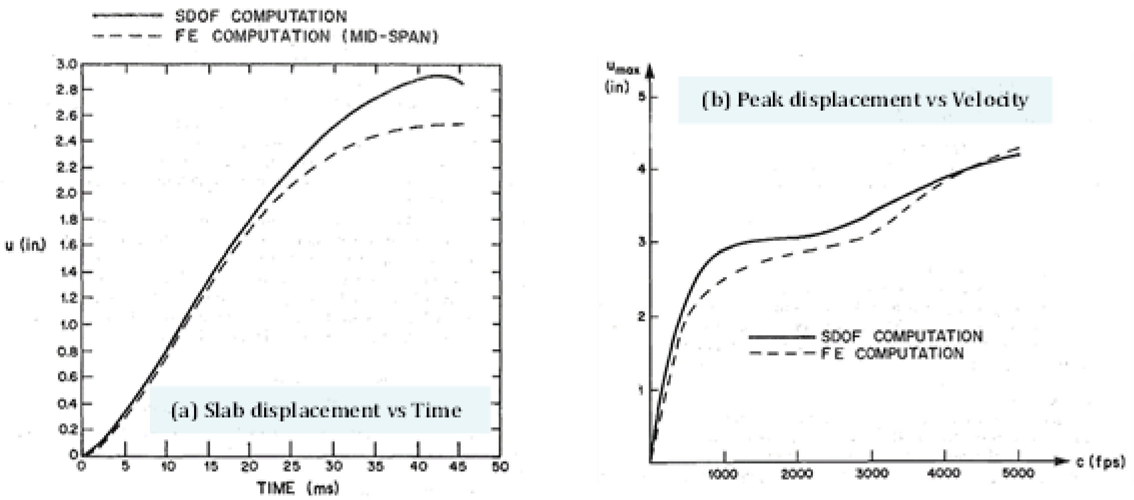


Figure 4. Underground protective structure modelled by [22]

As shown in Figure 5, comparison between decoupled SDOF and FE computations shows a good agreement, especially concerning early time peak responses (see Fig, 5(a)) when the effects of reflections from the surface or discontinuities within the soil are not significant. Besides, it is observed that a substantial reduction of the response may be achieved only by a material that has a velocity (c) more than 1,000 fps (see Figure 5(b)). The response beyond that value is not very sensitive to back-fill specifications. Similarly, Sashidhar and Nalini [24] proposed design of burster slab (see Figure 6) which located on the top of underground structures to prevent a weapon from penetrating through the soil and damage the structure. The authors also highlighted that the underground protective structure that constructed without the burster slab need to be buried at deeper depth compared to with burster slab.



(a) **(b)**

Figure 5. Deformation response of burster slab buried structure[22]

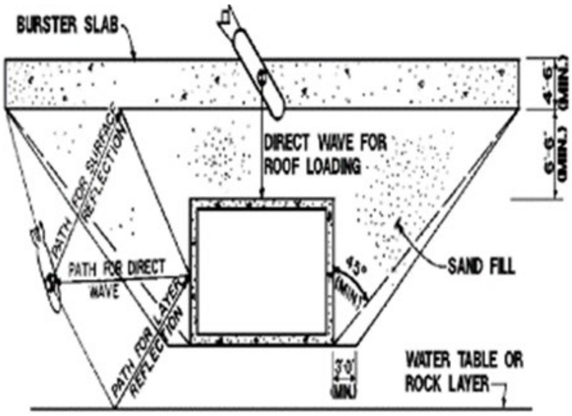


Figure 6. Geometry of underground structure proposed by [24]

3.2 Tunnel Response Under The Impact Of A Surface Explosion

Apart from that, numerous researches have been conducted to investigate the blast response of underground tunnels when subjected to the external surface (*i.e.* [26–35]) blast loads. In tunnelling engineering, the strength and durability of the tunnel lining (*e.g*. circular or rectangular shaped) play a vital role in representing the whole performance of the tunnels apart from the other remaining components. Damages of the tunnel lining may result in the failure and disturbance to the tunnel facilities. Thus, crucial attention needs to be given as early as in the analysis and design of the tunnel lining. In order to evaluate the performance and response of the tunnel under blast explosion, the sensitivity of tunnel lining upon several parameters such as the intensity of blast loading, size of the crater, dynamic undrained shear strength, dynamic Young's modulus, and soil-damping ratio have to be taken into account.

