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Dynamic Analysis of Reinforced Concrete Walls Subjected to Blast Loading

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Introduction

Purpose of this research

- In this study, the dynamic analysis of reinforced concrete (RC) walls subjected to blast loading were conducted to evaluate the variation in deformation depending on wall thickness, diameter of reinforcing bar (rebar), and reinforcement ratio.
- Previous studies were referred to make use of the blast loads generated by the detonation of trinitrotoluene (TNT) at ground surface; and the dimensions, reinforcement details, and material properties of the RC walls containing radioactive materials in nuclear facilities.
- For the dynamic analysis, the experimental data provided by "Structure to Resist the Effects of Accidental Explosions" (UFC 3-340-02) were used.

Materials and methods

Description of blast-loading environment

- The blast wave generated by hemispherical TNT surface burst was assumed to be perpendicularly propagated to the 3×3 m RC wall as shown in Fig. 1.
- Figs. 2 and 3 present the peak reflected pressures and load durations with the TNT charge weights of 3─30 kg and the standoff distances of 0.5─10 m referred in the previous study.
- The values of blast loads were used for the dynamic analysis of RC walls.

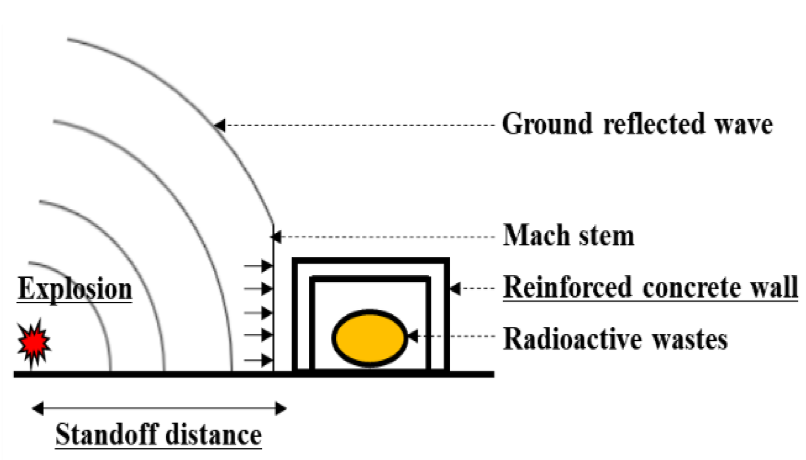

Fig. 1. Surface burst blast environment.

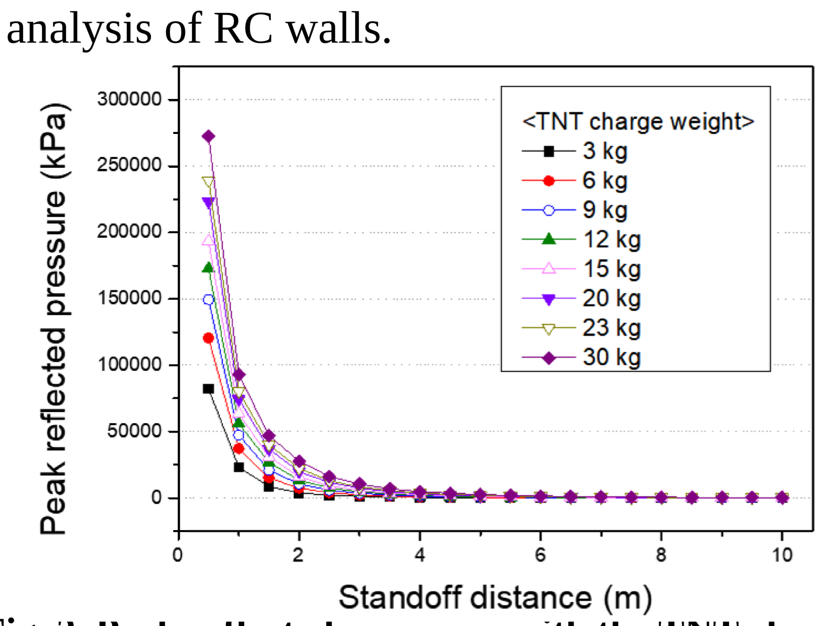

Fig. 2. Peak reflected pressures with the TNT charge weights of 3─30 kg as a function of standoff distance.

