Scaling Effect in Kinetic Energy Projectile Penetration of Concrete

Wei Chen[1], Rong Chen[2], Jianzhou Li[3], Xiaojun Li[4], Yuxin Sun[1*], Shengyao Zhu[1]

[1]National Key Laboratory of Transient Physics, Nanjing University of Science and Technology, Nanjing, Jiangsu 210094, China
[2]China Academy of Launch Vehicle Technology, Beijing 100076, China
[3]North Huaan Industry Group Co. Ltd, Qiqihar, Heilongjiang 161046, China
[4]Institute of Defense Engineering, AMS, PLA, Beijing 100850, China

*Corresponding author's e-mail: yxsun01@163.com

Abstract. This paper investigates the intrinsic mechanisms of the scaling effect in concrete penetration, validated by a high-velocity experiment. We identify fixed-size coarse aggregates as the fundamental cause for the breakdown of geometric similarity, which leads to this effect. A 2D mesoscopic finite element model, explicitly describing random aggregates, was developed to study this phenomenon. Numerical simulations successfully reproduced the key observation: dimensionless penetration depth increases with projectile scale. Furthermore, the study reveals that aggregate particle size is a more significant influencing factor than its strength.

Keywords: Penetration depth; Scaling effect; Concrete mesoscopic model

1 Introduction

In protective engineering, scaled-model experiments are widely used to study projectile penetration in concrete due to the cost of full-scale tests. However, direct extrapolation of these results using traditional similarity laws often leads to significant deviations. This phenomenon, known as the penetration scaling effect, severely challenges predictive accuracy.

The mechanism of the scaling effect in projectile penetration is complex and involves the coupling of multiple factors. Research indicates that the scaling effect arises when target constituents do not strictly adhere to similarity laws [1,2]. Other factors such as fracture development, heat conduction, projectile rotation, and boundary effects also contribute to the phenomenon [3,4]. Furthermore, dimensional analysis shows that the strain rate effect of the target material is a fundamental cause. A scaling effect will persist even if the projectile and target materials are perfectly scaled, because the strain rate depends not only on the penetration velocity but also on the absolute size of the projectile itself [4,5].

This study investigates the scaling effect in projectile penetration of concrete using both high-velocity experiments and numerical simulations. A 2D mesoscopic model

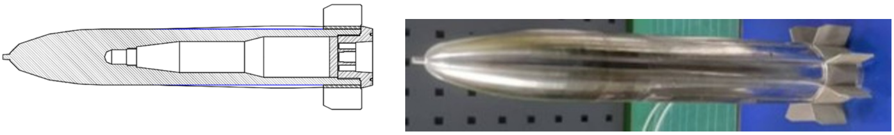
Y. Liu et al. (eds.), *Proceedings of the 2025 2nd International Conference on Civil Engineering Structures and Concrete Materials (CESCM 2025)*, Advances in Engineering Research 288,
https://doi.org/10.2991/978-94-6463-932-2_30

with random aggregates was developed to simulate penetration across various scales and velocities, allowing for an analysis of the penetration scaling law's applicability and its influencing factors.

2 Numerical Model Validation

2.1 High-Velocity Penetration Experiment of a 3kg-Class Kinetic Energy Projectile

This study utilized a 125mm caliber cannon to conduct an experimental investigation on the penetration of a reinforced concrete target by a 3kg-class projectile at a velocity of 1200 m/s. The test projectile was made of high-strength, high-toughness 35CrMnSi steel, and the target was reinforced concrete with a compressive strength of 39.2 MPa. The projectile used was a kinetic energy penetrator with an ogive nose, consisting of a 35CrMnSi steel casing and an internal inert filler. The 35CrMnSi steel was heat-treated (quenched and tempered), achieving a yield strength of approximately 1000 MPa. The specific geometric parameters of the projectile are: length 310.9 mm, diameter 47 mm, and total mass 2.96 kg. Figure 1 shows the cross-sectional view and a photograph of the projectile.



