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Effect of one way reinforced concrete slab characteristics on structural response under blast loading

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Abstract. In evaluating explosion-protection capacity, safety distance is broadly accepted as the distance at which detonation of a given explosive causes acceptable structural damage. Safety distance can be calculated based on structural response under blast loading and damage criteria. For the applicability of the safety distance, the minimum required stand-off distance should be given when the explosive size is assumed. However, because of the nature of structures, structural details and material characteristics differ, which requires sensitivity analysis of the safety distance. This study examines the safety-distance sensitivity from structural and material property variations. For the safety-distance calculation, a blast analysis module based on the Kingery and Bulmash formula, a structural response module based on a Single Degree of Freedom model, and damage criteria based on a support rotation angle were prepared. Sensitivity analysis was conducted for the Reinforced Concrete one-way slab with different thicknesses, reinforcement ratios, reinforcement yield strengths, and concrete compressive strengths. It was shown that slab thickness has the most significant influence on both inertial force and flexure resistance, but the compressive strength of the concrete is not relevant.

Keywords: explosion; SDOF; safety distance; RC slab; sensitivity analysis; slab thickness

1. Introduction

Detonations of high-order explosives and gas explosions are always happening. Accidents caused by explosions are infrequent, but cause great damage to nearby personnel and property. In order to mitigate the damage, a safety distance at which allowable structural damage is expected should be secured (Badshah *et al*. 2017). The safety distance is the minimum required distance between detonation point and structure envelope, at which the structure does not fail and internal assets can survive during and after attack. To estimate structural damage under blast loading, an actual experiment is arguably the best way to estimate the damages. So experiment related to estimate the damages are still in progress (Li *et al*. 2017, Yuan *et al*. 2017, Wu *et al*. 2019). However, explosion tests are limited to obtaining the data needed to develop or validate damage analysis methods, such as hydro codes (AUTODYN and LSDYNA) because of high costs (Shentsov *et al*. 2016). A hydro code can consider structure-blast interactions and capture detailed local structural damage (Toy and Sevim 2017, Mohammed and Parvin 2013) requiring large computational resources and long calculation time. Since many structural analyses need to be conducted to find the stand-off distance at which the structural damage meets specific criteria, a hydro code is not efficient for stand-off distance calculation. As an alternative, a Single-Degree of Freedom (SDOF) model can be used, in which computing time is short and only a few input variables are required without significant accuracy loss (Shin and Lee 2018). Since SDOF is based on a single dynamic governing equation, non-dimensional analysis is possible (McDonald *et al*. 2018). Thus, SDOF has been widely used for Pressure-Impulse diagrams or safety distance analyses where many calculations are required (Feldgun *et al*. 2016, PDCTR-06. 2008, Rigby *et al*. 2012, Fischer and Häring 2009, El-Dakhakhni *et al*. 2009, Li and Meng 2002).

Since deaths of building occupants are mainly caused by the collapse of walls or slabs, safety distance can be measured by the slab response in an explosion. The problem is that input data for the response analysis are uncertain, especially for existing buildings. In order to compensate for this uncertainty, a sensitivity analysis of safety distance from slab characteristics is required.

The purpose of this paper is to analyze the safety-distance sensitivity of Reinforced Concrete (RC) slab uncertainties. A computer code for calculating safety distance was prepared consisting of blast, structural response, and safety-distance modules. Blast and structural-response modules calculate blast-loading characteristics (peak reflected pressure and impulse) based on the Kingery and Bulmash equation (Kingery and bulmash 1984) and corresponding structural deflections based on the SDOF model, respectively. A safety distance module finds the stand-off distance at a given TNT weight, where structural

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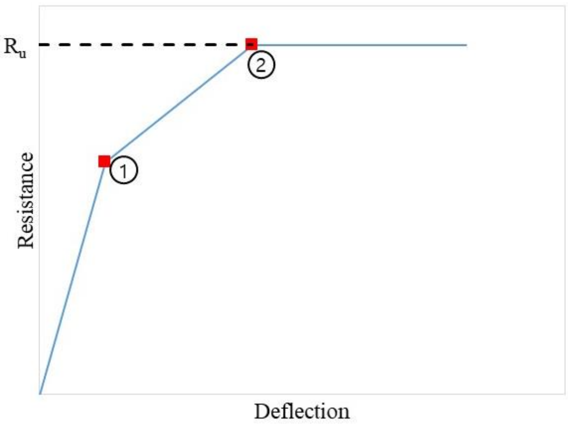

Fig. 1 Flexural-only resistance function

deflection meets failure criteria. Then, sensitivity analysis on safety distance is conducted for various RC slab characteristics. The selected variables are slab thickness, reinforcement ratio, yield strength of reinforcement, and compressive strength of the concrete.