Continuous research has been done by S. Koneshwaran *et al.* [27–29] to study the response of buried bored (*i.e.* circular-shaped) tunnels subjected to surface explosion. Taking advantages of the numerical method, the authors [27] have developed two numerical coupling techniques (see Figure 7). Two developed numerical techniques are (1) Fluid-Structure Interaction (FSI) in Arbitrary Lagrangian-Eulerian (ALE) simulation (*i.e*. Coupled FSI in ALE) and (2) Smooth Particle Hydrodynamics (SPH) with Finite Element Method (FEM) simulation (*i.e.* Coupled SPH–FEM). The ALE approach was developed, combining the best features of the Lagrangian and Eulerian solver while reducing their respective weaknesses. ALE can solve problems in fluid dynamics, solid mechanics and coupled problems describing fluid-structure interaction (FSI). Meanwhile, the SPH is a meshless computational Lagrangian hydrodynamic particle method developed for astrophysics problems in 1977. It initially dealt with modelling of interacting fluid masses in a vacuum without boundaries. Each of the proposed numerical techniques simulates similar model dimensions and material parameters.

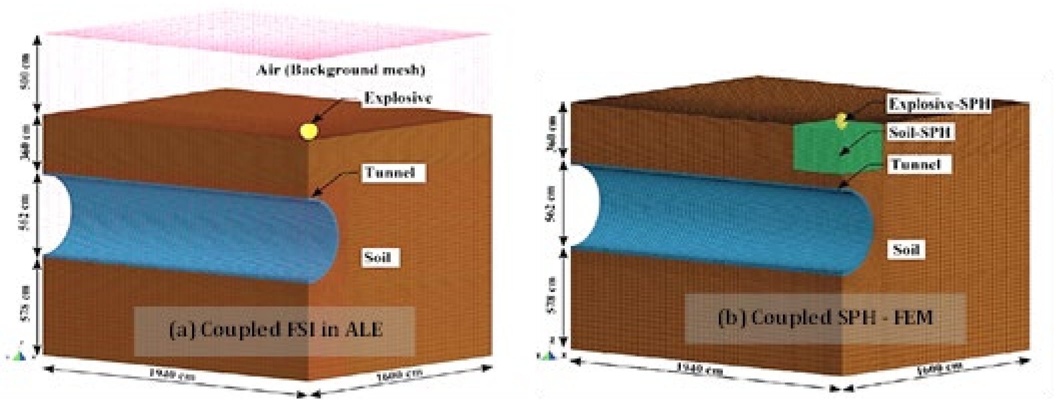


Figure 7. Numerical coupling techniques studied by [27–29]

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The results and outcomes of the two techniques were compared with results from existing test data. They found that the ALE technique is a better method for describing the tunnel response for surface explosion compared to the SPH technique which provides modelling accuracy and computational efficiency. Further study was extended by performing a sensitivity analysis of segmental tunnel [28, 29]. Using the sophisticated finite element software LS-DYNA, damage states of tunnels were identified, considering the influence of soil type, joint type and the number of segments forming the tunnel ring. Result denotes that, joint types may have influenced the response of tunnel segments when subjected to weaker blast loads, whereas the segments were damaged before the joint acting under higher blast loads. It is also highlighted that the increase in the number of segments did not improve the blast performance of the tunnel and concluded that the tunnel is more vulnerable to surface explosions, which occur directly above the centre of the tunnel than those that occur away from the tunnel centre.

On the other hand, Gui and Chien [35] have conducted the numerical investigation of surface blast-resistant analysis for a tunnel passing beneath Taipei Shongsan airport. The researchers recommended that, for cost-effective analysis, a designer should adopt a good ground dynamic soil parameters and give some allowance to the additional protective layer over the tunnel structure. The authors conducted a parametric study for a blast-resistant analysis for a tunnel subjected to the underground external explosion. The researchers highlighted that the six crucial parameters which control the level of damages of the structure, and there are the intensity of blast loading, size of crater formation, dynamic undrained shear strength, dynamic Young's modulus, and soil-damping ratio.

