ISSN: 1687-1006 p
ISSN: 2682-3640 e

The Egyptian International Journal of Engineering Sciences and Technology

Vol. 37 (2022) 7–16

https://eijest.journals.ekb.eg/

Effect of Blasts on Underground Tunnels- An Overview

Sally Hassan[a*] , Alaa Ata[b], Marwa Nabil[c], and Mahmoud Nawar[d]

[a] *Teaching Assistant at Structural Engineering Dept, Faculty of Engineering, Zagazig University, Zagazig, Egypt*
[b] *Professor of soil Mechanics and foundation, University of Hertfordshire-Hosted by GAF, School of Engineering and Computer Science, Egypt*
[c] *Associate Professor at Structural Engineering Dept, Faculty of Engineering, Zagazig University, Zagazig, Egypt*
[d] *Lecturer at Structural Engineering Dept, Faculty of Engineering, Zagazig University, Zagazig, Egypt*

ARTICLE INFO

Keywords:

1st blast loads
2nd underground tunnels
3rd soil dynamic
4th numerical analysis

ABSTRACT

Terrorist actions and defacements have become one of the widest threaten for humans and structures. Underground tunnels can be used as shelters against blast, so it is very important to study their behavior under blast loads. The safety of tunnels is lean because of the lack of suitable ways to discover these events early. Techniques are essential to quantify the resistance of underground structures against blasts as a protection and to calculate the risks caused by the failure of their elements. The appropriate advanced methods could be experimental, numerical, or a mixture of both. The experimental work is limited because of the cost and complication, and so numerical analysis is suitable for blast study in addition to available experimental tests. The parameters affecting the safety of tunnels such as the weight of explosive, lining material and thickness, soil stiffness, burial depth, thickness cover, shape of a tunnel, diameter of the tunnel, the standoff distance, the location of blast charge and also the effect of one tunnel to another in case of twin tunnel discussed by various researchers have been overviewed in the present work. The paper presents an overview of the effect of blast on tunnels for beginner researchers and structural engineers to understand such complex loading situation. New strategies which can be adapted to mitigate the effect of surface and internal blast loads on shallow and deep tunnels should be investigated. Studies should use numerical simulation of a tunnel buried in a saturated soil profile to imitate real-world conditions.

1. Introduction

Underground tunnels provide a fast and cost effective alternative in densely populated cities, compared with surface transport. Considering recent events, not in Egypt but worldwide in other global cities such as London (2005), Mosco (2010) , the specter of terrorism has become a factor threatening these tunnels.

The effect of explosions extends to humans in addition to structures. Injuries and health problems are the results of blasts as loss of lives. Surface blasts affect super and shallow structures, where internal blasts affect deep tunnels and buried structures.

The blasts doesn’t affect structures but also human being health leading in some cases to fatalities. They can cause very dangerous diseases like cancer. The building-up, movement, and transportability of explosive devices has become easy these days, so the increase of bomb attacks is significant. The explosions are not the leading cause of death and injury in terrorist attacks, but the structural damage and glass vulnerability are [1].

---

[*] Corresponding author. Tel.: +2-01009427099
E-mail address: sallyhassan@zu.edu.eg

Blast overpressures and durations are calculated for numerous different explosive charge sizes ranging from 28.35 to 907.20 grams of TNT. The results were associated with human blast tolerance limits and reveal that the about 1 % is at survived from death and the threshold of lung damage [2].

2. Explosions and Blast Phenomena

Blasts can be defined as a large-scale, fast, and unexpected release of energy. Blasts can be categorized based on their nature as chemical, physical or nuclear actions. Explosive materials could be classified based on sensitivity to ignition to primary and secondary explosives. The temperature of hot gases generating from a high compressed explosive is about 3000-4000 C^{o,} and the gases are under pressure up to $3*10^7$ kpa [3].

To study peculiarities of blasts, we need to know two equally vital components, charge weight (W) and the standoff distance (R) between the source of the explosion and the goal. When charges explode, a specific amount of energy is released, which varies from one type to another according to the weight of the charge. TNT (Trinitrotoluene) equivalent is provided as an "Explosive BenchMark." TNT is used to measure the energy released in detonations. A ton of TNT can release 4.184GJ of energyExplosives are different from one to another by their explosion characteristics such as detonation rate, effectiveness, and amount of energy released. Therefore, it is necessary to have a datum to assess the detonation characteristics of each types of explosive material. TNT equivalent of common explosives materials is shown in Table (1), [4]

Table 1. TNT equivalent of explosive materials, [4]

Explosions	TNT Equivalent
ANFO	0.82
Composition A-3	1.09
Composition B	1.1-1.2
Composition C-4	1.37
HBX-1	1.17
HMX	1.3
H-6	1.38
Minol II	1.2
TNT (Trinitrotoluene)	1
TRITONAL	1.07

Ground shock can occur when TNT charges are detonated on or near the ground surface, causing damage to superstructures or shallow-buried structures. The main cause of ground shock is the energy given to the earth by the explosion. A portion of this energy is communicated directly through the ground as a ground shock, while another portion is transmitted through the air as an air-induced ground shock. When an air-blast wave compresses the ground surface and delivers a stress pulse into the subterranean layers, this is known as air-induced ground shock. In general, air-induced ground motion is greatest at the ground surface and diminishes with depth.