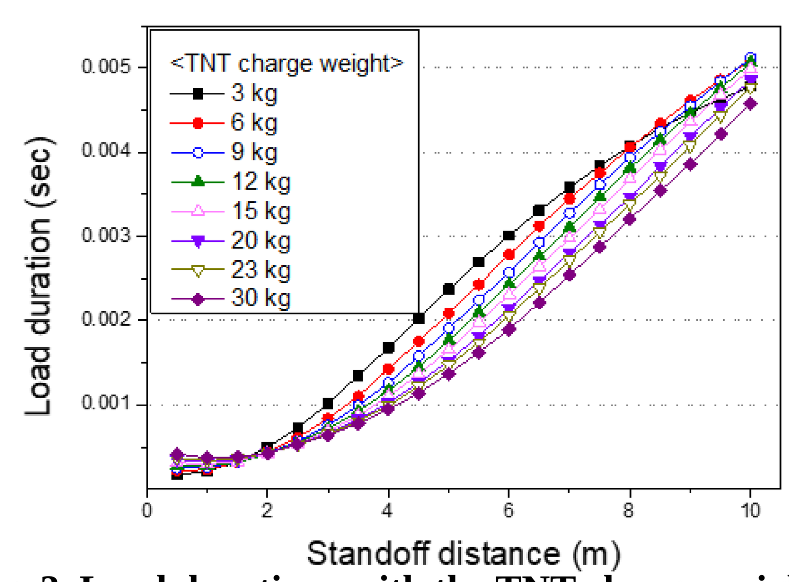

Fig. 3. Load durations with the TNT charge weights of 3─30 kg as a function of standoff distance.

Structural features of reinforced concrete walls

- In the previous study, the dimensions, reinforcement details, and material properties of the RC walls containing radioactive materials in nuclear facilities were examined.
- These data were used to identify the variation in deformation depending on wall thickness, diameter of rebar, and reinforcement ratio.
- As assumed in the previous study, the RC walls were considered to have the same area as the 3×3 m (Length (L)×Height (H)) in the direction of a blast wave, whereas wall thickness (D_t) is varied depending on case.
- As illustrated in Fig. 4, horizontal and vertical rebars were concerned to be symmetrically placed upward and downward. Lacings and stirrups were not considered.
- In this study, as summarized in Table I, the four cases were analyzed, respectively.