(a) (b)

Fig. 1. Test kinetic energy projectile

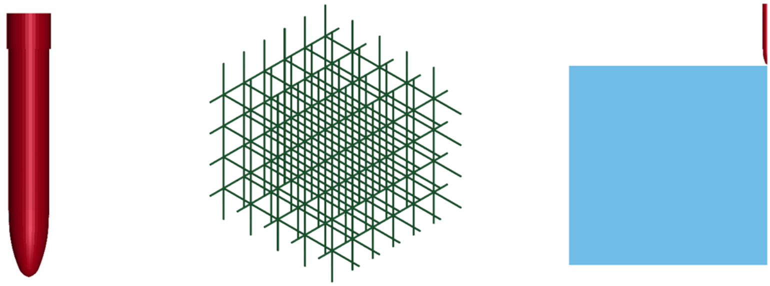
The experiment used a reinforced concrete target with dimensions of 2000 mm × 2000 mm × 1000 mm. The reinforcement within the target consisted of 10 mm diameter steel bars arranged in a bidirectional grid with a spacing of 200mm × 200mm. The distance between each layer of the reinforcement mesh was 150mm. Figure 2 shows the experimental layout. The experiment measured the impact velocity of one 35CrMnSi projectile penetrating the reinforced concrete target to be 1217.39 m/s.

(a) (b)

Fig. 2. Experimental layout

2.2 Finite Element Model

To simulate the penetration experiment, a three-dimensional finite element model comprising the projectile, reinforcement, and concrete was developed in LS-DYNA, as shown in Figure 3. A 1/4 symmetry model was employed, containing approximately 1.3 million Lagrangian elements. Following Mi Zhenguo et al. [6], the reinforcement was treated with shared nodes with the concrete. Contact between the projectile and target was defined using the eroding algorithm *CONTACT_ERODING_SURFACE_TO_SURFACE. Concrete failure was simulated based on a maximum principal strain criterion, implemented via the *MAT_ADD_EROSION keyword. The simulation used a cm-g-μs-K unit system, with the initial projectile velocity set to the experimental value of 1217.391 m/s.



(a) (b) (c)

Fig. 3. Finite element model

The mechanical behavior of the 35CrMnSi steel projectile was simulated using the Johnson-Cook(JC) material model. In conjunction with the literature from Mi Zhenguo et al. [6], the widely used HJC model, *MAT_JOHNSON_HOLMQUIST_CONCRETE, was selected for the concrete material. The rebar and inert filler were modeled using a kinematic hardening model, *MAT_PLASTIC_KINEMATIC. The specific parameter data for all the aforementioned materials were sourced from the relevant literature [7-8].

2.3 Model Validation

Table 1 presents a comparison between the experimental data and the numerical simulation results. Body erosion is only 0.6% and the error in residual velocity is 3.82%, indicating that the experimental data and simulation results are in good agreement, which validates the accuracy of the material parameters used.

Table 1. Comparison of experimental results with numerical simulation results

Result	Length of projectile	Residual velocity
Experiment	301.4mm	631.944m/s
Numerical simulation	299.6mm	607.791m/s
error	0.6%	3.82%

3 Scaling Effect Analysis of Geometrically Similar Kinetic Energy Projectiles Penetrating Inhomogeneous Concrete

To deeply investigate the penetration scaling effect dominated by the inhomogeneity of concrete from a mechanistic level, this chapter will employ mesoscopic numerical simulation methods. A mesoscopic finite element model of concrete refers to a model where material components, including mortar and aggregates, are modeled separately. To improve efficiency, the discussion in this section will be based on a 2D finite element model.

3.1 Establishment of a 2D Mesoscopic Finite Element Model for Concrete

The 2D mesoscopic model in this section is established using an efficient background grid method. The core idea is to "project" a pre-generated geometric model of coarse aggregates onto a regular finite element grid and then construct a two-phase medium by assigning different material properties to the elements. The finally generated finite element model is shown in Figure 4. This model successfully reproduces the core mesoscopic features of concrete materials, including the random distribution, irregular shapes, and high volume fraction of aggregates.

