Safety distances of cylindrical reinforced concrete piers under vehicle explosion

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Since the terrorist attacks on 11 September 2001, structural resistance to explosion has received increasing attention. As bridges are controlling factors in traffic systems, explosion-induced bridge damage will cause great economic loss and social impact, but there is a lack of anti-explosion research for bridges. The purpose of this work was to investigate the failure modes and safety distances of cylindrical reinforced concrete (RC) bridge piers on highways and urban viaducts as a result of vehicle explosion. TNT equivalents were selected to represent explosions of five different vehicles (car, sport utility vehicle/van, delivery truck, water truck and semi-trailer). The multi-Euler domain method, was adopted for structural analysis of the explosion process using the commercial software Autodyn. The results showed that RC piers have three failure modes at the base: full-section punching-shear failure and large displacement; shear failure of full-section concrete; local shear failure of concrete. The explosion energy decayed rapidly with distance. For the five vehicle explosions, the safety distances were found to be 2 m, 3 m, 4 m, 8 m and 14 m, respectively. The results of this work are meaningful for explosion-resistant design and damage assessments of existing highway cylindrical RC piers subjected to vehicle explosion.

Notation

A	initial yield stress
A_s	area of section
B	hardening constant
C	strain rate constant
E	elastic modulus of concrete
E_0	internal energy of unit volume
e	internal energy
f_c	concrete compressive strength
f_s	concrete shear strength
f_t	concrete tensile strength
G	shear modulus of concrete
m	thermal softening exponent
n	hardening exponent
p	pressure during explosion
T_H	homologous temperature
V	volume ratio
Y	yield stress
γ	adiabatic exponent of ideal air
ϵ_p	effective plastic strain
ϵ_p^*	normalised effective plastic strain rate
ρ	density

1. Introduction

Over the past 60 years, more than 550 terrorist attacks on bridges and buildings have been recorded (Pan *et al.*, 2017). Bridges are often the targets for terrorist attacks because of their large volume, great social impact and accessibility. As components supporting bridge superstructures, piers transfer dead load and live load to the foundation. The destruction of

bridge piers thus leads directly to bridge damage, resulting in excessive displacement of the superstructure or even collapse, affecting traffic safety and causing adverse social impacts. Damage evaluation and the safety distance of reinforced concrete (RC) piers of highway bridges during intentional and unintentional vehicle explosion are urgent issues for research.

Williamson *et al.* (2011a, 2011b) studied the influence of cross-sectional shape, length/depth ratio, and volume reinforcement ratio on the anti-explosion performance of bridges with ten different half-scale columns. Their results showed that the damage mode was base shear failure in cases the explosive charge was close to the ground. They proposed that the anti-explosion design of piers should be improved by 50%, with the transverse reinforcement ratio corresponding to the seismic design of piers.

Zong *et al.* (2017) investigated 11 RC piers during mid-field explosion and contact explosion, and formulated a relationship between the peak overpressure and proportional distance. Their results showed that, under non-contact explosion, an increase in the section area of the pier, the use of concrete reinforced with steel fibres, a square section form and spiral stirrups reduced the cross-section strain and restrained cracks. Under the action of contact explosion, RC piers can easily be punched and destroyed at the contact position. A square section and the axial force under the action of contact explosion are unfavourable to the explosion resistance of piers.

Based on existing piers, Liu *et al.* (2018) studied the bending failure modes of RC piers at their bottom, mid-height and top.

Figure 1. (a) Front diagonal view of test setup of Fujikura and Bruneau (2011); (b) failure mode after contact explosion; (c) failure mode after non-contact explosion

The damage status of the piers was evaluated using load–displacement curves of the piers before and after explosion. Thomas *et al.* (2018) investigated the structural reliability of circular RC bridge columns subjected to blast loading and sequential vehicular impact and explosive blast loading. The results showed that structural reliability under blast loading was highly sensitive to the diameter, reinforcement ratio and standoff distance.

