

Blast Wave Propagation and Casualty Distribution Evaluation in the Subway Station Subjected to Internal Blast Loading

Shi Yan*, Mingde Gao**, Baoxin Qi*** & Xuelel Jiang****

*School of Civil Engineering, Shenyang Jianzhu University, Shenyang, Liaoning, CHINA;
State Key Laboratory of Explosion Science and Technology, Beijing University of Technology, Beijing, CHINA.
E-Mail: syan1962[at]163[dot]com

**Liaoning Electric Power Survey & Design Institute, Shenyang, Liaoning, CHINA. E-Mail: 53773356[at]163[dot]com

***School of Civil Engineering, Shenyang Jianzhu University, Shenyang, Liaoning, CHINA. E-Mail: qibaoxin2005[at]163[dot]com

****School of Civil Engineering, Shenyang Jianzhu University, Shenyang, Liaoning, CHINA. E-Mail: zibinglan007[at]163[dot]com

Abstract—Subway station in modern cities is a densely populated area and is an enclosed space. In the event of sudden explosions, it not only can easily cause a large number of casualties, but also result in economic losses and abominable social impact. It is intended in the paper to establish a finite element model of the typical subway station with LS-DYNA software to analyze the blast wave propagation and evaluate the casualty's distribution. The blast wave propagation and overpressure peaks based on the scaled distances have been analyzed. Compared to other papers with the overpressure evaluation standards to analyze the personnel injury degree, a new evaluation standard which analyzes the personnel injury degree with the finite element dummy and the simplified explosion effect is put forward in the paper. Combined with the structure form of the subway station, the casualty distribution can be obtained.

Keywords—Blast Loading; Blast Wave Propagation; Casualty Distribution; Dummy; Overpressure Peak; Personnel Injury; Subway Station.

Abbreviations—Head Injury Criterion (HIC); LSTC Company Dynamic Software (LS-DYNA); Tri-Nitro-Toluene (TNT).

I. INTRODUCTION

WITH the development of the society, the subway has already become one of the main ways for the urban transportation. More than 15 cities in China will go on to construct the subway in the next ten years. The development trend of the subway construction is shown in Figure 1. However, because the population in subway stations is intensive and the environment is semi-enclosed, subway stations are becoming the primary target of terrorist attacks. The explosions in subway stations are listed in Table 1 and the explosion in London Subway Station is shown in Figure 2. Therefore, the evaluation of the casualty distribution is meaningful.

At present, research members domestic and abroad have studied on the propagation of blast waves and the dynamic response of subway station subjected to blast loading [Henrych, 1995; Hu & Yu, 2008; Qu & Li, 2010; Yang et al., 2010]. Although the personnel injury degree also has got a

certain evaluation, the evaluation standard of the shock wave injury usually adopts the overpressure standard which is based on animal killer experiment and used in humans by some similar relations [Yan et al., 2012]. In addition, because of ignoring the influence of overpressure duration, the overpressure standard has certain limitation.

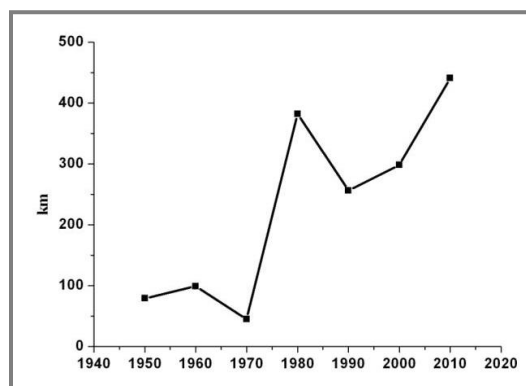


Figure 1: Trend of Subway Development



Figure 2: The Explosion of London Subway Station

Table 1: Explosion in the Subway Station

Time	Place	Casualty loss
1995.07.25	Paris	30 death & 70 injured
1996.06.11	Moscow	4 death & 7 injured
2004.02.06	Moscow	39 death & 70 injured
2005.07.07	London	56 death & 700 injured

This paper is intended to establish a finite element model of the typical subway station with LS-DYNA software to analyze the blast wave propagation and the personnel injury degree. The overpressure peaks based on the scaled distances have been analyzed and simplified to the triangle form. When the simplified explosion impacted on the finite element dummy, according to the new evaluation standard based on the finite element dummy, this paper can get the different personnel injury degree and casualties distribution.