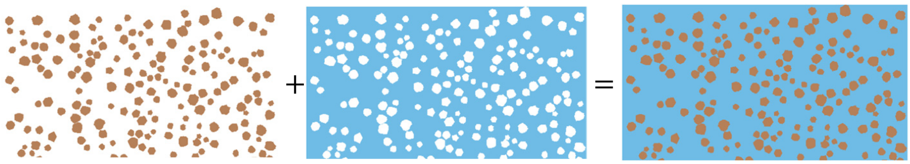


Fig. 4. 2D mesoscopic finite element model for concrete specimen

Based on the validated material parameters, a systematic 2D numerical simulation study was conducted. Using the 3kg projectile as a baseline, five geometrically similar projectiles were designed according to the principle of geometric similarity, with masses ranging from 3 kg to 375 kg and diameters from 4.70 to 23.5 cm. Their penetration processes were simulated at four velocities—500, 750, 1000, and 1250 m/s—for a total of 20 scenarios. The target model explicitly represents mortar and coarse aggregates, both using the HJC model, with the parameter selection method detailed in reference[9]. To accurately reveal the effect of inhomogeneity, all targets utilized an identical mesostructure: a 20% aggregate volume fraction, a 10–20 mm particle size range, and a 2 mm mesh size, with only the macroscopic dimensions scaled proportionally with the projectile. Material failure was controlled by the MAT_ADD_EROSION criterion to prevent excessive element distortion.

Figure 5(a) shows the von Mises stress distribution for the 3 kg projectile at a velocity of 1250 m/s. Due to the random distribution of aggregates, the stress field within the target exhibits a highly inhomogeneous characteristic. Stress waves reflect and superpose on the hard aggregate particles, leading to pronounced stress concentrations on the aggregates near the projectile nose, while the stress level in adjacent mortar regions remains relatively low.

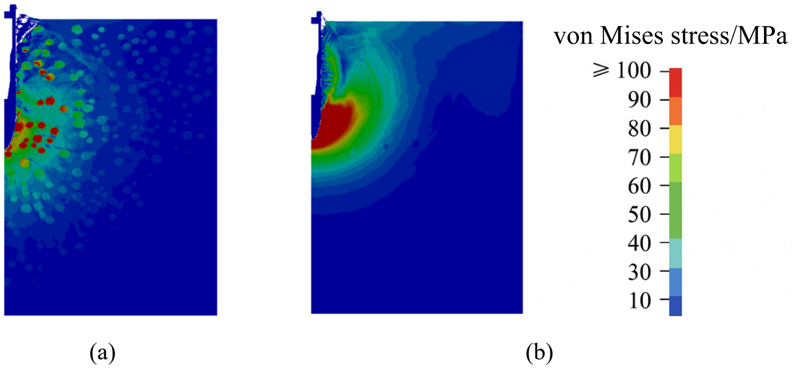


Fig. 5. Von Mises stress distributions in the inhomogeneous and homogeneous regarded concrete target under projectile penetrations

For comparison, Figure 5(b) shows the von Mises stress distribution for the same projectile penetrating a homogeneous concrete target, where the macroscopic strength of the homogeneous concrete was set to 40 MPa. Compared to the results from the inhomogeneous model in Figure 5(a), the stress field distribution in the homogeneous target is very regular and smooth, with stress contours propagating outwards in stable, near-semicircular or arc shapes.

The contrast in these two stress responses intuitively explains why the mesoscopic model can reproduce the scaling effect, whereas the homogeneous model cannot. The homogeneous model, due to its uniform resistance, inherently satisfies the scaling law. However, in the more physically realistic mesoscopic model, penetration resistance arises from the complex interaction between the projectile and discrete, fixed-size aggregates. The root of the macroscopic scaling effect lies in the scale-dependent nature of this interaction, meaning that when projectiles of different scales interact with aggregates of the same size, they produce different stress perturbations and energy dissipation modes.

3.2 Simulation Results and Analysis of Penetration Depth

The calculation results for all scenarios are summarized in Figure 6.