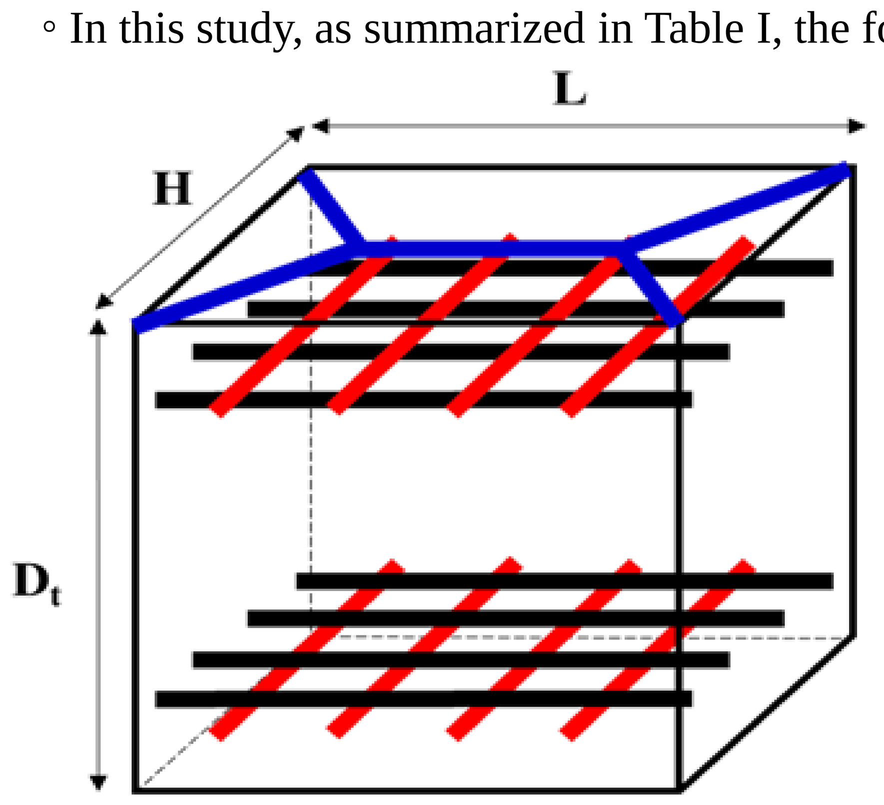

Fig. 4. Schematic drawing of reinforced concrete wall (Black line : horizontal rebar, Red line : vertical rebar, and Blue line : yield line locations).

Table I: The dimensions, reinforcement details, and material properties of reinforced concrete walls examined.

Properties	Unit	Case number 1	2	3	4
Length (L)	m	3	3	3	3
Height (H)	m	3	3	3	3
Wall thickness (D_t)	m	0.3	0.2	0.3	0.3
Cover thickness (D_{cov})	mm	20	20	20	20
Diameter of horizontal reinforcement (D_{hor})	mm	15.9	15.9	19.1	15.9
Diameter of vertical reinforcement (D_{ver})	mm	12.7	12.7	25.4	15.9
Ratio of horizontal reinforcement (p_{hor})	-	0.005	0.008	0.01	0.004
Ratio of vertical reinforcement (p_{ver})	-	0.003	0.005	0.017	0.004
Density of steel (ρ_s)	10^3 kg/m^3	7.854	7.854	7.854	7.855
The modulus of elasticity of reinforcing steel (E_s)	10^{11} Pa	1.999	1.999	1.999	1.999
Yield stress of reinforcing bar (f_y)	10^8 Pa	4	4	4	4.137
Density of concrete (ρ_c)	10^3 kg/m^3	2.403	2.403	2.403	2.403
The modulus of elasticity of concrete (E_c)	10^{10} Pa	2.616	2.616	2.757	2.664
Compressive strength of concrete (f'_c)	10^7 Pa	2.7	2.7	3	2.8

Case #1, #2 : The spacing of horizontal and vertical rebars is identical.

Assumptions for dynamic analysis

- For conservative analysis, the RC walls were concerned as the RC beams because beams are primary support members not to attain large plastic deformations.
- The RC walls were assumed to have the cross-section type I with no crushing or spalling because crushing of the concrete cover over the compression reinforcement is not exhibited in elements with support rotations less than 2 degrees.
- As presented in Fig. 5(a), the pattern of symmetrical yield lines was assumed to be developed on the RC walls through the process of first, second, and final yields because the blast loads were formerly assumed to be delivered uniformly on the RC walls.

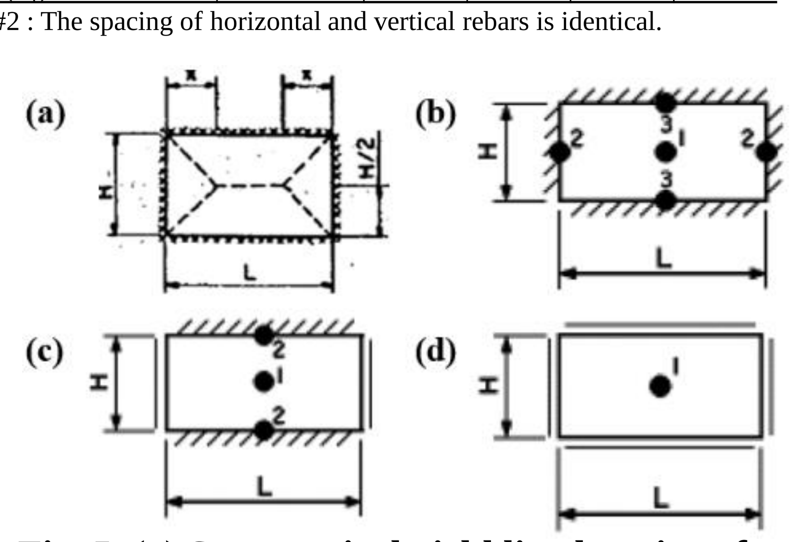

Fig. 5. (a) Symmetrical yield line locations for two-way element with four edges supported; and uniformly-loaded two-way elements with (b) all edges fixed, (c) two opposite edges fixed and two edges simply-supported, and (d) four edges supported.