II. FINITE ELEMENT MODEL

2.1. The Structure Type and the Finite Element Model of the Subway Station

In this paper, the subway station is a typical two-layer and three-span single arch structure form. The form of the platform is island platform. The size of the station is 26.6 m in width, 19.7 m in height and 33.8 m in length and the distance between the columns is 5.8 m. The area of the stair hole is 9.3m×2.3m. The thickness of the soil above and around the structure is 5m. The cross section of the subway station is shown in figure 3.

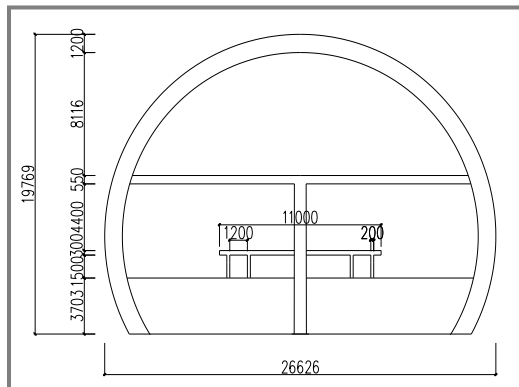


Figure 3: Cross Section

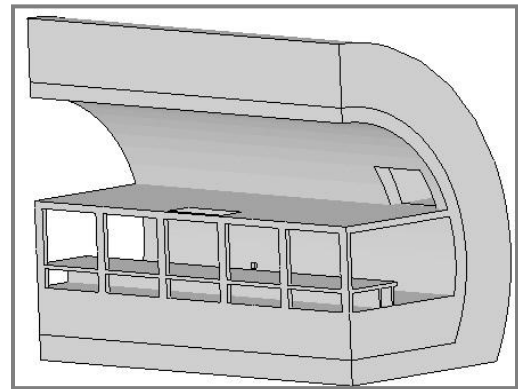


Figure 4: 1/4 Finite Element Model

In the numerical simulation, because the explosive is in the cross section center, above the platform 1.2 m, this paper takes 1/4 of the finite element model to calculate. Symmetric boundary condition is set in Symmetric section and non-reflected boundary condition is set in all other boundaries. The finite element model adopts 3DSOLID element. In order to ensure the accuracy, this paper meshes the model differently in different areas. This paper sets symmetric boundary which can constraint normal displacement in length ($Z=33.8m$) and in width ($X=0$). Non-reflected boundary condition is adopted in all other boundaries. The numerical model is shown in figure 4.

The high explosive burn material constitutive model and the Jones-Wilkins-Lee equation of state are used to model the explosive. The soil and reinforced concrete are modelled by rigid material. Air is modelled by Null material model and LINEAR_POLYNOMIA equation of state.

2.2. The Finite Element Model of the Dummy

In order to analyze the injury degree of the shock wave to the human body, this paper introduces the rigid finite element dummy. This is a rigid finite element dummy issued by LS-DYNA Company which adopts various element types, material models, and Constraint types [Guha et al., 2008; Livermore Software Technology Corporation, 2003]. This rigid finite element dummy can well show shock damage biological characteristics. The Rigid finite element dummy is shown in figure 5.

