Response of Fully Prefabricated Subway Stations Subjected to Internal Blast Loading

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Abstract. A new kind of fully prefabricated subway station is developed in Changchun, China. This study investigates the failure mechanisms of these stations subjected to medium internal blast loading. A series of numerical simulations are carried out using the finite element program LS-DYNA. From the results, the damage and failure of the station are progressive and occur when the main event of blast loading is over. The distribution of casualties is presented in the subway station. Results show that the joints of the fully prefabricated stations can help reduce the damage of the underground stations.

1. Introduction and literature review

1.1 Introduction
A new kind of fully prefabricated subway station is developed in Changchun, China. The stations are divided into seven components, manufactured in a factory and assembled in situ. It has considerable advantages in saving manpower and shortening construction time. Meanwhile, industrial production of the components can offer high-quality assurance and reduce environmental damage during construction. Therefore, this new kind of fully prefabricated subway station is well accepted and becomes quite popular with its considerable socio-economic benefits. At present, five fully prefabricated stations are successfully installed in Changchun Metro Line 2, as shown in Figure 1. The width of the station is 20.5 m, and the height is 17.45 m. The standard ring with a width of 2 m consists of seven components, as shown in Figure 2–3. In addition, closed cavity thin-wall components are designed for weight minimization and construction convenience.
The fully prefabricated stations are a new type of structure, and there is no mature code and experience for designing them. Therefore, it is necessary to carry out systematic research to study the stations’ performance under different loading conditions. This study aims to find the seismic response of the fully prefabricated subway stations subjected to internal blast loading and provide a reference for subsequent optimization design.
1.2 Literature review

Much research has been conducted on the dynamic response of underground structures due to explosion, involving cavities, constitutive models of rock and soil, structural dynamic response, explosion wave propagation in rock and soil, etc.

Figure 1. Scene pictures of fully prefabricated subway stations in Changchun Metro Line 2.

Figure 2. Side view of standard ring of fully prefabricated subway stations

Figure 3. Front view of standard ring of fully prefabricated subway stations
Many experimental studies were conducted, including the full-scale tests in Norway, the low-impact tests of shallow-buried structures in Switzerland, and the CONWEB tests at the U.S. Waterway Test Station.

Qian Qihu[1] explored the soil-structure mechanism in a one-dimensional explosion field. Yang Xiumin[2-3] studied shock wave propagation law in the free field of rocks under nuclear explosions. The Third Research Institute of the General Staff also conducted many field nuclear and conventional weapon explosions. Ma et al. [4] studied the dynamic response of an underground structure due to explosion through the centrifugal model test. De et al. [5] studied the effects of surface explosion on a tunnel through physical model tests.

Given the relatively high cost and risk factor of explosion tests, theoretical derivation and numerical simulation are widely used to study this problem. For example, Liu Jingbo [6] employed numerical analysis to analyze the explosion shock vibration environment for typical underground projects considering the interaction between rock and structure and obtained useful parameters in different working conditions. Kong Desen et al. [7] studied the response of the subway tunnel due to 10 kg TNT explosion with the fluid-solid coupling algorithm based on the Nanjing Metro tunnel. Han Yuzhen et al. [8-11] proposed a new approach in LS-DYNA to simulate blast wave propagation inside the tunnel and studied the interaction mechanism between soil and tunnels. Theoretical analysis and numerical simulation were employed to study the flow field distribution, casualties, dynamic response, and structural damage using a subway structure subjected to an internal explosion in Yan Qiushih[12].

The presentations of this study are organized as follows: series of finite element simulations for fully prefabricated subway stations in LS-DYNA are introduced. The findings from the simulation are then presented, and future research is discussed.

2. Numerical simulation model in LS-DYNA

The prototype model is based on the Jianshejie station in Changchun metro line2. The width of the station is 20.5 m, and the height is 17.45 m. The standard ring consists of seven components, as shown in Figure 4–5. Due to symmetry, only half of the model’s geometry is simulated to reduce computer resources, and the total length of the model is 50 m. The finite element method was employed and fixed, and symmetric boundary conditions were applied to the symmetric planes.

The dense saturated soil was modeled using the FHWA soil model. Most of the default parameters in LS-DYNA were employed in this study, calibrated by the model developer for dense granular soil [15-16]. The model has a modified Mohr-Coulomb surface to determine the pressure-dependent peak shear strength. At the crossing of the pressure axis, the modified surface is smooth, and it is perpendicular to the pressure axis. The yield surface is given as:

\[
F = -P \sin \beta + \sqrt{J_2 K(\theta)^2 + a_{hyp}^2 \sin \beta^2} - c \cos \beta = 0
\]

Where: \( P \) = pressure; \( \beta \) = model parameter related to internal friction angle; \( K(\theta) \) = function of the angle in the deviatoric plane; \( J_2 \) = the second invariant of the stress deviator; \( c \) = amount of cohesion; \( J_3 \) = third invariant of the stress deviator; \( a_{hyp} \) = parameter for determining how close to the standard Mohr-Coulomb yield surface the modified surface is fitted. Figure 6 shows a comparison of the Mohr-Coulomb yield surfaces in the shear stress-pressure space.
Thin-layer elements were used to simulate the interface between soil and the structure. The element thickness is much smaller than the other dimension (2D) or the other two dimensions (3D). However, ordinary solid elements are used to simulate the interfaces when the thickness is about 0.01–0.1 of the longer dimension. Figure 7 illustrates the application of thin-layer elements. The thin-layer elements between soil and lining were also modeled using the FHWA soil model, but their shear modulus and shear strength were assumed as two-thirds of that of soil.