Figure (1) shows a typical blast pressure-time history. It can be separated into two types of phases: positive and negative. Following the explosion, at a time t_A, the pressure at that location abruptly rises to a peak value of overpressure p_{50} , which is higher than the ambient pressure p_0. At the time $t_A + t_d$, the pressure decays to ambient levels, then to an under pressure P_{50}^- (forming a partial vacuum), before eventually returning to ambient circumstances. The amount p_{50} is also known as the incident peak overpressure or peak side-on overpressure. In a design, the negative phase is less important than the positive phase, and its amplitude P_{50}^- must be less than ambient atmospheric pressure p_0. The integrated area under the pressure-time curve is the incident impulse density associated with the blast wave, where The positive phase is referred to as t_d and the negative phase is referred to as t_d^-, [5]

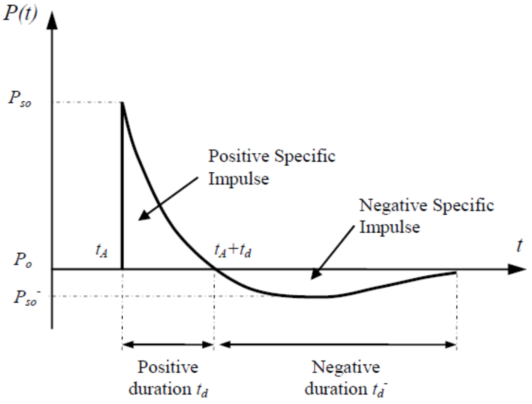

Fig. 1. Blast wave pressure Time history

When condensed materials explode in a square or circular cross-section tunnel, the blast wave shows two patterns: one-dimensional wave away from the explosive charge and three-dimensional wave near the explosive charge. The blast wave has a third, two-dimensional shape in a rectangular cross-section tube [6].

3. CRATER PRODUCED BY BLASTS

A conical-shaped crater is formed in the ground if the explosion is well above the surface. The crater's formation is influenced by the explosive quantity and the height or depth of the explosion Center in relation to the ground surface. Gravitational effects control the cratering process for underground explosions. When the depth grows, greater quantities of overburden subsoil must be dissolved and ejected outwards. This causes crater size to increase to a certain depth, after which it declines, or in other words, no crater creation is visible on the ground. [7, 8]. Figure (2) shows the shape of the crater with dimensions and formed zones.

Many researchers have discussed the theory of crater formation [7, 9]. A series of experiments are conducted by [10-12] to estimate empirical relations between the diameter and the depth of the crater for surface blasts. Numerical tests are carried out with various amounts of explosives above the soil surface. The effect of elevating the center of energy release of explosive loads is investigated and explained. The numerical model, in addition to the analysis process, has been confirmed using experimental crater diameter measurements. When the charge's weight increases, the crater becomes deeper. More energy is expended to expand the crater's depth despite its diameter, so it is more difficult to determine the apparent crater diameter, and the error could increase. Also, it shows that a 5% variation accounts for the variances between the soil properties, [13]

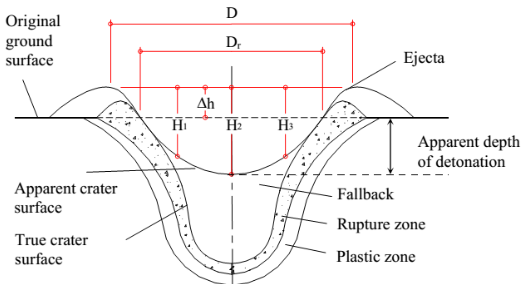

Fig. 2. Definitions of the crater dimensions, [9]

4. SOIL STRUCTURE INTERACTION (SSI)

The interaction of a structure with the nearby soil (SSI) is of practical concern for many years. Due to the numerous effects on the interaction between the soil and the structure, SSI is not a straightforward problem. The soil response influences structural motion, and the structural movement influences the response of the soil. At the soil-structure contact, structural distortion affects the distribution and amplitude of the neighboring earth pressure.

The SSI is very complex phenomena so engineers turned to simplify it. In 2001, Wang and Munfakh has used simplified free-field deformation methods to simplify SSI [14]. In 2008, In 2008, The constraints of free-field deformation methods were reduced by adding SSI effects, thanks to improved numerical methodologies [15].

The SSI effect on buried buildings is different depending on the confining stress field. The structural response would be transitory if the stress caused by the surrounding load had a large inertia impact, and this influence is called dynamic SSI. During an explosion-induced ground shock, the transient phase lasts only a few milliseconds, while it lasts much longer during earthquake excitation. Aside from the loading, the SSI is influenced by (i) size, material, and stiffness of the structure; (ii) adjacent soil, and (iii) building procedures (bored, mined, or cut-cover-tunnel). In an extreme circumstance, buried structures usually cannot resist the loads to which they are subjected, including soil, without utilizing the strength of the surrounding soil in a complex interaction [16].

In April 1992, The blast of the explosive, the transmission of stresses over the soil, the interaction of the structure with the soil, and the construction reaction were modeled in a single analysis [17].

The SSI effect is an important feature of tunnel-soil interaction under blast loads, according to all previous studies.