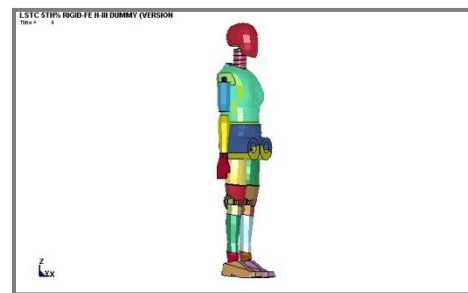


Figure 5: Rigid Finite Element Dummy

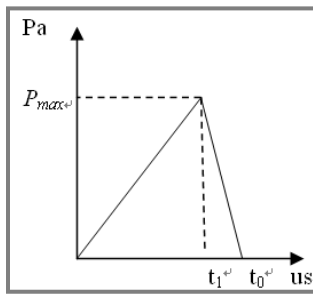


Figure 6: Pressure-Time Curve

2.3. Simplified Explosion Effect

Explosion is a kind of complex load form, and pressure strength as times changes. Overpressure peak is the most important influence factor of the personnel injury degree, therefore this paper simplifies the shock wave attenuation function relation to the triangle form as:

$$P(t) = \begin{cases} \frac{P_{max}}{t_1} t (0 \leq t \leq t_1) \\ P_{max} \left(\frac{t_0 - t}{t_0 - t_1} \right) (t_1 < t \leq t_0) \end{cases} \quad (1)$$

Where the $p(t)$ is defined as the overpressure, p_{max} is the overpressure peak, t_0 is the explosion effect time and t_1 is the overpressure peak time. The simplified triangle explosion pressure-time curve is shown in Figure 6.

III. EVALUATION STANDARD OF THE SHOCK WAVE INJURY

At present, the evaluation standard of the shock wave injury includes overpressure standard, impulse standard, and overpressure-impulse standard [NATO, 2006; US Department of Defense, 2004]. However, no matter what standards are based on animal killer experiment and used in humans by some similar relations [Li, 1990]. This paper puts forward a new evaluation standard which analyzed the personnel injury degree with the rigid finite element dummy and the simplified explosion effect. It can describe the personnel injury degree more truly that the new standard uses the rigid finite element dummy in numerical simulation.

The shock wave injury can be divided into two types: direct effect and indirect effect [Sun & Wang, 2008]. And the fatal head injury of direct effect mainly includes the skull fractures and the concussion. The cause of the concussion is generally suddenly acceleration, and then the brain produce relatively lag movement which causes shear stress and shear strain. Therefore, in order to simplify the calculation, this paper adopts the head synthesis acceleration of the rigid finite element dummy as the evaluation standard of the shock wave injury. For the rigid finite element dummy, Internationally HIC (Head Injury Criterion) calculation formula is often used as head injury standard. The HIC calculation formula defines as:

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a dt \right]^{2.5} (t_2 - t_1) \quad (2)$$

Where the α is defined as the head synthesis acceleration, 2.5 is the head weight index, and t_1 and t_2 is the time in the calculation process which make the HIC value is the largest. Generally, the safety limit of HIC is 1000, and the calculation time interval is 36 ms.

However, the HIC safety limit is only the death evaluation standard which can't distinguish different degree injuries. When the $HIC \leq 1000$, this paper introduces a formula which defines as:

$$D_r = \frac{HIC - 701.6}{701.6} \times 100\% \quad (3)$$

Where the D_r is defined as the relative deviation of the HIC, and 701.6 is the value of the HIC when there is no simplified explosion effect on the dummy. Through the simulation and calculation, the evaluation standard of the shock wave injury is listed in table 2 below.

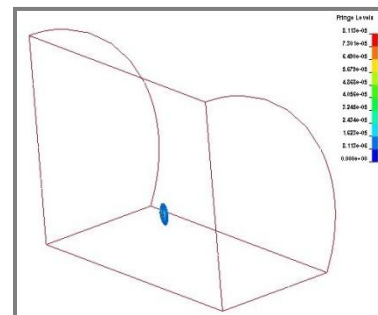
Table 2: Evaluation Standard of the Shock Wave Injury

HIC	$HIC \leq 1000$			$HIC \geq 1000$
D_r	0.12%	0.12%-0.75%	0.75%	/
Injury Degree	Without Injury	Moderate Injury	Serious Injury	Death

