

# INVESTIGATION OF LOCAL BEHAVIOR BY IMPACT OF PROJECTILE FOR REINFORCED CONCRETE PANELS

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## ABSTRACT

Local behavior is generated by the impact of a projectile within a proximal area from the position of the impact, and consists of penetration of the projectile into the structure, perforation of the projectile, scabbing of the structural material, etc. A protective structure like a containment wall of a nuclear power plant should prevent local behavior by the impact of a projectile from causing internal damage to the protective structure, so accurate evaluation of the local behavior is necessary. For evaluation of the local behavior, evaluation of the penetration behavior is a priority because the penetration is primary local behavior affecting the mechanism of perforation, scabbing. In this study, impact tests were performed with reinforced concrete panels and a hard projectile to evaluate the penetration behavior of a concrete structure, test results were discussed, and an empirical formula for prediction of penetration depth was evaluated by using the formula form suggested by Forrestal. The conclusion of this study is that the effect of deflection of RC panels on the penetration depth by the impact of a projectile can be neglected for tested conditions and the evaluated prediction formula of penetration depth generally shows good agreement with the test results.

*Keywords:* impact loading, local behavior, penetration depth, hard projectile, RC panels.

## 1 INTRODUCTION

Impact load due to impact of projectile makes structure deformed very fast. Then, local behavior occurred within proximal area of the impact is generated by fast deformation and failure of the structure. This local behavior generated by the impact consists of penetration, spalling, scabbing, perforation, etc as demonstrated in Fig. 1. Penetration is tunnelling into structure by the projectile, spalling is ejection of fragments of structural material from proximal face of the structure, and the spalling is generally accompanied with the penetration. Scabbing is ejection of fragments of structural material from distal face of the structure, perforation is complete passage of the projectile through thickness of the structure, and the perforation is generally accompanied with the scabbing in case of brittle structural material.

This local behavior generally does not lead to overall collapse of the structure, however fragments of structural material by scabbing and projectile by perforation can damage inside of structure. Therefore, protective structure such as containment wall of nuclear power plant should be designed to prevent the local behavior from damaging inside of the protective structure, and ASME BPVC [1] and ACI 349-13 [2] have suggested design of wall thickness of concrete structure to prevent the local behavior. ASME BPVC [1] suggests that concrete wall thickness shall be designed for penetration to be limited to 75% of total concrete wall thickness, and ACI 349-13 [2] suggests that concrete wall thickness shall be designed to be at least 20% greater than that required to prevent scabbing and perforation.

Therefore, accurate evaluation of local behavior is needed to design protective structure safely and economically for local behavior. Especially, accurate evaluation for penetration behavior is very important of all local behavior because penetration depth of projectile is directly used to design wall thickness of structure for ASME BPVC [1] and penetration behavior affects mechanism of scabbing and perforation.

In this study, impact tests with reinforced concrete panels and hard projectile and evaluation of impact test results were performed to evaluate penetration behavior of concrete



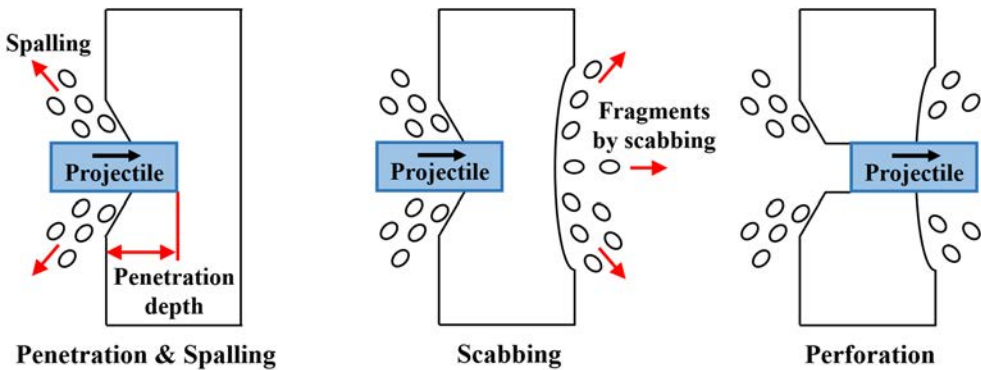


Figure 1: Local behavior by impact of projectile.

structure, and evaluation of the penetration behavior was performed by using form of prediction formula for penetration depth suggested by Forrestal et al. [3].