5. EXPERIMENTAL APPROACH

The Hopkinson or (cube-root) scaling rule governs the influence of a blast under great gravity, such as those experienced inside a geotechnical centrifuge [5]. Thus, the shock waves created at two different scaled distances by two explosive charges, having the same geometry and type of explosive but different quantities of charge would scale as the cube-root of the weight of explosives. If two explosions transmit similar shock waves, the weights of the waves differ by the cube of the distance.

$$Z=R/W^{1/3} \quad (1)$$

Marine canals, tunnels, military caches, auxiliary tunnels, and shelters are examples of underground RC (reinforced concrete) structures. Because of the significant risk of subsurface explosions, thorough research of the behavior of underground RC structures to blast actions is required. The experimental studies are so expensive and so difficult, so the scaled models are the solution.

A number of researchers [18-21] have effectively applied centrifuge modeling to model the explosion reaction of underground structures.

For boring tunnels, the blast reaction of bolted joints in the segmental lining is not predicted well in centrifuge models because gravitational fields are various in the test bucket, which leads to the limitation of using smaller models [8]. On a small scale, the detonation reaction of buried reinforced concrete constructions with changed backfills was tested using many tests of a Conventional Weapon Effects Backfill (CONWEB). The model in these tests was a small model of a slab of reinforced concrete attached to a reaction structure to show its detonation reaction.

Three charges of various weights were loaded sequentially on a tube of outer and inner diameters 100 and 80 cm, respectively. The tube was five meters long, and the charge is placed eccentrically as it is more realistic and practical than if the charge is located on the tunnel axis. The damage rates increase with the frequent blasting. It is suggested that, at the same geometry and TNT weight, additional repetition can lead to a whole loss of structure strength [22, 23].

Two centrifuge experiments were implemented by a large aluminum test box with a centrifugal acceleration of 50g. The effect of interior blasts in an underground tunnel under both dry and saturated soil was considered using a model of long aluminum tubes. The results showed that higher values of stresses found in tunnels in saturated soils compared to tunnels in dry soil because of the effect of pore water pressure [24].

Dynamic responses of buried arches were tested due to subsurface close-in blasts. The tested arch distorts at a main flexural mode with compression mode. The principal failure modes of the tested arch are Spalling, tensile cracks, and shear failures of the concrete and yielding of the steel. If four or five plastic hinge lines are developed, the arch will collapse [25].

Physical modeling of geofoam barriers is modeled to show the influence of geofoam on the resistance of underground tunnels to surface blasts. With increasing the thickness of geofoam only up to a certain thickness, the shielding geofoam barrier could improve the tunnel behavior. Beyond this thickness, a further increase in thickness would not affect in extra improvement [19].

A model of two field tests is used to study the effect of buried explosions in soil on the performance of underground RC box-shaped structures. Large-scale numerical and experimental studies of explosion acceleration were formed, and the studies focused only on the blasted acceleration on the front wall of the RC tunnel construction [26].

A shock tube was used to provide more safety conditions and reduce the expenses of real explosions. The primary tests were done with only the sand to define the reaction of the sand to a detonation and then by implanting an aluminum tube which is at a distance of 7.5 cm from the bottom of the bed. A couple of strain gauges were attached along the perimeter and the length of the pipe to capture soil-structure interaction [27].

6. NUMERICAL APPROACH

Carrying out different experiments is not cheap, numerical approaches are suitable implements to understand and estimate the act of considered structures with low expenses. Therefore, comparison of the effects from numerical analysis with field data will help to measure the act of sensors data logger, cables, and procedure of applied tests

6.1. NUMERICAL SIMULATIONS

The studies of the numerical simulation are reviewed as two parts: software review and previous numerical simulations.

6.2. AVAILABLE SOFTWARE

Publically available studies on the numerical simulation of soil behavior under high strain rates (blasting, explosions, or detonations) are not as extensive as those conducted on constitutive models. Most numerical simulations are conducted with several kinds of software: ABAQUS/Explicit, LS-DYNA, ANSYS, Air3D, and AUTODYN. The ABAQUS system includes ABAQUS/Standard, ABAQUS /Explicit, and the Visualization module, an interactive post processing program that provides displays. It outputs lists from output database files written by ABAQUS/Standard and ABAQUS/Explicit. ANSYS AUTODYN software, used in many applications, is an explicit analysis tool for nonlinear modeling dynamics of solids, fluids, and gases. It has been developed specifically for analyzing nonlinear, dynamic events such as impacts and blast loading of structures and components. LS-DYNA is a general purpose nonlinear finite element program compatible with distributed and shared memory solvers using Linux, Windows, and UNIX. It is suitable to investigate phenomena involving large deformations and complex contact conditions for structural dynamics problems. It allows switching between explicit and implicit time-stepping schemes.

6.3. PREVIOUS NUMERICAL STUDIES

The effect of underground and surface detonations on buried structures or structures on or above soil surface is numerically studied in many researches [28-31].

The effects of many factors under the surface or internal blasts on the possible damage of underground tunnels, containing the weight of explosive, lining material and thickness, soil stiffness, burial depth, thickness cover, the shape of a tunnel, the diameter of the tunnel, the standoff distance and also the effect of one tunnel to another in case of twin tunnel, are studied in many numerical studies.