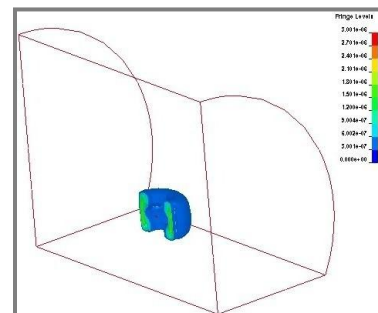
IV. NUMERICAL RESULTS AND DISCUSSIONS

4.1. Blast Wave Propagation in the Subway Station Subjected to Internal Blast Loading

As a result of the existence of various structure elements and staircase holes, the subway station is a half sealed and complex structure. Once an internal explosion happened in the subway station, the blast wave propagation is not similar to the explosion on the ground. The blast wave propagation is shown in shown in figure 7.



(a) $t = 0.2ms$



(b) $t = 5ms$

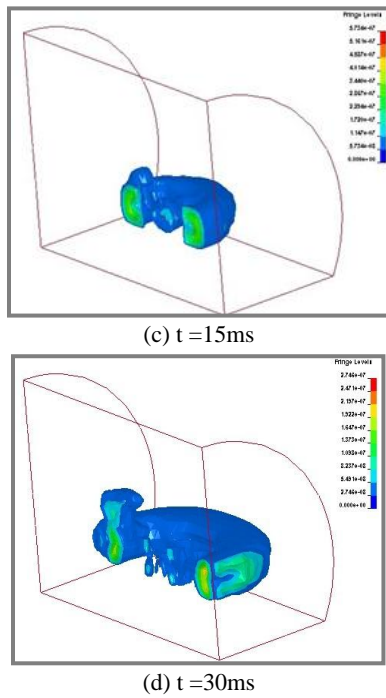


Figure 7: Blast Wave at Different Time

After the detonation of explosive, in a short time the blast wave can not contact the obstacle, then a nearly hemispherical shock wave front will appear. The wave will spread quickly and pressure declined. The blast wave encounters the platform and the station hall plate, and then reflection occurs. The blast wave can not spread in height, but can spread more quickly in length. The pressure significantly enhanced. The blast wave suddenly spread in height, mainly because of the role of the venting effect of the hole of the stairs. With the increase of the time, the blast wave reflects several times, the shape of the shock wave front is irregular, and there is a diffraction phenomenon.

4.2. The Distribution of the Overpressure Peaks based on the Scaled Distances

The pressure, the impulse, and the explosion duration all are related with the charge of explosive and the distance away from the explosion source [Li et al., 2005]. In order to consider the two influence factors comprehensively, this paper introduces the concept of the scaled distance. The scaled distance defines as:

$$\bar{r} = R/\sqrt[3]{W} \tag{4}$$

Where the \bar{r} is defined as the scaled distance, R is the distance away from the explosion source, and W is the charge of the explosive. This paper uses the charges of 5 kg, 10 kg and 20 kg TNT equivalent, and selects the distance 4 m, 8 m, 16 m, 20 m away from the explosion source as a reference points. Through the calculation, the scaled distances are listed in table 3 below.

A series of reference points in cross section are set up in this paper, and the location and number are shown in figure 8. Thus, this paper gets the distributions of the overpressure peaks based on the scaled distances which are shown in figure 9.

Table 3: Scaled Distances

\bar{r}		W (kg)		
		20.00	10.00	5.00
R(m)	4.00	1.48	1.86	2.34
	8.00	2.95	3.72	4.68
	16.00	5.90	7.44	9.36
	20.00	7.38	9.30	11.70