Many scholars have studied explosion damage to single column piers using scale models and numerical analysis, and methods for the evaluation of explosion damage and design methods for explosion resistance have been proposed (Bao and Li, 2010; Kyei and Braimah, 2017; Li *et al.*, 2017a, 2017b; Williams and Williamson, 2012). However, these methods ignore damage to the bent cap and the superstructure and simplify the boundary, meaning that the results obtained differ from real situations. Liu *et al.* (2015) investigated the damage mechanism of typical highway bridges under simplified blast loading. Fujikura and Bruneau (2011) reported the blast resistance of RC piers which met the requirements of seismic design. They concluded that seismically designed RC columns did not exhibit ductile behaviour under blast loading and failed in shear at the base rather than flexural yielding, as shown in Figure 1.

The energy release path of an explosive shock wave is directly related to the boundary form and structural size. Scaled models and simplified boundaries will therefore result in structural damage states different to those actually observed. The TNT equivalents of vehicle explosions are very large and experiments come with high risk and testing difficulty. Therefore, in the work reported in this paper, a numerical model was developed to evaluate the effects of vehicle explosions on columns and bent caps. TNT equivalents were selected to present an explosion of a car, sport utility

vehicle (SUV)/van, delivery truck, water truck and semi-trailer. Based on the section and reinforcement ratio of piers in existing seismic design for highway bridges (Ministry of Transport of the People's Republic of China, 2018; Ministry of Transport of the People's Republic of China, 2008), the damage status structure was evaluated according to the damage area, the damage degree and the failure mode of the pier concrete and the reinforcement. The safety distances of cylindrical RC piers during various vehicle explosions were also derived. These are presented in this paper and can be used as a reference for anti-explosion design, protection and evaluation of explosion damage for cylindrical RC piers.

2. Material properties and modelling

Due to the high risks involved in explosion tests (Fujikura and Bruneau, 2011; Williamson *et al.*, 2011a, 2011b; Zong *et al.*, 2017), numerical simulations become important methods to conduct research on structures under blast loads (Carta and Stochino, 2013; Li and He, 2018). Pan *et al.* (2017) used the commercial software Autodyn to carry out numerical analysis of the explosion resistance of a cable-stayed bridge

Figure 2. The Riedel–Hiermaier–Thoma concrete model

and a steel–concrete composite girder bridge. Li and He (2018) analysed explosive loads on and under a steel–concrete composite girder bridge and used a numerical method to

Table 1. Material parameters of concrete

f_c : MPa	f_t/f_c	f_s/f_c	E : MPa	G : MPa
40	0.1	0.18	32500	13000

Table 2. Material parameters of the Johnson–Cook equation

A : MPa	B : MPa	C	n	m
345	424	0.26	0.014	1.03

Table 3. Material parameters of air

ρ : g/cm ³	e : J/kg ¹	γ
0.00125	2.068×10^8	1.4

Table 4. Material parameters of the Jones–Wilkins–Lee state equation

R_1	R_2	A : MPa	B : MPa	ω	ρ : g/cm ³	V	E : J/kg
4.15	0.90	3.378×10^5	3.747×10^3	0.35	1.63	1.00	7.0×10^6

ascertain the damage area and structural stress distribution. Li *et al.* (2017b) performed a numerical study of a precast segmental column under blast loads using the hydro-code LS-Dyna. Validation of numerical methods has been shown by experiments by many scholars (Carta and Stochino, 2013; Shiravand and Parvanehro, 2017; Son and Astaneh-Asl, 2017).

2.1 Material constitutive model

A high-temperature field and high strain rate are commonly observed when structures are subjected to blast loads (Forni *et al.*, 2017), which respectively result in concrete weakening and enhancement. Analytical accuracy is dependent on the concrete constitutive law. The Riedel–Hiermaier–Thoma (RHT) concrete model, validated by Tu and Lu (2010), was used in this study. The model is shown in Figure 2. The concrete parameters used in this work are shown in Table 1.