Input parameters for utilization of UFC 3-340-02

- The values of the dimensions and reinforcement details of the RC walls were converted into the values of input parameters as described in Fig. 6 and Table II.
- Likewise, the values of input parameters were determined from the material properties of the RC walls and the general values provided by UFC 3-340-02, as summarized in Table III.

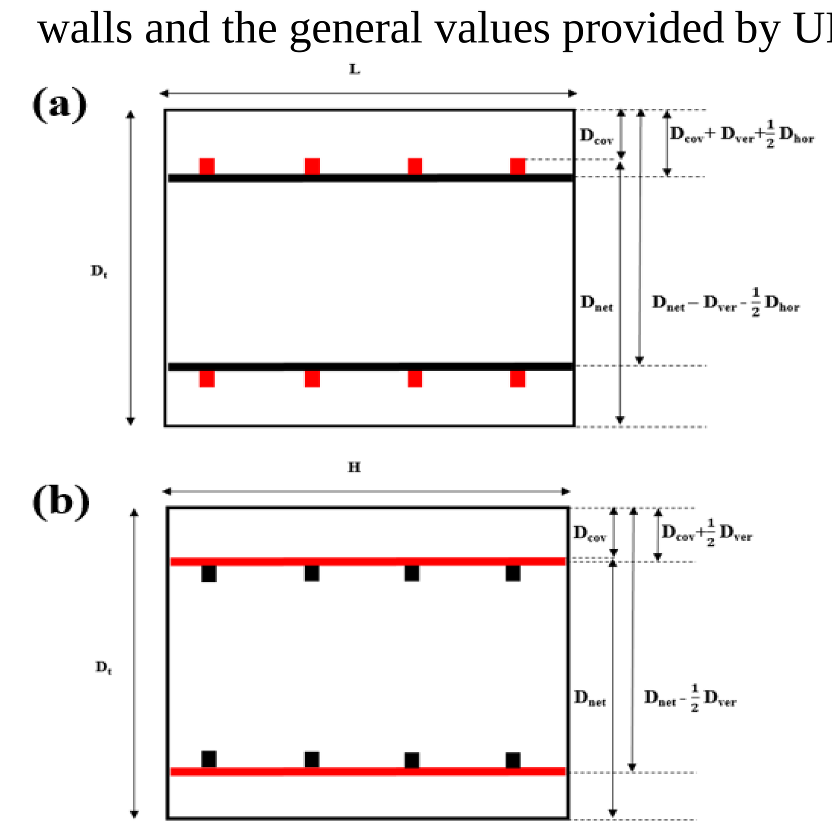

Fig. 6. Reinforced concrete cross-sections: (a) horizontal direction, and (b) vertical direction.

Table II: The input parameters derived from the dimensions and reinforcement details of reinforced concrete walls.

Input parameters	Related equations
Ratio of element length to height (L/H)	L/H = 1
Net section thickness (D_{net})	$D_{net} = D_t – D_{cov}$
Horizontal distance from compression fiber to centroid of compression reinforcement (D'_h)	$D'_h = D_{cov} + D_{ver} + D_{hor}/2$
Vertical distance from compression fiber to centroid of compression reinforcement (D'_v)	$D'_v = D_{cov} + D_{ver}/2$
Horizontal distance from compression fiber to centroid of tension reinforcement (D_h)	$D_h = D_{net} - D_{ver} - D_{hor}/2$
Vertical distance from compression fiber to centroid of tension reinforcement (D_v)	$D_v = D_{net} - D_{ver}/2$

Table III: The input parameters derived from the material properties of reinforced concrete walls and UFC 3-340-02.