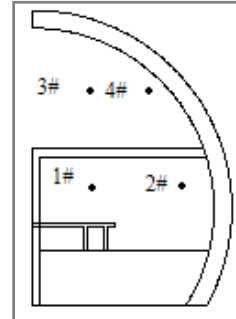
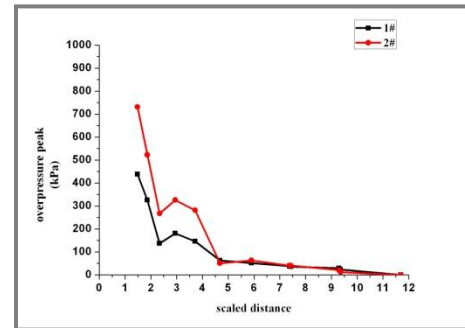
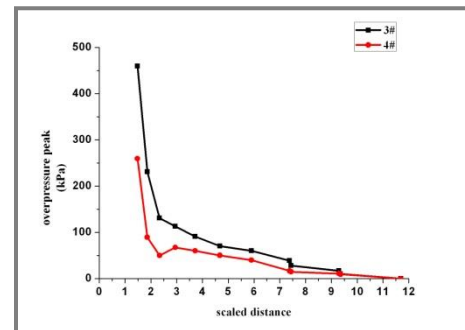


Figure 8: The Location and Number of the Reference Points



(a) The First Floor



(b) The Second Floor

Figure 9: Overpressure Peaks based on the Scaled Distances

From the figure 9(a), generally speaking, along with the increase of scaled distance, overpressure peak gradually decreases. However, the overpressure peak increases significantly when the scaled distance is 2.95. The reasons are the increase of charge is relatively large and the increase of the distance is relatively small. We can see the overpressure peak of the 2# is larger than the 1# from the scaled distance of 1.48 to 4.68. The reasons are the superposition of the incident and reflected waves at 2# and the venting effect of staircase hole at 1#. From the figure 9(b), the overpressure peaks of every reference points in second floor are smaller than in the first floor and along with the increase of scaled distance, the overpressure peak gradually decreases.

4.3. The Personnel Injury Degree

According to the overpressure peaks based on the scaled distances, we can get the different p_{max} . The overpressure peak time t_l approximate takes 15ms. Then different simplified explosion effects are obtained. When the dummy is subjected to the simplified explosion effects which come from the distribution of the overpressure peaks based on the scaled distances, this paper gets the HIC of each reference point. The figure 10 is the HIC of each reference point based on the scaled distances. When the $HIC \leq 1000$, through the calculation this paper gets the D_r of each reference point based on the scaled distances which is shown in figure 11.

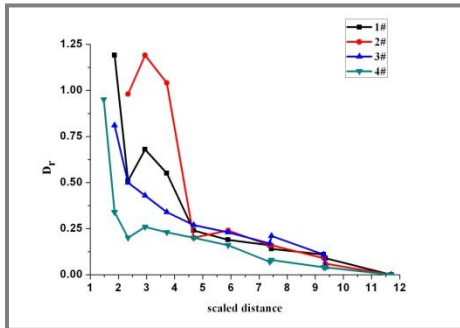


Figure 10: HIC

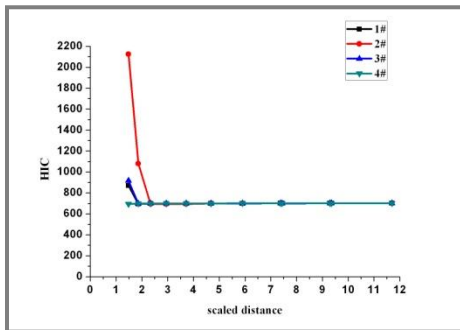
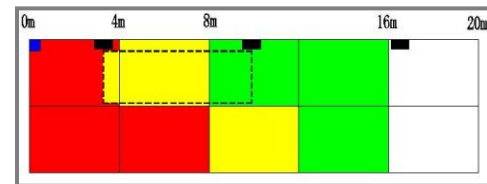


Figure 11: D_r

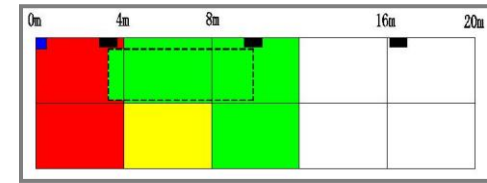
From the Figure 10, we can see the values of HIC are more than 1000 only in 2 # reference point when the scaled distances are 1.48 and 1.86. However, the others are approaching and are less than 1000. The reasons are venting effect of staircase hole at 1# and the smaller overpressure peaks in the second floor. From the Figure 11, along with the increase of scaled distance, D_r gradually decreases and the personnel injury degree becomes slightly. When the scaled distance is 2.95, because the overpressure peak increases significantly, the personnel injury degree is serious. The value of D_r is approaching when the scaled distance is 4.68.