The weight of TNT has an important influence on the tunnel reaction against internal and surface blast loads. The failure modes of tunnel lining are changed due to dissimilar charge weights. For a cast-iron lining tunnel, the severe rupture caused by the tensile strength could be propagated to farther distances due to lining vibration at high charges, but when the charges are reduced, only little fractures occur. The high charges didn’t cause only a failure in tunnel lining but also caused soil liquefaction [32]. For RC tunnels, detonation induced pressure on the tunnel lining, and the distortion of the tunnel lining and the surrounding soil increases as the charge weight increases [31, 33]. For deep tunnels, this effect is more trivial than in shallow tunnels [34].

As the TNT weight increases, an exponential increase in deformation is detected for unlined tunnels, and a nonlinear pattern is distinguished for lined tunnels [35]. For surface blasts on the tunnel, the level of destruction is right linked to the explosive size for the same model [19, 36]. The dynamic behavior of the shallow operating metro tunnel in soft soil under surface explosion is analyzed using ANSYS/LS-DYNA. The distribution and magnitude of the tunnel lining stress are affected by the tunnel depth and TNT equivalence where the vulnerable areas are in the upper part of the tunnel lining cross-section under TNT charge and an identified horizontal distance away from the explosive center [37].

The strength of blast loading is mostly determined by the charge's parameters, such as its weight and position. The location of charge for internal explosions has an important influence on the tunnel reaction. When the charge is attached to the tunnel lining, the tunnel suffers more damage than when the charge is positioned at the tunnel center point. As an alternative to creating a very stiff and expensive structure to withstand exceptionally high blasts, protective layers inside the tunnel construction can be used to absorb most of the blasting energy [38].

For RC circular curved tunnels exposed to internal explosions, when TNT charge is placed at the middle of the tunnel arc length, it produces deformation up to 500% more than when it is located at the quarter of the tunnel arc length. For tunnels with a greater arc, the deformation of the tunnel and the soil nearby the sidewall are less. A leading amount of ground heave was detected, and as the arc of the tunnel decreases, the ground level distortion decreases. The interior side of tunnel curvature should be considered against blast with protections, and the providing of appropriate strengthening must be prepared [39, 40].

For the mechanical reaction of a steel cylinder in soil under several blasts, a steel pipe is subjected to two blast loads, one at the ground surface and another buried in a rock layer away from the pipe. When two points explode simultaneously, the maximum plastic deformation and total energy are larger than in a one-point explosion. With increasing interval time between two-point explosions, a pipe's deformation and total energy drop slowly. With an increase in the ratio of the TNT charge or the diameter–thickness ratio, pipe deformation, plastic strain, and total energy would steadily increase [41].

Soil has a great impact on the performance of the tunnel embedded in whether the explosions are surface, internal, or buried in the soil. Internal explosions in tunnels embedded in saturated soil could cause a lasting decrease in the effective stresses of soil. Because of reduced stiffness and a larger deformation, the soil in a nearly full saturation stage with a little amount of free gas in the pore water displays a higher decrease in effective stresses. The effective stresses in the area of the tunnel may be lowered to make the soil liquefied early (zero effective stresses), and that depends on the loading amplitude and saturation degree [42]. If the soil around the tunnel is completely saturated, the soil expansion causes pore water cavitation, which reduces the soil bulk modulus dramatically. The reduction in bulk modulus caused by cavitation allows the soil to expand, resulting in creating a wide cavitation zone [43].

Surface explosions cause extensive destruction and damage to tunnels, and to reduce these damages, a sand layer could be used. It reduces high-frequency stress waves efficiently and reduces the destruction of the structure. The performance of underground structures could be affected by moisture content in the sand layer. If moisture content increases, blast energy is damped, and the destruction to underground constructions is decreased [44].

The tunnel response is determined by the soil stiffness. An internal explosion would cause less structural damage if the earth medium were stiffer. With increasing soil stiffness, the maximum effective plastic strain decreases dramatically [38]. The blast response of RC circular tunnels driven in saturated clay is more exposed to internal detonation compared with tunnels in dry sand [45].

For internal blasts, when the rising angle of friction for soil, the behavior of the tunnel embedded in improves. Lining and soil displacement decreases with an increasing friction angle of soil [31, 33].

For the surface blast effect on a circular RC tunnel, the impact of explosions on the bending moment and vertical at the tunnel crown has decreased as the modulus of elasticity, and internal friction angle of the soil have increased. The bending moment and vertical displacement of the crown of the tunnel are not affected by soil cohesiveness. The soil's modulus of elasticity is the best operative in decreasing the impact of explosions on the tunnel crown's vertical displacement [46].

The dynamic response and damage against the internal blast of single-track subway tunnels with cast iron lining are studied through numerical simulation. TNT weight, soil stiffness, burial depth, and grouting to improve ground stiffness and strength are studied. Tunnel lining stress increases significantly in soft soils, so grouting is suggested to improve soil stiffness around subway tunnels to increase blast resistance [47].

Dynamic response of tunnel in rock subjected to internal explosions can be changed with different weathering conditions of the rock mass. Rocks with a higher modulus of elasticity are exposed to higher blast pressure. The lower amount of ground shock wave propagation and higher attenuation of the shock wave is detected in the circumstance of higher weathered rock with low modulus [48].

Due to an explosion in the rock mass, a subterranean building in soft soil built over a rock mass is investigated. When the blasts occur, the shock waves go from a medium with a higher impedance (the rock) to a media with a lower impedance (the soil), causing the soil-lining contact (reflected) stresses to increase and the larger displacement of the tunnel, [49].