2. Safety distance calculation

2.1 Blast module

A shock wave as generated by detonation of a high explosive is characterized by an instantaneous rise in overpressure and short duration (UFC 3-340-02 2008). TNT can be a reference explosive for equating the characteristics of a shock wave, such as peak reflected overpressure and reflected impulse (Netherton and Stewart 2009). A blast module was prepared to calculate shock-wave characteristics based on the Kingery and Bulmash equation (Kingery and bulmash 1984) assuming a hemispheric TNT explosion, which is valid when the scaled distance is between 0.33 and 186.28 m/kg$^{1/3}$. The blast module was verified by comparison with the results of CONWEP (Hyde 1991), where the difference in the values of incident pressure and reflected pressure is less than 0.7%.

TNT equivalence can be used to take into account the explosive type (UFC 3-340-02 2008) and the presence of the warhead case, which reduces shock by the energy fracturing case and accelerating fragments. The TNT equivalent factor for the case effect is usually expressed as a function of the charge-weight/case-weight ratio (Fisher 1991, Filler 1976).

2.2 Structural response module

Structural response (deflection at mid-span) is analyzed by the SDOF model consisting of effective mass and resistance (Biggs and Bernard 1964). Damping was neglected, because it does not significantly affect the maximum deflection of the structure subjected to a blast (PDCTR-06 2008). The governing equation of the SDOF model is as follows

$$K_{LM} M \ddot{u} + R(u) = F \quad (1)$$

Table 1 Material properties and reinforcement details (Lee *et al*. 2017)

Concrete	
Density [kg/m^3]	2400
Compressive strength [MPa]	22.61
Elastic modulus [MPa]	22.35
Reinforcement	
Yield strength [MPa]	560.95
Tensile strength [MPa]	675.34
Elastic modulus [MPa]	202.804
Main reinforcement	D10 (nominal cross section area=71.33 mm^2)
Stirrup	D10 (nominal cross section area=71.33 mm^2)

where u is the deflection at mid-span, M is the mass, R is the resistance function, F is the applied loading, and K_{LM} is the load-mass factor, from which the SDOF system and continuous structure have the same work, strain, and kinetic energies, assuming that the structure deflects in a given mode shape.

Fig. 1 illustrates the resistance function of a fixed-fixed one-way RC slab with three stages:

- elastic resistance: the slab responds elastically until yielding is caused at both ends simultaneously (point ①).
- elastoplastic resistance: the slab resists with reduced stiffness up to the maximum load capacity (point ②).
- perfectly plastic resistance: the slab has constant resistance (R_u) assuming no strain hardening and membrane effects, when yield occurs at mid-span. Since mode shapes are different at each resistance stage, values of K_{LM} change depending on the stage (PDC-TR-06-08 2008).

Deflection history at mid-span is calculated by solving Eq. (1) based on the central difference formula with 0.01 ms time steps, zero initial velocity, and deflection conditions. To verify the blast and structural response modules, deflection histories from a real size test (Lee *et al*. 2017) and from analytical modules are compared. The tested specimen is a 2050 mm×1500 mm×150 mm fixed-fixed RC one-way slab subjected to the 100 kg TNT surface detonation with a 15 m standoff distance. Table 1 shows the material properties and reinforcement details from the test. The maximum deflection is 12.25 mm from the test measured by LVDT, and the predicted value from the analytical modules is 13.84 mm, showing only an 11% (1.59 mm) difference.

2.3 Safety-distance module

The safety distance is defined as the stand-off distance where the detonation of a selected TNT weight causes a failure of structural components (Russo and Parisi 2016). The degree of damage can be measured by the support rotation angle at maximum deflection (PDC-TR-06-08 2008) assuming that a rotation angle of a yielded cross section governs the damage level. Table 2 shows damage levels and corresponding support rotation angles for RC slabs with flexural behavior (Hou *et al*. 2018).