V. CASUALTIES ZONATIONS

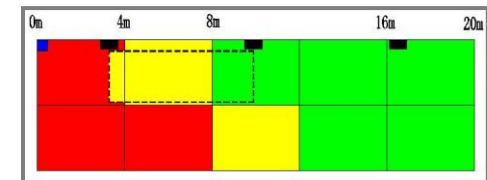
In this paper, according to the evaluation standard of the shock wave injury and the personnel injury degree, the subway station is divided into different casualty zonations which are shown in figure 12 and figure 13. The blue is explosive, the black is column and the dotted line is stairs hole. The red is death, the yellow is serious injury, the green is moderate injury and the white is without injury.



(a) 5 kg



(b) 10 kg

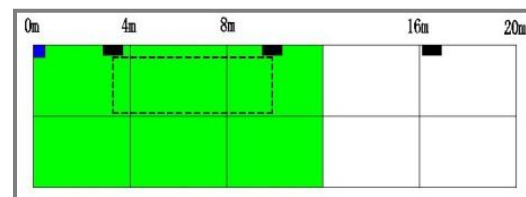


(c) 20 kg

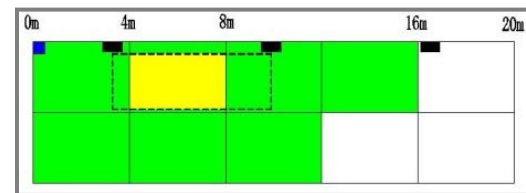
Figure 12: Casualty Zonation of the First Floor

From figure 12, we can see the personnel injury degree is related with the scaled distance. It is the most serious casualties zonation where the charge of TNT is largest and the distance away from the explosive source is most nearby. Although this paper doesn't consider the reflection of the columns, just considers the venting effect of staircase hole and the reflection of the walls. We can also see the decrease of the injury degree at staircase hole.

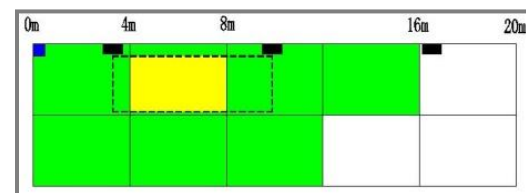
From figure 13, we can see the personnel injury degree of the second is smaller than the first floor and the most serious casualties zonation is at stairs hole.



(a) 5 kg



(b) 10 kg



(c) 20 kg

Figure 13: Casualty Zonation of the Second Floor

VI. CONCLUSIONS AND FUTURE WORK

- In this paper, the typical subway station subjected to internal blast loading simulation is analyzed by numerical simulation. We can find once an internal explosion happened in the subway station, because of the complexity of the structure, the blast wave propagation is very complex.
- In this paper, the typical subway station subjected to internal blast loading simulation is analyzed by numerical simulation and the distribution of the overpressure peaks based on the scaled distances is obtained.
- This paper summarizes the evaluation standard of the shock wave injury domestic and abroad and puts forward a new evaluation standard which analyzed the personnel injury degree with the rigid finite element dummy and the simplified explosion effect.
- According to the evaluation standard of the shock wave injury and the personnel injury degree, the subway station is divided into different casualty zonation which can estimate the personnel injury degree.

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Shi Yan. He earned his Ph.D degree in Dalian University of Technology, China. He works at School of Civil Engineering, Shenyang Jianzhu University as a professor. Now he is the director of disaster prevention institute, Shenyang Jianzhu University, China. His current research interests are including: (1) smart materials and structures; (2) seismic and anti-explosion design of civil engineering; (3) structure control and structural health monitoring. He has published 240 papers and 5 books.