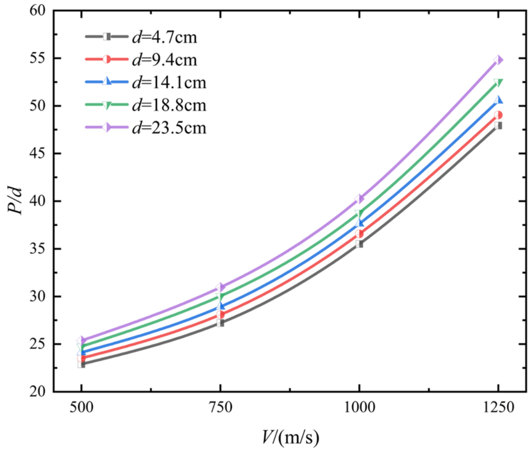


Fig. 6. The calculation results for projectiles of different scales penetrating concrete

As can be seen from the data in the figure, the dimensionless penetration depth P/d at the same velocity is not a constant. Instead, it increases with the scale of the projectile, and this scaling effect is less evident for smaller projectiles but becomes pronounced for larger ones. Taking the impact velocity of 1250 m/s as an example, when the projectile mass increases from 3kg to 375kg (a 5-fold increase in diameter), the dimensionless penetration depth P/d increases from 47.94 to 55.13， a relative increase of 15%.This phenomenon is the scaling effect in the projectile penetration process, indicating that the classic geometric scaling law is not applicable here. Furthermore, scaling effect is exacerbated by higher impact velocities.

3.3 Analysis of the Influencen of Aggregate Strength on Penetration Depth

To investigate the effect of coarse aggregate strength on the impact resistance of concrete, this section conducted numerical simulations of a 3kg projectile (d=4.7cm) at 1250 m/s penetrating a 2D mesoscopic concrete target containing coarse aggregates of different strengths. Except for the aggregate strength, which was set to 120 MPa, 150 MPa, and 180 MPa respectively, all other simulation parameters, such as mortar properties and aggregate volume fraction, were kept constant. The numerical simulation results are shown in Table 2. The data show that as the compressive strength of the aggregate increases, the penetration depth shows a slight increase. When the aggregate strength is increased from 120 MPa to 180 MPa, the dimensionless penetration depth increases from 47.94 to 48.69, an increase of only 1.5%. It can be found that for the conditions studied in this section, the effect of aggregate strength on penetration depth is not significant. In these scenarios, the macroscopic failure mode of the target, rather than the crushing strength of the aggregates themselves, plays a dominant role in determining the final penetration result. Furthermore, experiments by Frew et al.[10] also found that concrete targets made with aggregates of different hardness (limestone and quartzite) showed very little difference in their anti-penetration performance.

Table 2. The calculation results of penetration depth for different aggregate strengths

Aggregate strengths (MPa)	Dimensionless Penetration Depth(P/d)
120	47.94
150	48.38
180	48.69

3.4 Analysis of the Influence of Coarse Aggregate Size

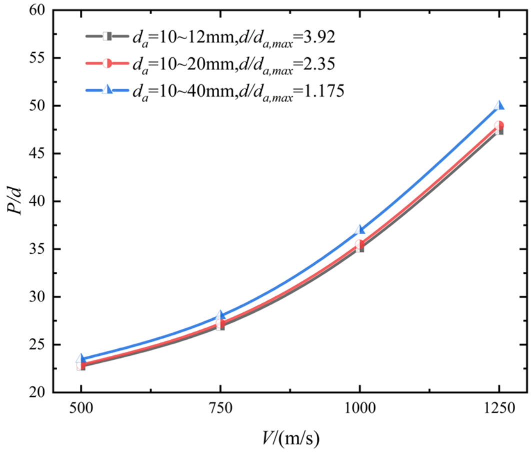


Fig. 7. The calculation results of penetration depth for different coarse aggregate Sizes