3.3 Tunnel Response Under The Impact Of A Subsurface Explosion

Another type of external blast explosion is a subsurface explosion or also defined as shallow buried explosives. The impact of a subsurface explosion on tunnels structures has been investigated by numerous researchers (*i.e.* [36–41]). Luccioni and Ambrosini [36–38] have conducted several studies to investigate the blast response of tunnel using numerical simulation. For validation purposes, the obtained numerical results were compared with experimental approaches presented by the previously available literature. The authors investigated the effect of the subsurface blast with an explosive charge in a range of 10 to 100 kg of equivalent T.N.T. They proved that the obtained numerical results have a good agreement with the experimental works produced by other previous research, where the maximum crater diameter (*e.g.* Figure 8) is between the range of $0.4 < \lambda_c < 0.6$. (where λ_c is the depth of detonation divided by one-third of explosive's mass). They also concluded that the shape of the explosive load and the type of soil slightly influence the crater diameter but did affect the velocity and energy transfer of blast wave.

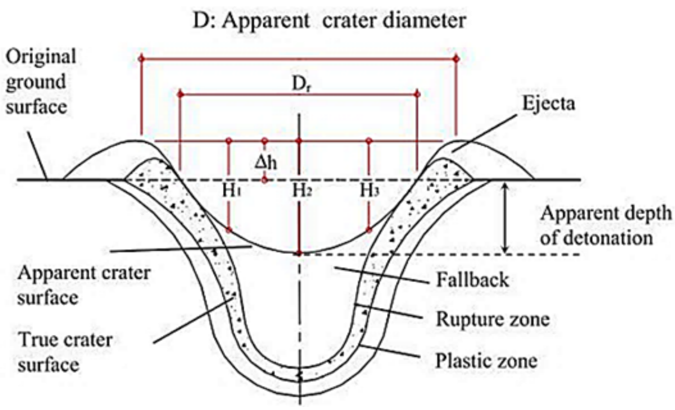

Figure 8. Conventional crater [36–38]

Interesting research conducted by Mohamed H. Mussa *et al*. [30], assessed the damage of underground box tunnel under the impact of a surface explosion. The researchers performed a numerical simulation using the ANSYS/LS-DYNA software. The studies investigated the damage behaviour of an underground box frame tunnel caused by four different TNT charge weight of surface explosion, *i.e.* 227kg, 454kg, 1814kg, and 4536kg which placed in sedan, van, small delivery truck (SDT), and container carrying, respectively. The Arbitrary Lagrangian-Eulerian (ALE) technique was used to simulate and monitor the propagation of the blast pressure waves into the soil. The validation results indicated that the pressure

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waves propagated into the soil as hemispherical waves, and the peak pressure values closely matched the predicted values of the technical design manual TM5-855-1, except for considerable distances.

The authors revealed that the velocity and acceleration increased significantly at depth 4 m, as compared with depth 3 m due to the existence of tunnel structure which produced a reflected wave as described in Figure 9. They also stated that the interaction between the explosive charge weight, tunnel lining thickness, and burial depth, whereby the tunnel lining thicknesses of 500 and 750 mm at different burial depths were effective at reducing the influence of the explosive charge weight. Interestingly, the authors highlighted the damage estimation revealed that a box tunnel could resist a container explosion with 4536 kg of TNT when it was placed at a depth of 8 m with a lining thickness of 750 mm.