Table 2 Component damage level (PDC-TR-06-08 2008)

Component Damage Level	Description of Component Damage	Support rotation angle
Blowout	Component is overwhelmed by the blast load causing debris with significant velocities	Over 10°
Hazardous Failure	Component has failed, and debris velocities range from insignificant to very significant	5° ~10°
Heavy Damage	Component has not failed, but it has significant permanent deflections causing it to be unrepairable	2° ~5°
Moderate Damage	Components has some permanent deflection. It is generally repairable, if necessary, although replacement may be more economical and aesthetic	Elastic deflection ~2°

(a) Heavy damage

(b) Hazardous failure

(c) Blowout

Fig. 2 Damage shapes (Lee *et al*. 2017)

Heavy damage (Fig. 2(a)) and moderate damage do not have significant influence on the overall structural damage. Since hazardous failure (Fig. 2(b)) and blowout (Fig. 2(c)) cause significant structural load carrying capacity loss, hazardous failure criteria are selected for safety distance calculation. That is, safety distance is assumed to be the stand-off distance where detonation causes a 5° support rotation. More than heavy damage is not expected when the structure is beyond the safety distance.

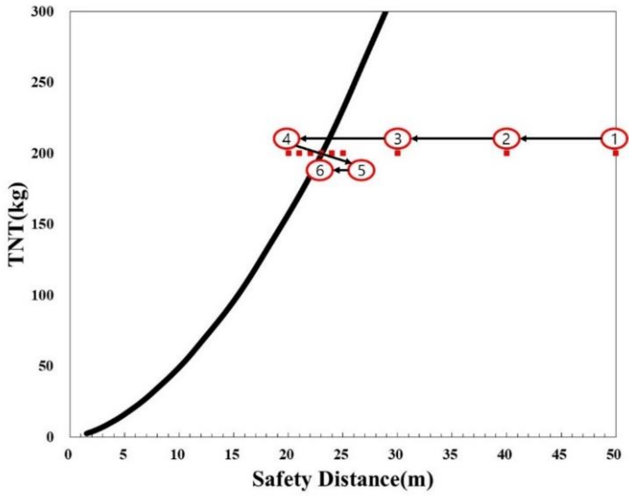

Fig. 3 Safety-distance calculation algorithm

Fig. 3 shows a charge weight – safety distance diagram, representing the safety distance of various charge weights. An algorithm to calculate the safety distance at a given charge weight is as below:

- The initial stand-off distance is set to be long enough to not cause any damage (for example, 50 m for 200 kg TNT)-(Fig. 3①)
- Maximum deflection is calculated using blast and structural behavior modules at decreasing distances (10-m steps) until maximum deflection causes more than 5° of support rotation.
  -(Fig. 3 ①-④)
- Then maximum deflection is calculated for increasing distances with smaller steps (1-m steps) until the blast causes less than 5° of support rotation.-(Fig. 3 ④-⑤)
- Steps 2 and 3 are repeated with decreasing distance steps, until a step is 10 cm
  -(Fig. 3 ⑤-⑥)

3. Sensitivity analysis

3.1 Setting variables

Just as for existing structures, the precise values of slab characteristics cannot be identified. Four variables are selected for a one-way RC slab, including thickness of the slab, compressive strength of the concrete, yield strength of longitudinal reinforcement, and reinforcement ratio. The range of each variable is set by using data from the literature.

Based on the data collected from 71 cities in 41 countries during the last 50 years (Ellefsen and Fordyce 2012), the thickness of an external wall is between 15 cm and 45 cm, and that of a roof is 10 cm. Korean Standard Specification (KS) stipulates that the thickness of the one-way RC slab should be more than 10 cm, but there are no suggestions for a maximum value. Hence, the range of slab thickness is set between 10 cm and 40 cm. The worldwide survey (Ellefsen and Fordyce 2012) shows that the range of concrete compressive strength is between 305 kg/cm^2

Table 3 Variable ranges

Variable	Range
Slab thickness	100~400 mm
Concrete Compressive Strength	18~60 MPa
Reinforcement yield strength	400~600 MPa
Reinforcement ratio	0.001~0.003