To address the influence of coarse aggregate size on the impact resistance of concrete, this section conducted numerical simulations for a 3kg projectile (d=4.7cm) penetrating 2D mesoscopic concrete targets containing coarse aggregates of different size ranges(d_a=10~12mm,10~20mm,10~40mm). Apart from the different coarse aggregate sizes, other simulation parameters such as mortar properties and aggregate volume fraction were kept constant. The relationship between dimensionless penetration depth and velocity for different coarse aggregate sizes is shown in Figure 7. From the graph, it can be seen that within the studied velocity range, the penetration result is closely related to the projectile-to-aggregate size ratio($d/d_{a,max}$). When the maximum aggregate size increases from 12mm to 40mm, the dimensionless penetration depth increases from 47.41 to 49.95, an increase of 5.4%. It can be found that for all cases where $d/d_{a,max} \geq 1.175$, the concrete containing larger aggregates has a relatively lower (macroscopic) compressive strength[11], and consequently, the penetration depth is deeper. In other words, under these conditions, the (macroscopic) compressive strength of the concrete, rather than the aggregate size itself, plays a more dominant role in enhancing the target's impact resistance. Therefore, when designing protective structures against such threats, if conditions permit, using larger-sized aggregates to produce concrete might, counter-intuitively, reduce its penetration resistance.

4 Conclusion

This study investigated the physical mechanisms and influencing factors of the scaling effect in concrete penetration. The main conclusions are:

(1) The fundamental cause of the scaling effect is the breakdown of geometric similarity due to fixed-size aggregates. Our mesoscopic model, based on this mechanism, successfully reproduced this phenomenon, showing that dimensionless penetration depth increases with projectile scale, an effect exacerbated by higher impact velocities.

(2) Aggregate strength has a limited effect on anti-penetration performance. In contrast, aggregate size is a more significant factor. Counter-intuitively, under certain conditions, using larger aggregates can weaken the structure's overall protective capability by altering its macroscopic mechanical properties.

References

1. Cheng Yuehua, Jiang Pengfei, Wu Hao, et al. (2022) On penetration depth of typical earth-penetrating projectiles into concrete targets considering the scaling effect. Explosion and Shock Waves, 42(6): 85-99.
2. Peng Yong, Lu Fangyun, Fang Qin, et al. (2019) Analyses of the size effect for projectile penetrations into concrete targets. Explosion and Shock Waves, 39(11): 58-68.
3. Jiang Dong, Huang Ruiyuan, Yu Daojian, et al. (2017) Similarity laws and scaling of penetration tests. Mechanics in Engineering, 39(6): 561-565.
4. Jiang Dong, Shi Wenqing, Huang Ruiyuan, et al. (2021) Scale effects and similarity laws on high/hypervelocity impact penetration. Scientia Sinica (Physica, Mechanica & Astronomica), 51(10): 106-113.
5. Wu Biao, Ren Huiqi, Chen Li, et al. (2020) Experimental study and theoretical analysis of size effect on projectile penetrating concrete. Protective Engineering, 42(2): 1-10.
6. Mi Zhenguo, Shi Yunbo, Zhang Jie, et al. (2021) Research on HJC constitutive model of concrete target for penetration effect. China Measurement & Test, 47(7): 31-35.
7. Xin C, Xue Z, Tu J et al. (2020) Handbook of Common Material Parameters for Finite Element Analysis. China Machine Press, Beijing.
8. Shi Y (2020) Numerical simulation study on the anti-penetration mechanical properties of reinforced concrete target slabs. Ph.D. Dissertation, Northeastern University, Shenyang.
9. Peng Y, Wu H, Fang Q and Gong Z M (2018) Geometrical scaling effect for penetration depth of hard projectiles into concrete targets. Int. J. Impact Eng., 120: 46–59.
10. Frew D J, Hanchak S J, Green M L, et al. (1998) Penetration of Concrete Targets with Ogive-Nose Steel Rods. Int. J. Impact Eng., 21(6): 489-497.
11. Zhang W H, Zhang Y S (2015) Research on the static and dynamic compressive properties of high performance cementitious composite (HPCC) containing coarse aggregate. Arch. Civ. Mech. Eng., 15(3): 711–720.