Besides the concrete constitutive law, the steel constitutive model of the stirrups and longitudinal steel bars directly affects the shear and flexural capacity of bridge columns. After comparison with experimental results and numerical

Figure 3. Arrangements of gauges

Figure 4. Arrangements of reinforcements in pier (dimensions in cm)

simulations performed by Forni *et al.* (2016), the Johnson–Cook model was found to simulate precisely the strain–stress properties of steel during explosion. The model defines the yield stress Y as:

$$1. \quad Y = \left(A + B \varepsilon_p^n \right) \left(1 + C \ln \varepsilon_p^* \right) \left(1 - T_H^m \right)$$

The parameters was indicated in Table 2. Many scholars have defined B to be $1.23A$ (Hashemi *et al.*, 2017; Li *et al.*, 2017a; Nystrom and Gylltoft, 2011).

To reflect standard atmospheric pressure, air was simplified to be ideal air:

$$2. \quad p = (\gamma - 1) \rho e$$

Figure 5. Arrangements of reinforcements in bent cap (dimensions in cm)

Table 5. Impact heights and TNT equivalents of representative vehicle classes (Thomas *et al.*, 2018)

Vehicle		Impact height: m	TNT equivalent: kg
Car	0.61	227
SUV/van	0.91	454
Delivery truck	1.22	1814
Water truck	1.5	4536
Semi-trailer	1.8	27 215

where e , γ and ρ are the internal energy, adiabatic exponent and density, respectively. These parameters are listed in Table 3.

To simulate energy transmission factually, the Jones–Wilkins–Lee state equation was adopted to model the explosive material and ambient air with the flow-out boundary condition. This equation is:

$$3. \quad p = A \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E_0}{V}$$

The values of these parameters are shown in Table 4.

2.2 Finite-element modelling

Autodyn is an explicit analysis tool for modelling the non-linear dynamics of solids, fluids, gases and their interactions

Figure 6. Analysis model in Autodyn. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

(Zhu *et al.*, 2019). The accuracy of this analytical method has been verified by several researchers (Li and He, 2018; Pan *et al.*, 2017; Winget *et al.*, 2005). To balance accuracy and analytical time, the element sizes of the piers and bent cap were set to 10 cm and 15 cm, respectively (Pan *et al.*, 2013). Solid164 elements were adopted for the concrete while the reinforcement was modelled using Beam161. The RC piers were selected to be 10 m high and 1.5 m in diameter to represent bridge piers existing extensively in highway bridges. The distance between the piers was set to 5.8 m, meeting the layout for construction machinery and the stress requirements of the piles. The height of the bent cap and block were 1.6 m and 0.9 m, respectively, in accordance with current codes (Ministry of Transport of the People's Republic of China, 2008; 2018). To evaluate the response of piers under vehicle explosion accurately, gauges were arranged as shown in Figure 3. To represent a real situation during an explosion, the arrangement of longitudinal reinforcements and stirrups was selected according to design drawings widely used for highway bridges. The stirrups were 10 mm in diameter, with stirrups in the base and top of piers in 4 m lengths, as shown in Figure 4. The longitudinal reinforcement was 28 mm in diameter, with a reinforcement ratio of 1.46%. The stirrups and longitudinal reinforcements of the bent cap were selected to be 12 mm and 28 mm, respectively, with a separation of 15 cm (Figure 5).

Analyses were performed for each of the five vehicle types described in Table 5. The impact heights and TNT equivalents of representative vehicle classes have been verified by many scholars (DoHS, 2009; Mestrovic *et al.*, 2008; Thomas *et al.*, 2018; Zhou *et al.*, 2017). In order to investigate the performance of the columns and the bent beam under explosion, a consolidation boundary was adopted in the base while a gap was

Figure 7. Contact car explosion: (a) damage mode; (b) displacement. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

established to model the relative displacement between the pier and the bent cap beam. The TNT equivalent was placed near the pier to simulate the worst scenario (Figure 6).