Table 4 Vehicle-specific value range by weight

Transportation	Explosive mass (lb)	Explosive mass (kg)
Luggage	20~100	9.07~45.36
Automobiles	100~500	45.36~226.80
Vans	500~1300	226.80~589.67
Trucks	1300~	589.67~

Table 5 Level of variables

	Variable value				
Level	Level 1	Level 2	Level 3	Level 4	Level 5
Slab thickness (mm)	100	175	250	325	400
Reinforcement ratio	0.001	0.0015	0.002	0.0025	0.003
Reinforcement yield strength (MPa)	400	450	500	550	600
Concrete Compressive Strength (MPa)	18	28.5	39	49.5	60

(29.91 MPa) and 326 kg/cm^2 (31.97 MPa). In the KS, the standard strength for normal concrete is between 18 MPa and 35 MPa, and that for high-strength concrete is between 40 MPa and 60 MPa. Therefore, the range of the concrete compressive strength is set as 18 MPa to 60 MPa. For the reinforcement yield strength, Jorge Madias (Madias *et al.* 2017) found out that the range of the yield strength falls generally between 420 MPa and 600 MPa. Yield strength is set in between 400 MPa and 600 MPa. For the reinforcement ratio, values between 0.001 and 0.003 are selected based on the minimum reinforcement ratio, and one for the balanced reinforcement ratio. Slab length was selected as 3 m.

Table 3 summarizes the ranges of slab thickness, concrete compressive strength, reinforcement yield strength, and reinforcement ratio.

FEMA 426(Chipley 2003) data were used to select weights of TNT. In FEMA 426, the TNT amount depends on vehicle types, as shown in Table 4. The TNT weight of VBIED ranges from 45.36 to 589.67 kg. Truck threat was excluded, since this size of explosive is difficult to obtain in Korea. Base on FEMA data, 100 kg, 250 kg, and 500 kg of TNT were selected as threats.

For sensitivity of slab thickness, concrete compressive strength, reinforcement ratio, and reinforcement yield strength on safety distance, each variable has five levels, as shown in Table 5. Safety distance calculations were conducted for each TNT weight (100, 250, 500 kg).

Safety distance is assumed to be an exponential function of slab thickness, concrete compressive strength, reinforcement ratio, and reinforcement yield strength, as follows

$$\log\,(R) = \alpha + \beta_1 \log\,(\rho_N) + \beta_2 \log\,(f_{yN}) + \beta_3 \log\,(f_{cN}) + \beta_4 \log\,(t_{tN}) \quad (2)$$

Table 6 Regression coefficients and ANOVA

	Coefficient	df	Adj SS	F	P
TNT: 100 kg					
α	0.65115				
β_1	-0.363934	4	2.35	10999	0
β_2	-0.359819	4	0.31	1467	0
β_3	-0.0112985	4	0.00	12	0
β_4	-1.30387	4	48.15	225365	0
Error		608	0.03	R2=99.94%	
Total		624	50.84		
TNT: 250 kg					
α	0.890408				
β_1	-0.369855	4	2.42	14320	0
β_2	-0.367329	4	0.32	1927	0
β_3	-0.0148742	4	0.00	27	0
β_4	-1.32989	4	50.05	295334	0
Error		608	0.02	R2=99.95%	
Total		624	52.84		
TNT: 500 kg					
α	1.07053				
β_1	-0.374938	4	2.49	15941	0
β_2	-0.372703	4	0.33	2149	0
β_3	-0.0181782	4	0.00	45	0
β_4	-1.33998	4	50.79	324640	0
Error		608	0.02	R2=99.96%	
Total		624	53.65		

where R is the safety distance (m), α, β_1, β_2, β_3, β_4 are coefficients (m), and ρ_N, f_{yN}, f_{cN}, and t_N are the normalized variables, as below

$$\rho_N = \rho/0.002,\ f_{yN} = f_y/500$$
$$f_{cN} = f_c/39, \quad t_N = t/250 \quad (3)$$

where ρ is the reinforcement ratio, f_y is the reinforcement yield strength (MPa), f_c is the concrete compressive strength (MPa), and t is the thickness of the slab (mm).