Input parameters	Related equations
Dynamic increase factor for rebar (DIF_s)	$DIF_s = 1.17$
Dynamic design stress of rebar (f_{ds})	$f_{ds} = f_y \times DIF_s$
Dynamic increase factor for concrete (DIF_c)	$DIF_c = 1.19$
Dynamic design stress of concrete (f_{dc})	$f_{dc} = f'_c \times DIF_c$
Dynamic increase factor for shear (DIF_{sh})	$DIF_{sh} = 1.1$
Dynamic design stress for shear (f_{dsh})	$f_{sh} = f'_c \times DIF_{sh}$
Poisson's ratio (v)	v = 0.167

Dynamic analysis of reinforced concrete walls

- The properties of first, second, and final yields occurring in the RC walls were calculated by using the experimental data, equations, and calculation procedures given in UFC 3-340-02.
- Dynamic design factors such as ultimate resistance(R_u), equivalent maximum elastic deflection(X_E), equivalent elastic stiffness (K_E), and effective natural period of vibration (T_n) were calculated.
- With the values of dynamic design factors, an acceleration-impulse extrapolation numerical method was used to derive the maximum deflection (X_m) induced by blast loads as presented in Fig. 7
- The deformation criteria of protection category 1($\theta_m \leq 2$), which is the highest level that protects personnel against the uncontrolled release of active radiological materials and equipment from blast pressures, was used for analysis

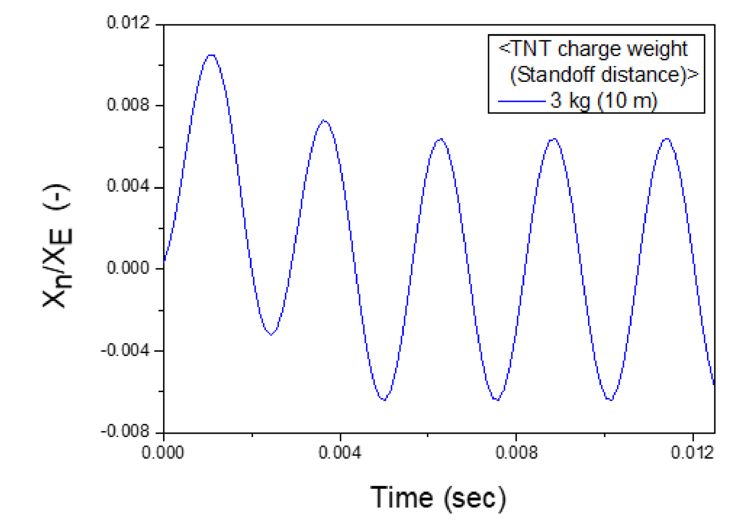

Fig. 7. An example of the deflection prediction in a RC wall using an acceleration-impulse extrapolation numerical method (X_n : deflection depending on time step).

$$\theta_m = \frac{X_m}{X_E} \quad \text{[degrees]}$$

[Maximum support rotation(θ_m)]

Results and discussion

- Fig. 8 shows that support rotation tends to increase as either the standoff distance decreases or the TNT charge weight increases.
- it was confirmed that the support rotations of cases #1─4 decrease to less than 2 degrees when the 30 kg TNT charge is detonated at a distance of more than 3 m.