2 PENETRATION BEHAVIOR BY IMPACT

2.1 Penetration resistance force

When impact of projectile occurs against target, the projectile penetrates into the target while destroying material of the target around proximal part of impact if projectile is more rigid than stiffness of target. This rigid projectile which deformation of the projectile doesn't occur during penetration is called as hard projectile. During penetration of the hard projectile, force to resist penetration is acted on contact surface between the projectile and the target by the law of action and reaction. Then, the force acting on target generates structural behavior of the target including local behavior, and simultaneously the force acted on projectile decelerates velocity of the projectile as demonstrated in Fig. 2.

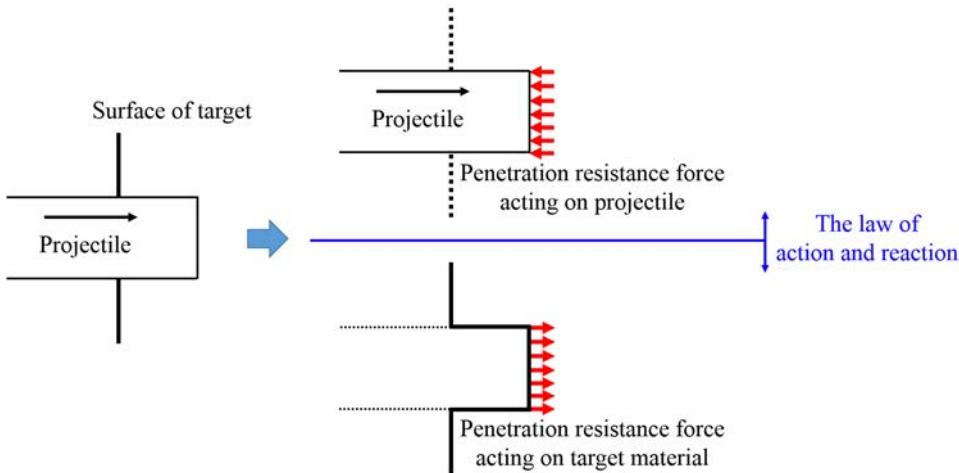


Figure 2: Penetration resistance force.

Penetration resistance force acting on rigid projectile during penetration for concrete target was suggested by Forrestal et al. [3] based on cavity expansion theory in eqns (1), (2). In eqn (1),  $z$  is current penetration depth of projectile,  $d$  is diameter of projectile,  $k$  is ratio of  $d$  to depth of crater region equal to region of a rise of penetration resistance force during initial time of impact,  $F$  is penetration resistance force, and  $c$  is rate of  $F$  for time during the crater region. In eqn (2),  $P$  is final penetration depth of projectile,  $f_c$  is unconfined compressive strength of concrete diameter of projectile,  $S$  is dimensionless coefficient related to material strength,  $N$  is coefficient for nose shape of projectile defined in eqn (3),  $\rho$  is density of concrete, and  $V$  is current velocity of projectile. In eqns (3) and (4),  $\Psi$  is caliber-radius-head of projectile

$$F = cz \text{ for } 0 < z < kd, \quad (1)$$

$$F = \frac{\pi d^2}{4} (Sf_c + N\rho V^2) \text{ for } kd < z < P, \quad (2)$$

$$N = \frac{8\Psi-1}{24\Psi^2} \text{ for ogive nose}, \quad (3)$$

$$N = 1 - \frac{1}{8\Psi^2} \text{ for blunt nose}. \quad (4)$$

For term  $k$ , Li and Chen [4] suggested  $k$  as form of eqn (5).  $\alpha$  is ratio of  $d$  to crater depth for flat nose projectile, and  $H$  is nose length of projectile

$$k = \alpha + H/d. \quad (5)$$

## 2.2 Evaluation of penetration depth

The penetration resistance force decelerates velocity of projectile, and is acting on projectile until velocity of projectile becomes zero. Then, final penetration depth of projectile can be calculated by process in eqns (6)–(9) from the Newton's 2nd law. In eqns (6)–(9),  $V_s$  is impact velocity of projectile,  $V_1$  is velocity of projectile at  $z = kd$ , and  $m$  is mass of projectile. The penetration resistance force of eqns (6)–(9) and the final penetration depth of eqns (6)–(9) are derived under assumption that target has infinite thickness, which means there is no effect of global behavior of the target such as internal strain energy by deflection of the target