3. Bridge performance and discussion of results

The damage to cylindrical RC bridge piers under five scenarios was studied: car explosion, SUV/van explosion, delivery truck explosion, water truck explosion and semi-trailer explosion. With an increase in distance, the explosion energy decreased

rapidly, while the damage mode and degree of explosion decreased gradually. When the explosive overpressure reached the pier, the structure vibrated violently. Combined with the explosive energy attenuation curve, the analysis time was determined to be 15 ms. The damage zone, displacement and vibration history were used to evaluate the damage modes and mechanisms after the explosions.

After analysis of the explosion damage to the piers, the safety distance for pier explosion resistance was evaluated.

Figure 8. Damage mode under car explosion at distance of: (a) 1 m; (b) 2 m. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

Figure 9. Contact SUV/van explosion: (a) damage mode; (b) displacement. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

Equation 4 is put forward for a quantitative evaluation of damage under vehicle explosion:

$$4. \quad DF = \frac{\int (DL) dA_s}{A_s}$$

where DF is the damage factor of the full section, DL is the damage level and A_s is the area of the section. When $DF = 1$, there is failure of the full section; no concrete failure occurs if $DF = 0$.

For the contact car explosion, Figure 7(a) shows that the RC pier suffered shear failure at the base, with a failure zone of almost 1.2 m. The maximum displacement was 55 mm after response to the blast wave as a result of shear failure (Figure 7(b)). With an increase in distance, the explosive energy decayed rapidly. The damage factors were found to be 0.040 and 0.003 respectively for distances of 1 m and 2 m (Figure 8). The safety distance for the cylindrical RC bridge pier for a car explosion was thus determined to be 2 m.

Figure 10. Damage mode under SUV/van explosion at distance of: (a) 1 m; (b) 3 m. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

Figure 11. Contact delivery truck explosion: (a) damage mode; (b) displacement. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

With an increase in TNT equivalent (i.e. SUV/van explosion), the damage zone increased to 1.8 m at the base of the RC column (Figure 9). The stirrups yielded in shear and the longitudinal reinforcements showed slight buckling. The final displacement was 210 mm due to shear failure at the base. For an explosion 1 m away, the damage factor was 0.330 (Figure 10). At a distance of 3 m, the explosion energy

attenuated to result in only slight damage to the pier; the safe distance is thus 3 m.

Compared with a SUV or van, the TNT equivalent of a delivery truck is significantly increased. Figure 11 shows that, for a contact delivery truck explosion, the bottom 2.5 m of pier concrete was completely damaged and the longitudinal

Figure 12. Damage mode under delivery truck explosion at distance of: (a) 1 m; (b) 4 m. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

Figure 13. Contact water truck explosion: (a) damage mode; (b) displacement. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

reinforcements showed obvious buckling. The punching displacement was 653 mm at the base while the deformation due to the interaction of the pier and bent cap was 13 mm inwards, corresponding to the experimental situation shown in Figure 1(b). The damage factors for explosions at distances of 1 m and 4 m were found to be 1.000 and 0.008, respectively (Figure 12). The safety distance for a cylindrical RC bridge pier subjected to delivery truck explosion is thus 4 m.

The explosive TNT equivalent of a water truck is about 2.5 times that of a delivery truck. Under the action of such explosive load, the stirrups were sheared within the bottom 4 m of the pier, making it difficult for deformation of the longitudinal reinforcement to be restrained, resulting in a displacement of

123 mm at the base of columns, as shown in Figure 13. Figure 14 shows the failure modes during non-contact explosion of the water truck: compared with the contact explosion, the non-contact explosions showed shear failure without large deformation. With an increase in distance, local shear failure was only slight; the safety distance was determined to be 8 m.

The piers subjected to explosive impact from a semi-trailer showed very exaggerated displacement. Failure of the stirrups and the shear failure of piers on the other side of the impact resulted in the piers completely losing their bearing capacities, resulting in collapse of the superstructure, as shown in Figure 15. Even with an increase in distance, the explosive

Figure 14. Damage mode under water truck explosion at distance of: (a) 1 m; (b) 2 m; (c) 4 m; (d) 6 m. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

Figure 15. Contact semi-trailer explosion: (a) damage mode; (b) displacement. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

shock wave from the semi-trailer still caused shear failure of the double piers, as shown in Figure 16. For sufficient decay in explosive energy, the safety distance was determined as 14 m, producing a damage factor of 0.003.