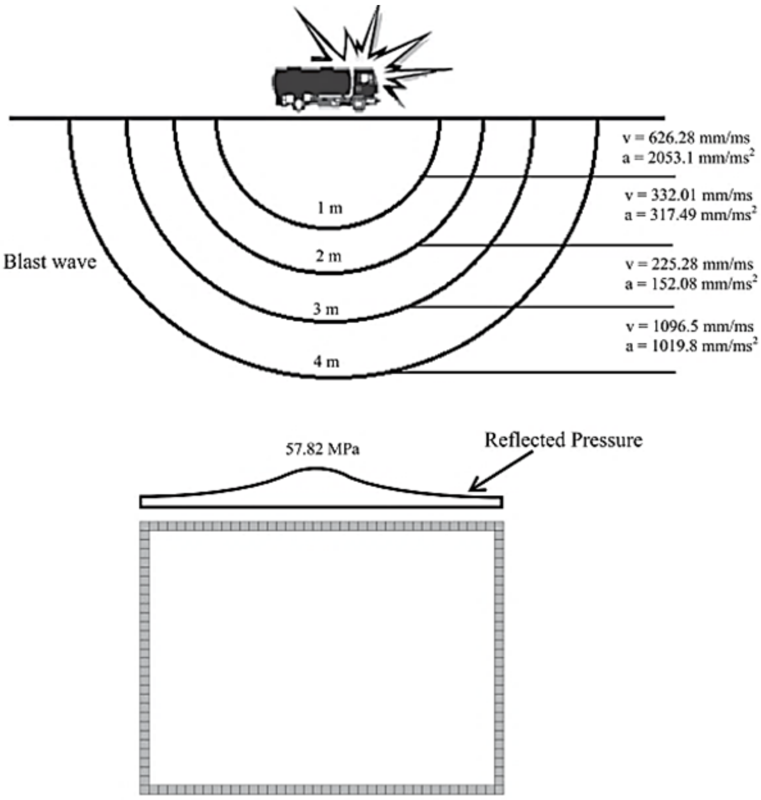

Figure 9. Mechanism of blast wave propagation [30]

Latest works by Q. Zhou *et al.* [31] proposed the use of basalt fibre reinforced polymer (BFRP) bars to reinforce the shallow-buried concrete urban utility tunnels (UUTs). The authors designed and constructed two types of tunnel model, namely, (i) shallow-buried BFRP bars reinforced UUT (BBRU) and (ii) shallow buried steel bar reinforced UUT (SBRU). This effort is proposed as a solution to improve the corrosion-resistance of UUT and provide excellent survival capability when subjected accidental explosion. The study compared the obtained results between tunnel reinforced with BBRU and SBRU (see Figure 10). Based on the comparison, the BRRU provided an excellent elastic performance under intense explosion cases, which makes the BRRU much stiffer and more durable than the SBRU. The tunnel reinforced with BBRU experienced smaller displacements, strains, and more evenly distributed longitudinal cracks. The author also revealed and suggested that the BRRU might be a better choice for coastal and protective UUTs.

In this paper, the merits and shortcomings of the 2D and 3D numerical approaches in investigating the effect of a buried explosion to the underground structure were highlighted. Serkan Ucer [42] discovered that the most striking difference between the analyses results of 2D and 3D is the reverse horizontal displacement of the tunnel lining at the bench level of the Bolu Tunnels due to the loss of 3D effect of tunnel lining. The 2D analyses resulted in higher internal forces in the intermediate lining compared to 3D analyses. In comparison, 3D analyses provide excellent agreement results with real site data even though it is very time-consuming due to many nodes, element and meshes. Alternatively, the required analysis time may be reduced using intelligent 3D analysis as proposed by [43].

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It is noticeable that the 2D analyses tend to yield less accurate results such as overestimate the values of forces and moments, which may result in uneconomical design [44]. Conversely, [39] revealed that the 2D model could predict the blast wave propagation satisfactorily in the soil medium, which is acceptable for the analysis of buried structures subjected to blast loading. In overall, it can be concluded that the 2D analyses may provide reasonably accurate results with a simple model which suitable for preliminary analysis [39, 43]. Meanwhile, 3D analyses should be adopted for analysis of structure with complex geometries which gives a more realistic solution of soil-structure interaction to simulate all modes of deformation of the damaged tunnels rigorously [42, 44]. It is widely accepted though that two-dimensional plane strain models provide a reasonable approximation of the problem. In addition, [44] suggested that the modern and sophisticated geotechnical engineering software (GTS) as an excellent finite element software for 3D analysis of tunnel which may speedy the works and provide reasonably accurate results.