$$m \frac{d^2 z}{dt^2} + F = 0 \rightarrow m \frac{d^2 z}{dt^2} = m \frac{dV}{dt} = m \frac{dV}{dz} \cdot \frac{dz}{dt} = m \frac{dV}{dz} V = -F, \quad (6)$$

$$\int_0^P dx = \int_{V_s}^0 \left( -\frac{mV}{F} \right) dV = \int_{V_s}^{V_1} \left( -\frac{mV}{F} \right) dV + \int_{V_1}^0 \left( -\frac{mV}{F} \right) dV, \quad (7)$$

$$\int_0^P dx = kd + \int_{V_1}^0 \left( -\frac{4m}{\pi d^2} \cdot \frac{V}{Sf_c + N\rho V^2} \right) dV, \quad (8)$$

$$P = kd + \frac{2m}{\pi d^2 \rho N} \ln \left( 1 + \frac{N\rho V_1^2}{Sf_c} \right). \quad (9)$$

In order to evaluate penetration depth by using prediction formula for penetration depth derived by eqns (1)–(9), Frew et al. [5] and Forrestal et al. [6] performed penetration test with ogive-nose projectile and concrete cylinder target having large thickness which can neglect global behavior of the target, and assumed value of  $k$  to be 2 by measuring crater depth of the cylinder target. Test results of [5] and [6] are summarized in Table 1, and show that the smaller diameter of the projectile is, the larger value of  $S$  is. Forrestal et al. [6] discussed that this result is because of scale effect by diameter of projectile.  $G_{\max}$  in Table 1 is maximum diameter of aggregate.



Table 1: Test results of [5] and [6].

Test	$G_{\max}$ , mm	Impact velocity, m/s	Projectile diameter, m/s	$S$	
				$f_c = 23 \text{ MPa}$	$f_c = 39 \text{ MPa}$
4	9.5	442–1225	20.3 and 30.5	15.6	11.8
5		140–456	76.2	7.17	9.2

2.3 Effect of global behavior of structure on penetration depth

When impact of projectile occurs against the target considered as structure, penetration resistance force due to the impact can generates not only local effects but also global behavior of the structure target. This global behavior by deflection of structure affects velocity term of eqn (2) because contact surface which the penetration resistance force acts between projectile and material of the structure moves relative to projectile by deflection rate of structure as demonstrated in Fig. 3. Also, deflection of proximal area of the structure should be subtracted from the penetration depth calculated by eqn (9) to calculate real penetration depth because displacement of projectile is not equal to penetration depth but equal to sum of real penetration depth of projectile and deflection of the structure as demonstrated in Fig. 4.

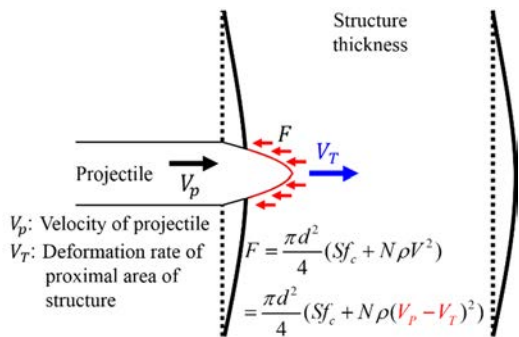


Figure 3: Effects of deflection rate of structure on penetration resistance force.

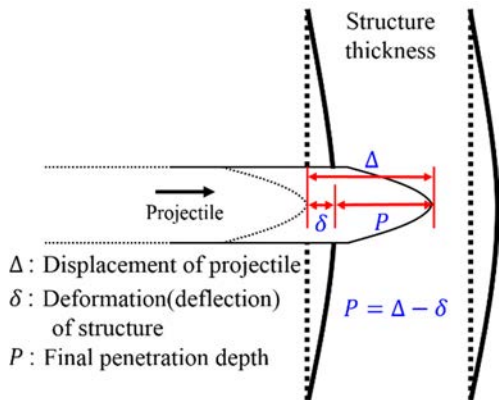


Figure 4: Effects of deflection of structure on penetration depth.

Therefore, prediction formula for penetration depth of eqn (9) can't be directly applied for concrete structure if effect of the global behavior is large, so evaluation of global effect is necessary to evaluate penetration behavior for the target of structure level.