4. Failure mechanism of cylindrical RC piers subjected to vehicle explosion

The final failure modes of the structure due to the instantaneous release of explosive impact energy were analysed. During the failure process, the peak pressure and vibration velocity histories were used to investigate the damage mechanisms due to explosion. Figure 17 shows the pressure–time history during the contact vehicle explosions for the car, SUV/van, delivery truck, water truck and semi-trailer: the peak pressures were found to be 2710 MPa, 4240 MPa, 5680 MPa, 7530 MPa and 10 900 MPa respectively. Due to the degradation of stiffness during the explosions, the relationship between explosive overpressure and TNT equivalent was found to be non-linear.

With an increase in distance, the overpressure decayed rapidly, as shown in Figure 18 for the case of the semi-trailer. The overpressure was found to be 1520 MPa for contact explosion while, at a distance of 12 m, the overpressure was just 6.17 MPa. This shows the importance of installing isolation devices to avoid damage due to approaching explosions.

The vibration velocity due to impact energy is also of significance. Figure 19 shows the velocity history of gauges arranged in the pier under contact car explosion. Gauge 3 and gauge 24

were selected to reflect the shear displacement at the base of the column. The velocity history shows that the vibration was consistent with the overpressure. At the peak value of impact overpressure, the displacement velocity reached 8 mm/ms. With energy attenuation, the vibration velocity gradually decreased to zero. A large punching displacement was observed at the base of the pier while deformation due to the interaction of the pier and bent cap was negligible, corresponding to the experimental result shown in Figure 1(b).

Figure 20 shows the vibration velocity history for a car explosion at a distance of 1 m, again considering gauges 3, 11 and 24. The vibration velocities of these gauges all fluctuated around zero. As a result, shear failure occurred in the base without large displacement, as also shown in Figure 1(c).

Through an investigation of the failure modes and damage mechanisms due to vehicle explosions, the safety distances are concluded. Figure 21 shows that the safety distances are 2 m, 3 m, 4 m, 8 m and 14 m respectively, for explosions due to car, SUV/van, delivery truck, water truck and semi-trailer impact. This paper is meaningful to explosion-resistant design and damage assessment of existing highway cylindrical RC piers under vehicle explosion.

5. Conclusions

The failure modes and safety distances of cylindrical RC bridge piers subjected to vehicle explosions were investigated. TNT equivalents were selected to represent the explosion of a

Figure 16. Damage mode under semi-trailer explosion at distance of: (a) 1 m; (b) 2 m; (c) 4 m; (d) 6 m; (e) 8 m; (f) 12 m. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

Figure 17. Peak pressure–time history during contact vehicle explosions

Figure 20. Vibration velocity–time history under car explosion at a distance of 1 m

Figure 18. Peak pressure–time history during explosion of semi-trailer

Figure 21. Damage factors due to vehicle explosions as a function of distance

Figure 19. Vibration velocity–time history under contact car explosion

car, SUV/van, delivery truck, water truck and semi-trailer. To precisely reflect the fluid-solid coupling characteristics during blast loading, the multi-Euler domain method was

adopted. The following conclusions were drawn from this study.

- Due to vehicle explosion, the cylindrical RC piers showed three failure modes at the base: (a) full-section punching-shear failure and large displacement, (b) shear failure of the full section of concrete and (c) local shear failure of the concrete. The shear capacity of piers should thus be improved if they could suffer damage due to intentional or unintentional vehicle explosion.
- With an increase in distance from the explosion, the overpressure and damage modes decayed rapidly. It is thus particularly important to install isolation devices to avoid approaching vehicle explosions.
- For different anti-explosion requirements and traffic needs, protection from vehicle explosions should be suitably applied. Safety distances were determined in this work and were found to be 2 m, 3 m, 4 m, 8 m and

14 m for car, SUV/van, delivery truck, water truck and semi-trailer explosions, respectively.

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