Each coefficient is obtained by regression analysis based on 625 safety distance data. The main effect and sensitivity of each factor are analyzed by ANOVA, using MINITAB

3.2 Sensitivity analysis results

Linear-regression coefficients and ANOVA results for effects of the four variables on safety distance are shown in Table 6 (100, 250 and 500 kg of TNT) with coefficients of determination greater than 99.9%. The P(t) values in Table 6 show that normalized reinforcement ratio, reinforcement yield strength, concrete compressive strength, and thickness of the slab are significant at a greater than 99.9% confidence level.

Substituting the coefficients in Table 6 into Eq. (2), regression equations for safety distance can be derived, showing that safety distance is affected in the order of slab thickness, reinforcement ratio, reinforcement yield strength, and concrete compressive strength.

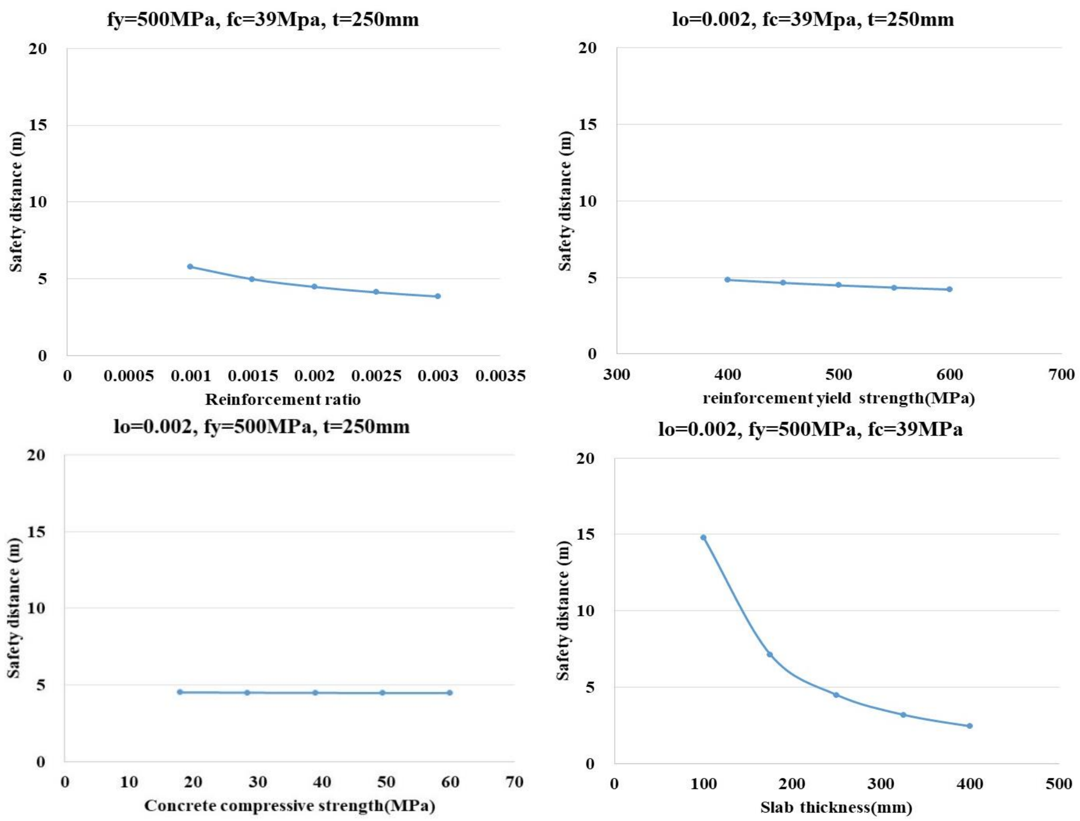

Fig. 4 Effects of Variables on Safety Distance (100kg TNT detonation)

$$\begin{gathered}R = 1.9177(\rho_N)^{-0.363934}(f_{yN})^{-0.359819} \\ (f_{cN})^{-0.0112985}(t_{tN})^{-1.30387} \text{ for TNT 100 kg} \\ R = 2.436(\rho_N)^{-0.369855}(f_{yN})^{-0.367329} \\ (f_{cN})^{-0.0148742}(t_{tN})^{-1.32989} \text{ for TNT 250 kg} \\ R = 2.916(\rho_N)^{-0.374938}(f_{yN})^{-0.372703} \\ (f_{cN})^{-0.0181782}(t_{tN})^{-1.33998} \text{ for TNT 500 kg}\end{gathered} \tag{4}$$