### 3 IMPACT TEST AND TEST RESULTS

In order to evaluate penetration behavior of concrete structure, four impact test simulating impact situation of hard projectile against containment wall of nuclear power plant were performed with reinforced concrete panels and projectiles of steel material.

#### 3.1 Reinforced concrete panel

Reinforced concrete (RC) panel was designed by scaling containment wall of APR 1400 nuclear power plant as demonstrated in Fig. 5. APR 1400 is current nuclear power plant model of Shin-Kori 3 units constructed in Republic of Korea. Containment wall of APR 1400 nuclear power plant has wall thickness of 1.2 m, rebar spacing of 305 mm, and uses rebar of 57 mm diameter. Thickness of RC panels to test was designed to have 500 mm which is 1:2.4 ratio for the wall thickness of APR 1400 nuclear power plant. The ratio of 1:2.4 was applied to diameter of rebar and rebar spacing of the RC panels, then the RC panels was designed to have rebar of 25 mm diameter and rebar spacing of 130 mm. However, only rebar spacing of center of the RC panels was designed to have 150 mm in order to prevent projectile from colliding with rebar of the RC panels for evaluation of critical impact situation. Unconfined compressive strength of concrete for four RC panels tested was that one of the four RC panels was 35.8 MPa and the other three panels were 40.5 MPa. Density of concrete was 2,379 kg/m<sup>3</sup>. Rebar of 400 MPa yield strength was used, and cover thickness of the RC panels was 40 mm.

#### 3.2 Projectile

ACI 349-13 and ASME 2010 BPVC consider pipes as impact object for the containment wall by tornado or explosion, and the US Nuclear Regulatory Commission considers schedule 40 pipe as tornado-generated missile for nuclear power plant. Therefore, projectiles were designed to have 100 mm diameter by scaling 219 diameter schedule 40 pipe at the ratio of

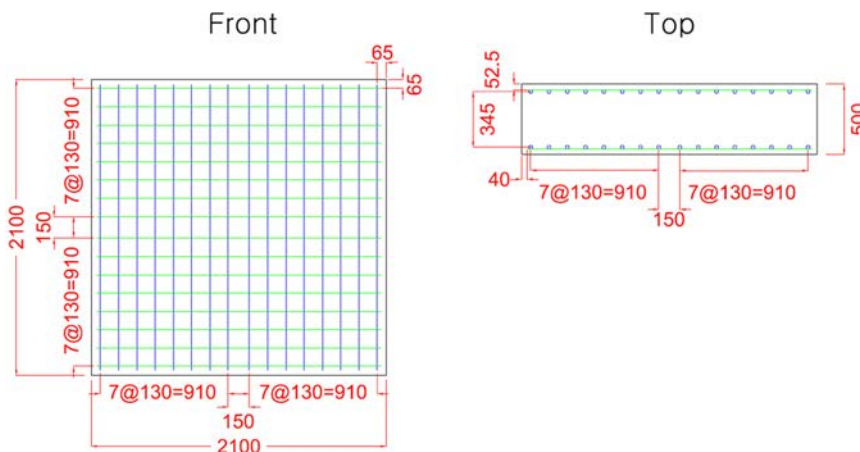


Figure 5: Reinforced panel used to impact test.

1:2.4 referring to these guidelines. Mass of projectiles is 35.5 kg, and material of the projectiles is steel. Nose shapes of the projectiles were designed in two type of flat shape and blunt shape which has radius of curvature of nose equal to diameter of the designed projectile as demonstrated in Fig. 6. Nose length of blunt projectile is 13.4 mm. Blunt nose shape of projectile is referring to previous impact test program performed by Technical Research Centre of Finland, VTT [7].

3.3 Impact test program

Impact tests were performed by apparatus of 250 mm Single Stage Gas Gun in Seoul National University shown in Fig. 7. The 250 mm Single Stage Gas Gun launches projectile by air pressure, and can test for diameter of projectile up to 250 mm, mass of projectile up to 100 kg, and impact velocity of projectile up to 470 m/s. High speed cameras were used to observe behaviour of projectile during penetration. Also, linear variable potentiometer was used to measure deflection of RC panel for evaluation of effect of global behaviour, so it was installed at center of distal face from impact.