The air and ambient layer are simulated using linear 3D solid elements in the LS-DYNA. The elements were 8-node hexahedrons integrated using the 8-point Gaussian method. The air and ambient layer are assumed to be ideal gas and modeled using the MAT_NULL material model, the equation-of-state EOS_LINEAR_POLYNOMIAL of which is given as:

\[ p = (\gamma - 1) \frac{\rho}{\rho_0} E_0 \]  

(2)

According to previous numerical studies, the specific heat ratio was assumed as 1.4 [13]. \( \rho_0 \) is the initial density of air and was considered to be 0.00129 g/cm\(^3\). Parametric studies were conducted using varying \( \rho_0 \) to investigate its effect. \( E_0 \) was assigned a value of 2.5e\(^{-1} \) MPa according to Schwer [13] and assuming an initial air temperature of 20\(^\circ\)C.
The constitutive model *MAT_CONCRETE_DAMAGE_REL3 in LS-DYNA is adopted to simulate concrete. It is a three-invariant model, uses three shear failure surfaces, includes damage and strain-rate effects, and has origins based on the Pseudo-TENSOR Model (Material Type 16). The most significant user improvement provided is a model parameter generation capability based solely on the unconfined compression strength of the concrete. In addition, an equation-of-state is also required for the pressure-volume strain response. Brief descriptions of all the input parameters are provided below; however, it is expected that this model will be used primarily to automatically generate the model parameters based on the unconfined compression strength of the concrete. These generated material parameters and the generated parameters for *EOS_TABULATED_COMPACTION are written to the d3hsp file. In addition, the *MAT_CONCRETE_DAMAGE_REL3 constitutive model includes the option of considering reinforcement (rebar) in a smeared fashion, but the reinforcement does not need to be modeled in a discrete manner using beam elements.

Figure 8. Fixed strength surfaces of the concrete model in (a) Deviatoric plane, (b) Rendulic plane, and (c) 3D stress space.

3. Results

3.1. Wave propagation process of pressure in the station

Figure 9 shows an in-depth propagation process of the blast wave inside the station. The blast wave spreads rapidly from the wave source to the vault and bottom of the station and then propagates longitudinally.
Figures 10–13 show the locations of stress concentration in each location. Stress peaks mainly appeared at the change of cross-sectional shape. Therefore, optimizing the shape of the cavity and the station or using alternative materials in future research design can yield a reduction in stress concentration.
3.2. Displacement and strain in the station

Displacement and deformation results were also obtained from the simulation. Figures 14–15 show the horizontal and vertical displacements of the station due to a 200 kg TNT blast loading. The station's positions that deformed the most are those that experienced the most stress and thus the weakest part of the structure.

3.3. Distribution of casualties

The explosion in the subway station mainly causes enormous personnel casualties, and as such, the damage radius needs to be estimated. For the casualties of the huge explosions, the overpressure thresholds corresponding to the different injury levels given are similar to the evaluation standards provided by other researchers[6]. Therefore, this article adopts the overpressure threshold as the evaluation standard for the personnel casualties in subway stations. According to its overpressure evaluation criteria, the level of casualties is divided into light injury, moderate injury, serious injury, and death. The corresponding overpressure threshold for each injury level is shown in Table 1 and the distribution of casualties due 200 kg TNT equivalent explosion in the fully prefabricated subway station is presented in Figure 16. Since the explosive equivalent is substantial, the subway station suffers heavy casualties.

| Injuries     | Light injury | Moderate injury | Derious injury | Death      |
|--------------|--------------|-----------------|----------------|------------|
| Overpressure/kPa | 13.73        | 29.43           | 49.05          | >127.49    |

Table 1. Overpressure thresholds corresponding to different levels of casualties
Figure 16. Distribution of casualties due to 200kg TNT in the station

4. Conclusions and future research
This study investigated the failure mechanisms of fully prefabricated subway stations subjected to medium internal blast loading. A series of numerical simulations are carried out using the finite element program LS-DYNA. The damage and failure of the station are progressive and occur when the main event of blast loading is over. The distribution of casualties is presented in the subway station. Results show that the joints of the fully prefabricated stations can help reduce the damage of the underground stations.

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