Figs. 4-6 shows the effects of the four variables on the safety distance. Whereas the effects of concrete compressive strength and reinforcement yield strength are weak, the slab thickness has a significant effect on the safety distance, because the larger slab thickness increases the resistance $R(u)$ by a longer moment arm between the top and bottom reinforcements, and increases the inertial force $K_{LM}M\ddot{u}$ in Eq. (1). In resistance function (Fig. 1), ultimate resistance, R_u, for a fixed-fixed uniformly loaded one-way slab is as below

$$R_u = \frac{8\left(M_u^{midspan} + M_u^{support}\right)}{L^2} \quad \text{(Pa)} \tag{5}$$

where L is the span length, $M_u^{midspan}$ is the moment capacity at midspan, and $M_u^{support}$ is the moment capacity at support, which can be expressed as follows, assuming only tensile reinforcement

$$M_u^{midspan} = M_u^{support} = \rho f_y (t-c)^2 \left(1 - \frac{\rho f_y}{2\beta f_c}\right) \quad \text{(N mm /mm)} \tag{6}$$

where c is the concrete cover depth, β is the factor dependent on concrete compressive strength.

Table 7 Safety distance sensitivity

Variables (minimum-maximum)	Difference of safety distances from maximum and minimum values of variable(m)		
	TNT 100 kg	TNT 250 kg	TNT 500 kg
Reinforcement ratio (0.001-0.003)	1.90	3.35	5.15
Reinforcement yield strength (400-600 MPa)	0.66	1.17	1.79
Concrete compressive strength (18-60 MPa)	0.06	0.14	0.26
Slab thickness (100-400 mm)	12.36	22.12	33.89

The sensitivity of slab characteristics on safety distance is summarized in Table 7. Slab thickness has the greatest influence on the safety distance, followed by reinforcement ratio, reinforcement yield strength and concrete compressive strength.

4. Conclusions

The effects of slab characteristics on Safety distance were analyzed based on SDOF system. Target structural component was selected as fixed-fixed one-way RC slab with slab thickness of 100-400 mm, 18-60 MPa concrete compressive strength, 400-600 MPa reinforcement yield strength, and 0.001-0.003 reinforcement ratio. As threats, surface detonation of 100 kg, 250 kg and 500 kg TNT was assumed. Through regression analysis, it was found that