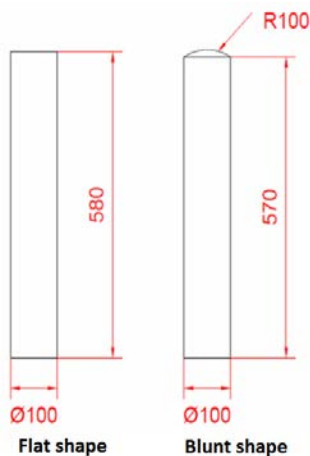


Figure 6: Projectiles used to impact test.



Figure 7: 250 mm Single Stage Gas Gun in Seoul National University.

As presented in Table 2, four impact test were performed with nose shape and impact velocity of projectile as variables to evaluate penetration behaviour of RC panels. Tests 1 and 3 didn't measure the deflection of RC panel because failure of linear variable potentiometer could occur by impact of concrete fragments from scabbing.

### 3.4 Impact test results

Impact test results are summarized in Table 3. Impact duration in Table 3 is the time from the impact moment of projectile to the moment which the projectile stops which means time during penetration behavior. Then, the test results showed final penetration depth increases with increasing impact velocity for each nose shape of projectile and the final penetration depth for blunt nose shape is larger than that of flat nose shape. Failure mode of RC panels after impact of projectile showed cavity by penetration of projectile accompanied with spalling at impact face of RC panels, and hair cracks at distal face of the impact as shown in Fig. 8.

Table 2: Variables of impact test.

Test	$f_c$ , MPa	Nose shape	Impact velocity, m/s
1	35.8	Flat	123
2	40.5		103
3		Blunt	124
4			113

Table 3: Results of impact test.

Test	$f_c$ , MPa	Nose shape	Impact velocity, m/s	Final penetration depth, mm	Maximum deflection, mm	Impact duration, m sec
1	35.8	Flat	123	127	-	2.20
2	40.5		103	94	3.33	1.95
3		Blunt	124	117	-	2.10
4			113	103	5.21	1.88



Figure 8: Failure mode of RC panel by impact (Test 2).

## 4 EVALUATION OF PENETRATION BEHAVIOR

### 4.1 Evaluation for effect of global behavior

Deflection and deflection rate measured during the impact duration are presented in Fig. 9. As shown in Fig. 9, Deflection and deflection rate during impact duration were 0.48 mm and 0.23 m/s for Test 2 and 1.50 mm and 0.75 m/s for Test 4, respectively. The deflection and the deflection rate for Test 2 are only 0.48% of the final penetration depth and 0.22% of the impact velocity, respectively. For Test 4, the deflection and the deflection rate are only 1.46% of the final penetration depth and 0.71% of the impact velocity, respectively. Therefore, effect of the global behaviour can be neglected for tested condition because small value of the deflection and the deflection rate have very little effect on penetration resistance force and penetration depth as demonstrated in Figs 3 and 4. From this result, it was verified that penetration depth of RC panels can be evaluated by using the prediction formula of eqns (1)–(9).

### 4.2 Evaluation for penetration depth

Evaluation for penetration depth was performed by using the prediction formula of penetration depth derived by eqns (1)–(9). For flat nose projectile, nose shape factor  $N$  is 1 because  $\Psi$  is infinite for flat shape. Then, nose shape factor  $N$  for blunt nose projectile is 0.875 because  $\Psi$  is 1.  $S$  and  $\alpha$  are unknown term for eqns (1)–(9), so that were empirically determined to show good agreement of penetration depth with test results of penetration depth over time measured by high speed camera. Determined values of  $S$  and  $\alpha$  for each test results are presented in Table 4 and Fig. 10 shows the graphs comparing the test results of penetration depth with evaluated penetration depth by using the mean value of  $S$  and  $\alpha$ . Error in Table 4 is difference between test result and predicted final penetration depth. The mean value of  $S$  determined from test results is very similar with the value of 7.17 for  $f_c = 23$  MPa of [5] in Table 1, and evaluated penetration depth generally showed good agreement with test result.