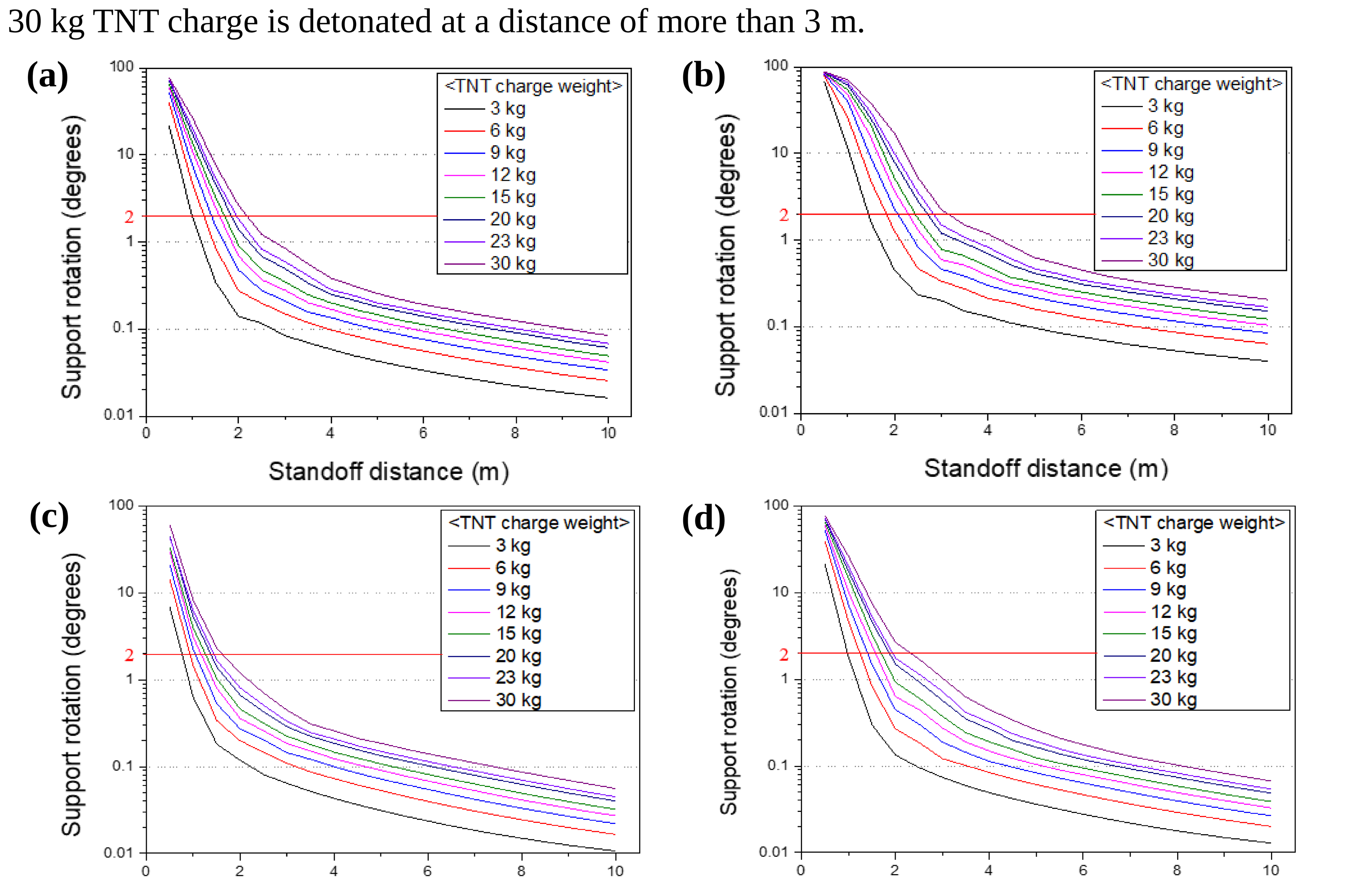

Fig. 8. Support rotations of (a) case #1, (b) case #2, (c) case #3, and (d) case #4 with the TNT charge weights of 3─30 kg as a function of standoff distance.

- As shown in Figs. 8(a) and (b), even though the cases #1 and #2 have the same diameter and spacing of horizontal and vertical rebars, the support rotation of case #1 is smaller than that of case #2.
- Considering that the wall thickness of case #1 (D_t=0.3 m) is thicker than that of case #2 (D_t=0.2 m), the result implies that a thick RC wall has better explosion resistance.
- Figs. 8(c) and (d) present that the support rotation of case #3 is smaller than that of case #4, whereas the cases #3 and #4 have the same wall thickness.
- The diameter of the horizontal and vertical rebars for case #3 (D_{hor}=19.1 mm, D_{ver}=25.4 mm) is larger than that for case #4 (D_{hor}=15.9 mm, D_{ver}=15.9 mm), and the reinforcement ratio for case #3 (p_{hor}=0.01, p_{ver}=0.017) is greater than that for case #4 (p_{hor}=0.004, p_{ver}=0.004).
- It represents that a large-diameter of rebars with a high reinforcement ratio strengthens resistance.