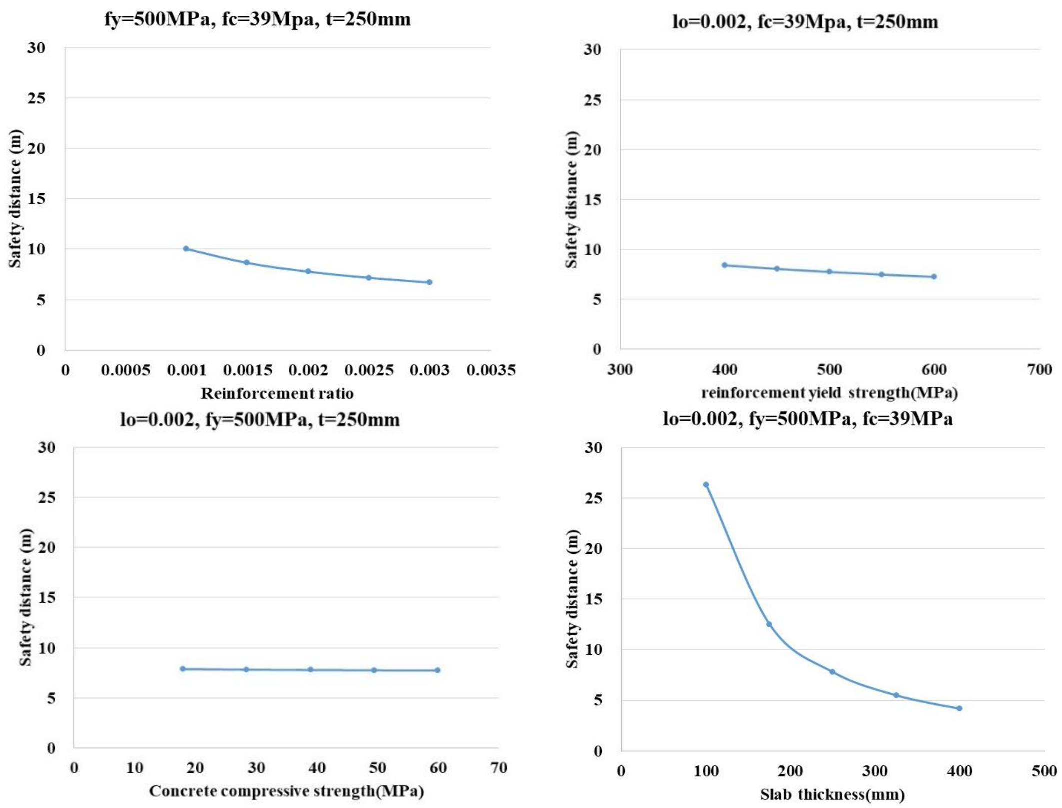

Fig. 5 Effects of variables on safety distance (250 kg TNT detonation)

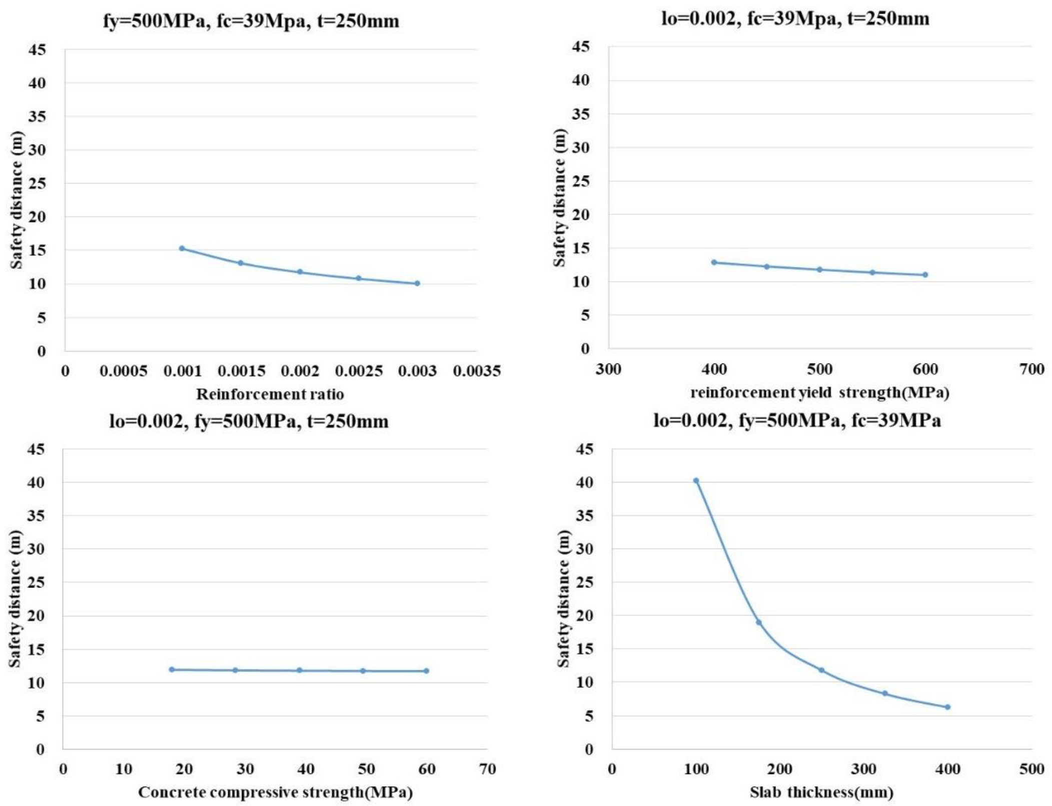

Fig. 6 Effects of variables on safety distance (500kg TNT detonation)

safety distance is affected in order of slab thickness, reinforcement ratio, reinforcement yield strength and concrete compressive strength. The reinforcement ratio and yield strength induces change of the ultimate resistance, and show similar effects on safety distance. Concrete strength shows insignificant change in safety distance since most resistance comes from reinforcement. Slab thickness has most significant influence, since inertia force is linearly dependent to it and ultimate resistance to its square value. Therefore, slab thickness should be most carefully assessed when safety distance is calculated.

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