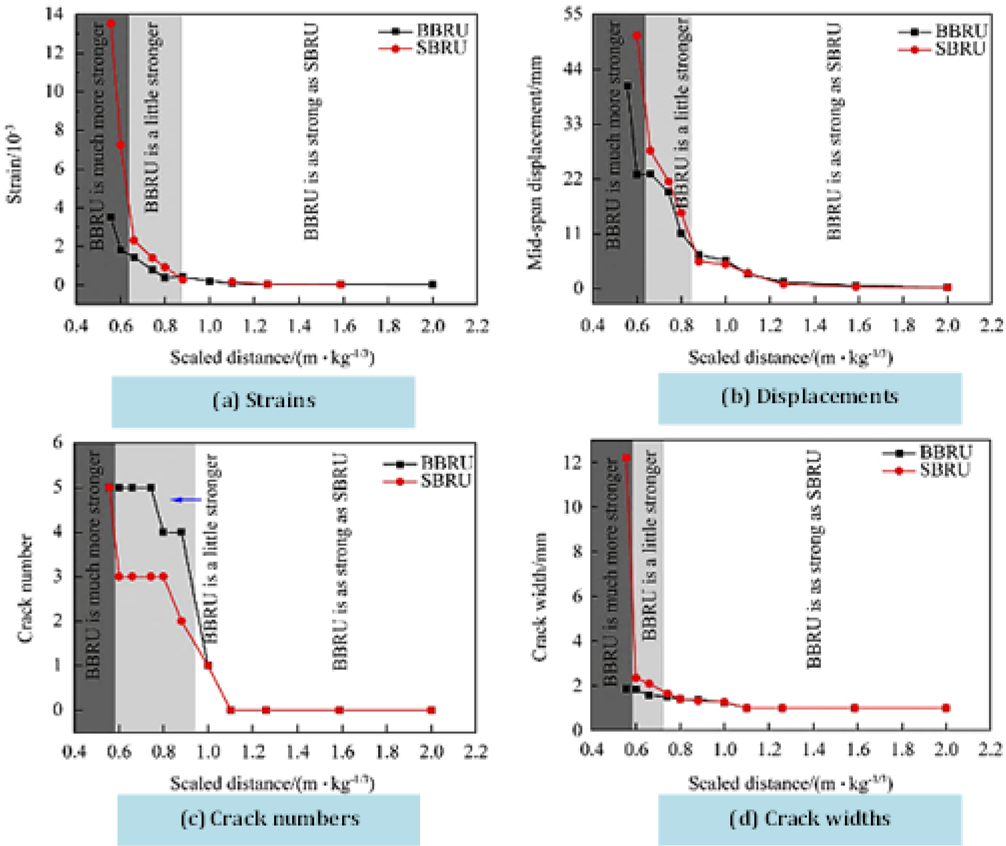

Figure 10. Comparison between blast response of tunnel reinforced with BBRU and SBRU [31]

4.0 CONCLUSION

In this paper, literature was reviewed various numerical approaches adopted in investigating the behaviour and response of underground structures when subjected to external blast loads is presented. In particular, the efficiency of numerical techniques in predicting the dynamic blast response of underground structures is critically discussed. The review includes a comparison of the adopted methodology and investigates the influence of uncertainties parameters on modifying the predicted damage of the structures. Besides that, the present article aims to provide a better understanding of the theory and recent studies on the numerical techniques used for simulation of tunnel subjected to external blast loads. On the hand, the advantages and effectiveness of the numerical method in predicting the blast response of such structures are included. It shows that the most influential parameters are taken into consideration when analysing the blast response of underground structures are characteristic of an explosive charge (*i.e.* type, location and weight of explosives), structural characteristics, soil condition, and burial depth. In addition, research may add more parameters depending on their scope and purpose of research. It also suggested that the 3D analyses should be adopted for analysis of with complex underground structure because it provides a more realistic solution of soil-structure interaction to

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simulate all modes of deformation of the damaged tunnels rigorously. It is widely accepted though that two-dimensional plane strain models provide a reasonable approximation of the problem. The information provided in this review paper might be beneficial for protecting the critical underground structures as well as improve public awareness and preparedness towards unpredictable extreme hazards.

5.0 ACKNOWLEDGEMENT

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