The effect of three different sedimentary rocks, Sandstone, Silty Sandstone, and Mudstone, on tunnels due to internal explosions, are studied. Due to the rock's low internal friction angle and Young's Modulus, the Mudstone rock tunnel has shown the lowest response. The Sandstone rock tunnel, on the other hand, has shown to be the most successful in terms of blast load resistance [50].

The influence of changed unconfined compressive strengths (UCS) of rock types like dolomite, shale, sandstone, granite, basalt, and quartzite medium, on unlined tunnels due to internal blast loading is investigated. The maximum total induced energy from the internal explosion was found to be in dolomite and the lowest in quartzite. The peak displacement and the level of damage are inversely proportional to the UCS in the rock tunnel when exposed to an internal explosion. Rock with a higher UCS value exhibits less deformation and is more resistant to tunnel stability concerns [51].

For circular tunnels in the rock layer subjected to surface detonation, higher rock strength increases the tunnel resistance to blast load but decreases attenuation too. It is obvious that tunnel stability to blast load cannot be estimated in a direct mode; "the stronger, the better" does not apply in this case, so, under definite circumstances, effects for weak and strong rock masses are similarly [52, 53].

If segmented bored tunnels are exposed to surface detonations, the geometric shapes and numbers of the segments affect the tunnel response. When exposed to the identical surface explosion, the blast response of a buried tunnel in fully saturated soil is more severe in terms of crack formation and bolt failures than the blast response of a tunnel buried in either partially saturated soil or dry soil [8, 54].

LS-DYNA was used to simulate the blast reaction of a metro tunnel in Shanghai that was subjected to a surface explosion. The peak pressure, the effective stress, and the peak vertical acceleration show a significant increase when the bulk modulus Ku decreases by half [37].

The performance of different tunnel lining material (single-layered steel plate, plain concrete (PC) slab, steel fiber reinforced concrete (SFRC) slab, sandwich Steel-Dytherm foam-steel (SDS) panel, and steel-polyurethane foam-steel (SPS) panel, subjected to internal blast in sandy soil is studied. Liners of soil exposed to the explosion were studied. Compared to PC and SFRC linings, SDS and SPS sandwich panel linings create significantly less soil displacement under blast stress. The displacement of the steel plates is roughly identical to that of the SDS and SPS sandwich panels [55, 56]. The density and stiffness of cast iron are high compared to concrete so the numerical research shows that reinforced cement concrete (RCC) tunnels experience severe destruction compared to cast-iron tunnels. The zone of maximum stress damage in RCC is double that of cast-iron tunnels [45].

The effect of cross-sectional shapes (circular, box, and horseshoe) is carefully studied on the dynamic response of tunnels subjected to an internal explosion. In comparison to the other shapes, a box tunnel has major vertical displacement. The plastic deformation in circular tunnels is dispersed across the lining where the magnitude of maximum principal plastic strain is low, but the plastic strain inbox and horseshoe tunnels are focused primarily on the corners and sidewalls Because the circular sections are so excellent at evenly spreading the load, the circular lining's great load-carrying capacity may be due to its curvature, [45].

In the comparison of circular and square cross-section tunnels, if square-shaped tunnel with height equals to the outer diameter of the circular tunnel are exposed to internal explosions, the effect of the circular tunnel would undergo more blasting destruction under internal blasts compared to the square-shaped. For the square-shaped tunnel, the maximum effective plastic strain response and the maximum overpressure would occur at the corner of the tunnel and with quite less reaction at the center of the top plate. The maximum overpressure inside the square-shaped tunnel is lower than that inside the circular tunnel, and so, the square-shaped tunnel would suffer less blasting damage than the circular tunnel with the same height [38].

LS-DYNA is used to model and investigate the outcome of many shapes of tunnels for surface explosions where the Kobe box shape subway tunnel is used as an example to evaluate and compare with semi ellipse, circular, and horseshoe shapes. For surface loads, The circular and horseshoe tunnels are more vulnerable to demolition than the box shape tunnel; nevertheless, the semi-ellipse tunnel is more resistant to blasts than the Kobe box design subway tunnel [57].

The lining thickness of the tunnel plays an important role in blast resistance, however, increasing the lining thickness renders the section uneconomical without adding much to blast resistance. Hence, For any coming tunnel, a study should be conducted to determine the best blast-resistant liner thickness based on the soil type, burial depth, and the TNT weight charges. For a circular RC tunnel embedded in saturated clay or dry sandy soil subjected to internal blasts, a reduction is observed in the displacement and deformation of the lining, and the blast induces damage when the thickness of the tunnel lining increases [31, 33, 45].

For an underground box frame tunnel affected by a surface burst, the lateral displacement of the tunnel roof and wall center show an equivalent association with the tunnel lining thickness. The results show that as the tunnel lining thickness increases, the displacement decreases for the same tunnel burial depth and TNT charge [58].

For a circular RC tunnel embedded tunnel in quartzite rock and exposed to the internal explosion, The thickness of the tunnel lining has a considerable impact on the tunnel's stability, but up to a limit only and in smaller diameter tunnel, the increase in tunnel lining thickness has not much consequence, However, for tunnels of bigger diameter, there is a decrease in the deformation in rock when the thickness of tunnel lining increases. As the diameter of the tunnel increases, the distance between the TNT charge and the concrete lining increases, which reduces the deformation in the tunnel lining. The deformation vs. weight of the TNT profile distinguishes clearly with an increase in the diameter of tunnel lining [34, 35].