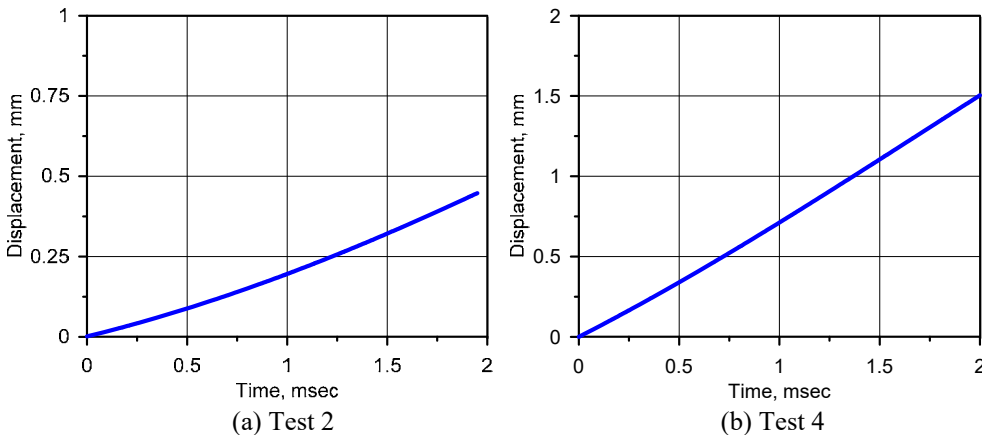


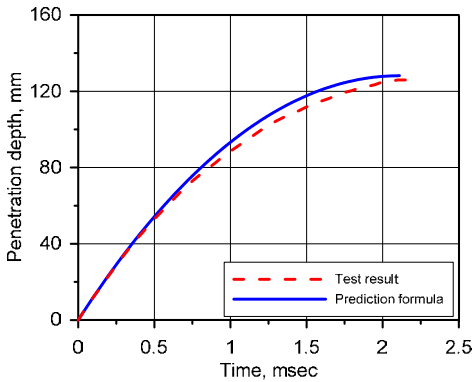
Figure 9: Deflection over time during impact duration.



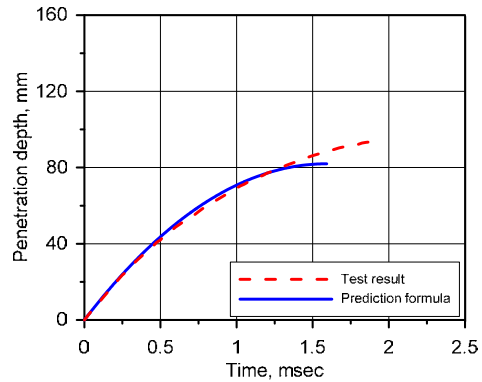


Table 4: Evaluation results of term  $S$  and  $\alpha$ .

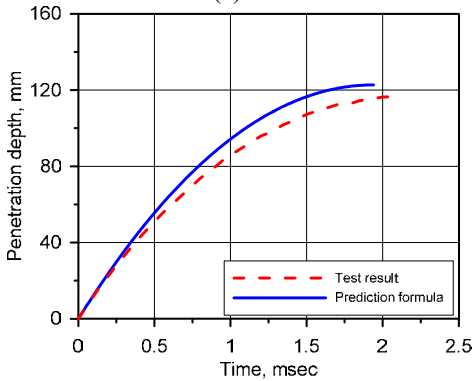
Test	$f_c$ , MPa	Determined term			Final penetration depth prediction, mm	Error, %
		$S$	Mean $S$	$\alpha$		
1	35.8	7.40	7.14	0.05	128	0.78
2	40.5	6.17			82	12.77
3		7.55			123	5.13
4		7.45			105	1.94



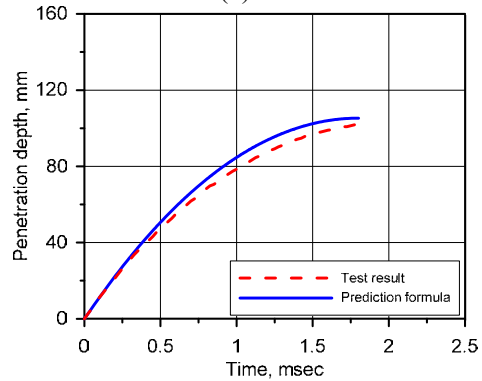
(a) Test 1



(b) Test 2



(c) Test 3



(d) Test 4

Figure 10: Comparison of penetration depth for test result and prediction formula.

## 5 CONCLUSION

In this study, the penetration behavior of RC panels scaling containment wall of nuclear power plant was evaluated and following conclusions were derived.

- For tested condition, global behavior by deflection of RC panels has little effect on local behavior for penetration depth.
- Penetration depth of RC panels can be predicted by using prediction formula form suggested by Forrestal et al. [3].
- Evaluated prediction formula of penetration depth generally shows good agreement with test result.



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