Burial depth significantly affects the response of underground tunnels under the surface, internal or buried in soil TNT charges. For surface blasts or buried in soil charges, the distribution and magnitude of the stress field of the tunnel lining are influenced by the tunnel depth. Due to the reduction of compressive waves in the soil and the strength of wave pressures being lowered due to the damping effect of soil, the tunnel response reduces as the distance from the blast center increases [29, 37, 46, 57].

If subway tunnels were in saturated soft soil or dry sand and exposed to the internal explosion, increasing the buried depth of the tunnel structure improves the confinement on the tunnel. So the maximum effective plastic strain, stress of the lining under internal blasting load are decreased. Because of the low confinement from the ground, lining stress could be severe with a shallow burial depth. The tunnel could be harshly damaged even with a modest internal detonation, so it is more essential to take into consideration during design the blast resistance of the subway tunnel with a slight burial depth [38, 47].

Burial depth considerably affects the maximum lining stress of a tunnel in rock layers under internal blast loading. In both lined and unlined tunnels, the stability of the tunnel has improved as the depth of overburden has increased. The maximum deformation in the different cases has concluded that deeper tunnels are safer than shallow tunnels in rocks [34, 35].

The standoff distance has an excessive influence on the performance of the tunnel under blast load. A restricted area or green zone is suggested around the tunnel to save it against explosions [36].

In most metro systems, two tunnels run parallel to each other, with internal blast loading in one tube causing damage and deformation of the RC lining in the other tunnel, as well as soil mass, which is determined by charge weight and clearance between the tunnels. For twin RC tunnels in sandy soil, to avoid the effect of the explosion in one tunnel to another, the center to center distance of tunnels should be chosen through numerical analysis [59].

For twin RC tunnels in clay soil, The maximum lining stress and the influence of blast wave on a tunnel next to another tunnel subjected to internal blast are less if the spacing between the two tunnels is greater than 2.2 times the diameter of the tunnel [60].

For a case of cast iron twin tunnel embedded in clayey sand soil and subjected to internal blast, liner thickness has strong effect on the stress generated in the liner and damage of tunnel. At the smaller thickness of the liner, the maximum von Mises stress increases significantly. It may cause damage to the liner and tunnel. At a higher thickness of the liner, maximum von Mises does not show significant changes, so the designed liner thickness should be optimum. Like surface blasts, the soil near the tunnel considerably influences the strength of the tunnel during the burst. To maintain the yielding created as a result of the explosion, the soil should have a higher Young's modulus value. The structure liner provided in tunnel starts deforming at the explosion of 65 kg TNT, which may be the limiting quantity of TNT for the safety of twin tunnel structure. If the amount of explosives will increase beyond this, it will lastingly distort the structure and may lead it to failure [61].

7. Conclusion

If underground tunnels collapse, the structure and people will be lost. Tunnels are designed to withstand static loads and earthquakes, but data are shortened in design against blasts. The parameters affecting the safety of tunnels such as the weight of explosive, lining material and thickness, soil stiffness, burial depth, thickness cover, the shape of a tunnel, the diameter of the tunnel, the standoff distance, the location of blast charge and also the effect of one tunnel to another in case of twin tunnel discussed by various researchers have been overviewed in the present work. The paper presents an overview of the effect of blast on tunnels for beginner researchers and structural engineers to understand such complex loading situation Experimental work is recommended to be a reference for future work. New strategies which can be adapted to mitigate the effect of surface and internal blast loads on shallow and deep tunnels should be investigated. Future studies should use numerical simulation of a tunnel buried in a saturated soil profile to imitate real-world conditions.

References

[1] A. M. Remennikov, "A review of methods for predicting bomb blast effects on buildings," Journal of battlefield technology, vol. 6, pp. 5-10, 2003.

[2] P. Gibson, "Blast Overpressure and Survivability Calculations for Various Sizes of Explosive Charges," 1994.

[3] TM-5-1300, "Design of Structures to Resist the Effects of Accidental Explosions," US Department of the Army Technical Manual, Washington DC1990.

[4] J. H. A. R. Jayasooriya, "Vulnerability and damage analysis of reinforced concrete framed buildings subjected to near field blast events," Queensland University of Technology, 2010.

[5] W. E. Baker, Explosions in air, 1973.

[6] D. Uystepruyst and F. Monnoyer, "A numerical study of the evolution of the blast wave shape in rectangular tunnels," Journal of Loss Prevention in the Process Industries, vol. 34, pp. 225-231, 2015.

[7] J. Bull and C. Woodford, "Camouflets and their effect on runway support," Computers & structures, vol. 69, pp. 695-706, 1998.

[8] S. Koneshwaran, "Blast response and sensitivity analysis of segmental tunnel," Queensland University of Technology, 2014.

[9] B. Luccioni and D. Ambrosini, "Influence of the soil properties on craters produced by explosions on the soil surface," Mechanical Computational, vol. 23, pp. 571-590, 2004.

[10] R. D. Ambrosini and B. M. Luccioni, "Craters produced by explosions on the soil surface," 2006.

[11] R. D. Ambrosini, B. M. Luccioni, R. F. Danesi, J. D. Riera, and M. Rocha, "Size of craters produced by explosive charges on or above the ground surface," Shock Waves, vol. 12, pp. 69-78, 2002.

[12] B. Luccioni, D. Ambrosini, G. Nurick, and I. Snyman, "Craters produced by underground explosions," Computers & Structures, vol. 87, pp. 1366-1373, 2009.

[13] D. Yankelevsky, Y. Karinski, and V. Feldgun, "Re-examination of the shock wave’s peak pressure attenuation in soils," International journal of impact engineering, vol. 38, pp. 864-881, 2011.

[14] J.-N. Wang and G. Munfakh, Seismic design of tunnels vol. 57: WIT Press, 2001.

[15] J.-x. Xu, "Analysis of structural response under blast loads using the coupled SPH-FEM approach," Journal of Zhejiang University-SCIENCE A, vol. 9, pp. 1184-1192, 2008.

[16] T. C. Sandford, "Soil-structure interaction of buried structures," Transportation in the New Millennium, 2000.

[17] J. T. Baylor, "Parameters affecting loads on buried structures subjected to localized blast effects," Army Engineer Waterways Experiment Station Vicksburg Ms Structures Lab1992.

[18] A. De and R. Conry, "Modeling of surface blast effects on underground structures," in Geo-Frontiers 2011: Advances in Geotechnical Engineering, ed, 2011, pp. 1534-1543.

[19] A. De and T. F. Zimmie, "Effects of surface explosion on underground tunnel and potential mitigation measures," Transportation Infrastructure Geotechnology, vol. 3, pp. 74-90, 2016.

[20] A. De, T. F. Zimmie, T. Abdoun, and A. Tessari, "Physical modeling of explosive effects on tunnels," in Fourth International Symposium on Tunnel Safety and Security, 2010, pp. 159-167.

[21] B. L. Kutter, L. M. O'Leary, P. Thompson, and R. Lather, "Gravity-scaled tests on blast-induced soil-structure interaction," Journal of Geotechnical Engineering, vol. 114, pp. 431-447, 1988.

[22] P. Prochazka and D. Jandeková, "Effect of explosion source location on tunnel damage," International Journal of Protective Structures, vol. 11, pp. 448-467, 2020.

[23] P. P. Prochazka and M. J. Válek, "The Effect of Explosion in a Tunnel Tube on its Damage," in Key Engineering Materials, 2018, pp. 265-270.

[24] S. Nezilli, "Responses of Underground Structures Subjected to Blast Loading," 2014.

[25] H. Chen, J. Zhou, H. Fan, F. Jin, Y. Xu, Y. Qiu, et al., "Dynamic responses of buried arch structure subjected to subsurface localized impulsive loading: Experimental study," International Journal of Impact Engineering, vol. 65, pp. 89-101, 2014.

[26] M. R. Soheyli, A. Akhaveissy, and S. Mirhosseini, "Large-scale experimental and numerical study of blast acceleration created by close-in buried explosion on underground tunnel lining," Shock and Vibration, vol. 2016, 2016.

[27] P. Vivek, T. Sitharam, G. Jagadeesh, and K. Reddy, "Response of embedded pipeline to surface blast loading," in 30th International Symposium on Shock Waves 1, 2017, pp. 749-754.

[28] A. M. Benselama, J.-P. Mame, F. Monnoyer, and C. Proust, "A numerical study of the evolution of the blast wave shape in tunnels," Journal of hazardous materials, vol. 181, pp. 609-616, 2010.

[29] N. Nagy, M. Mohamed, and J. Boot, "Nonlinear numerical modelling for the effects of surface explosions on buried reinforced concrete structures," Geomechanics and Engineering, vol. 2, pp. 1-18, 2010.

[30] B. M. Luccioni and R. D. Ambrosini, "Evaluating the effect of underground explosions on structures," Mecánica Computacional, pp. 1999-2019, 2008.

[31] R. Tiwari, T. Chakraborty, and V. Matsagar, "Dynamic analysis of tunnel in soil subjected to internal blast loading," Geotechnical and Geological Engineering, vol. 35, pp. 1491-1512, 2017.

[32] L. Zhang and X. Yang, "Soil-tunnel interaction under medium internal blast loading," Procedia engineering, vol. 143, pp. 403-410, 2016.

[33] R. Tiwari, T. Chakraborty, and V. Matsagar, "Dynamic analysis of underground tunnels subjected to internal blast loading," in World Congress of Computational Mechanics (WCCM XI), Barcelona, 2014.

[34] M. Zaid and M. R. Sadique, "The response of rock tunnel when subjected to blast loading: finite element analysis," Engineering Reports, vol. 3, p. e12293, 2021.

[35] M. Zaid and M. R. Sadique, "Numerical modelling of internal blast loading on a rock tunnel," Adv Comput Des, vol. 5, 2020.

[36] A. Ata, M. Nabil, S. Hassan, and M. Nawar, "Numerical analysis of underground tunnels subjected to surface blast loads " Frattura ed Integrità Strutturale, vol. 55, pp. 159-173, 2021 2021.

[37] Y. Yang, X. Xie, and R. Wang, "Numerical simulation of dynamic response of operating metro tunnel induced by ground explosion," Journal of rock mechanics and geotechnical engineering, vol. 2, pp. 373-384, 2010.

[38] H. Yu, Z. Wang, Y. Yuan, and W. Li, "Numerical analysis of internal blast effects on underground tunnel in soils," Structure and Infrastructure Engineering, vol. 12, pp. 1090-1105, 2016.

[39] R. Tiwari, T. Chakraborty, and V. Matsagar, "Dynamic analysis of curved tunnels subjected to internal blast loading," in Advances in Structural Engineering, ed: Springer, 2015, pp. 405-415.

[40] R. Tiwari, T. Chakraborty, and V. Matsagar, "Analysis of curved tunnels in soil subjected to internal blast loading," Acta Geotechnica, vol. 15, pp. 509-528, 2020.

[41] J. Zhang, H. Zhang, L. Zhang, and Z. Liang, "Buckling response analysis of buried steel pipe under multiple explosive loadings," Journal of Pipeline Systems Engineering and Practice, vol. 11, p. 04020010, 2020.

[42] V. Osinov, "Blast-induced waves in soil around a tunnel," Archive of Applied Mechanics, vol. 81, pp. 543-559, 2011.

[43] V. A. Osinov, S. Chrisopoulos, and T. Triantafyllidis, "Numerical analysis of the tunnel-soil interaction caused by an explosion in the tunnel," Soil Dynamics and Earthquake Engineering, vol. 122, pp. 318-326, 2019.

[44] R. Basirat, A. Niri, and R. Izadifard, "The effect of sand layer thickness and moisture content on underground structures behavior due to surface blasting," J Eng. Res, pp. 31-42, 2015.

[45] R. Prasanna and A. Boominathan, "Finite-element studies on factors influencing the response of underground tunnels subjected to internal explosion," International Journal of Geomechanics, vol. 20, p. 04020089, 2020.

[46] H. Entezari Zarch and K. Barkhordari, "Effect of Surface Blasting on Subway Tunnels-A Parametric Study," Journal of Analytical and Numerical Methods in Mining Engineering, vol. 6, pp. 63-72, 2017.

[47] H. Liu, "Dynamic analysis of subway structures under blast loading," Geotechnical and Geological Engineering, vol. 27, p. 699, 2009.

[48] R. Tiwari, T. Chakraborty, and V. Matsagar, "Dynamic analysis of tunnel in weathered rock subjected to internal blast loading," Rock Mechanics and Rock Engineering, vol. 49, pp. 4441-4458, 2016.

[49] V. Feldgun, Y. Karinski, and D. Yankelevsky, "A coupled approach to simulate the explosion response of a buried structure in a soil-rock layered medium," International Journal of Protective Structures, vol. 4, pp. 231-292, 2013.

[50] M. Zaid and M. R. Sadique, "Blast resistant behaviour of tunnels in sedimentary rocks," International Journal of Protective Structures, p. 2041419620951211, 2020.

[51] M. Zaid, M. R. Sadique, and M. Samanta, "Effect of unconfined compressive strength of rock on dynamic response of shallow unlined tunnel," SN Applied Sciences, vol. 2, pp. 1-13, 2020.

[52] A. Mitelman, "Numerical analysis of the effects of external blasts on tunnels," University of British Columbia, 2015.

[53] A. Mitelman and D. Elmo, "Modelling of blast-induced damage in tunnels using a hybrid finite-discrete numerical approach," Journal of Rock Mechanics and Geotechnical Engineering, vol. 6, pp. 565-573, 2014.

[54] S. Koneshwaran, D. P. Thambiratnam, and C. Gallage, "Performance of buried tunnels subjected to surface blast incorporating fluid-structure interaction," Journal of Performance of Constructed Facilities, vol. 29, p. 04014084, 2015.

[55] T. Chakraborty, M. Larcher, and N. Gebbeken, "Comparative Performance of Tunnel Linings under Blast Loading."

[56] T. Chakraborty, M. Larcher, and N. Gebbeken, "Performance of tunnel lining materials under internal blast loading," International Journal of Protective Structures, vol. 5, pp. 83-96, 2014.

[57] B. Mobaraki and M. Vaghefi, "Numerical study of the depth and cross-sectional shape of tunnel under surface explosion," Tunnelling and Underground Space Technology, vol. 47, pp. 114-122, 2015.

[58] M. H. Mussa, A. A. Mutalib, R. Hamid, S. R. Naidu, N. A. M. Radzi, and M. Abedini, "Assessment of damage to an underground box tunnel by a surface explosion," Tunnelling and Underground Space Technology, vol. 66, pp. 64-76, 2017.

[59] R. Tiwari, T. Chakraborty, and V. Matsagar, "Dynamic analysis of a twin tunnel in soil subjected to internal blast loading," Indian Geotechnical Journal, vol. 46, pp. 369-380, 2016.

[60] R. Prasanna and A. Boominathan, "Response of tunnels due to blast loading," in 8th Int. Symp. on Geotechnical Aspects of Underground Construction in Soft Ground, Seoul, South Korea, 2014, pp. 235-238.

[61] A. K. Verma, M. K. Jha, S. Mantrala, and T. G. Sitharam, "Numerical Simulation of Explosion in Twin Tunnel System," Geotechnical and Geological Engineering, vol. 35, pp. 1953-1966, 2017.