Testing Technique for Penetration Depth of Projectile into Steel Reinforced Concrete

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Abstract. This paper explores two typical testing techniques, the pre-buried method and the detecting method, for measuring the depth of penetration (DOP) of projectiles into steel reinforced concrete based on empirical equations. Advantages and disadvantages of the two techniques are analyzed.

Introduction

Issues on projectile penetration effects on steel reinforced concrete are widely concerned as most protective constructions are made of steel reinforced concrete. Among all these concerns, the penetration depth of projectiles is one of the top topics. However, there is still not accessible to an analytic solution to DOP for a lack of loading mechanisms of projectiles during penetration as well as the complexity of the mechanical properties of the steel reinforced concrete. In engineering applications, empirical equations of penetration depth versus entry velocity of projectile are often obtained by fitting such depths measured under different conditions. An accurate and convenient testing method for DOP is a key step toward working out a valid empirical equation. This paper focuses on discussing the advantages and disadvantages of various testing techniques for DOP.

Empirical Equation of Penetration Depth

There are more than 40 empirical equations to predict the penetration depths of projectiles into rocks or steel reinforced concrete. [1] A typical prediction among them is Berezan Equation (eq.1).

$$h_p = K_p \lambda_1 \lambda_2 \frac{P}{d^2} V \cos\left(\frac{\alpha + n\alpha}{2}\right) \tag{1}$$

where h_p the penetration depth of a projectile, K_p the resistance factor to penetration yielding of a material, λ_1 the shape factor, λ_2 the diameter factor, P the projectile mass, d the projectile diameter, V the impact velocity, α the angle of entry, and n deviation factor.

Empirical equations for soft medium have high accuracy, while those for solid medium like rocks and concrete are not. Only a few empirical equations with relative higher accuracy are used in practical application [2][3], such as WES Equation (eq.2), France Standard Formula, Young's Equation[4] (eq.3), U.S. Army Equation (eq.5), Forrestal M.J. Equation[5] (eq.6) and equations of cavity expansion theory[6] (eq.7).

$$H = \frac{M}{A} \cdot \frac{N_{rc}}{\rho} \cdot \left\{ \frac{V_0}{3} \cdot \left[\frac{\rho}{Y_{rc}} \right]^{0.5} - \frac{4}{9} \cdot \ln\left[1 + \frac{3}{4} V_0 \left[\frac{\rho}{Y_{rc}} \right]^{0.5} \right] \right\} \tag{2}$$

$$\frac{\rho v_0}{f_c} = 1.89 \left(\frac{\rho H^2 d}{M} \right)^{\frac{4}{3}} \tag{3}$$

$$\begin{cases} H = 0.0008 \, S \, N \left(\frac{m}{A} \right)^{0.7} \ln\left(1 + 2.15 V^2 \times 10^{-4}\right) & V < 61 m/s \\ H = 0.000018 \, S \, N \left(\frac{m}{A} \right)^{0.7} \ln\left(V - 30.5\right) & V \geq 61 m/s \end{cases} \tag{4}$$

$$H = 3.5 \times 10^{-4} M \, d^{-1.785} V_0^{1.5} \bigg/ \sqrt{f_c} + 0.5d \qquad (5)$$

$$H = \frac{2M}{\pi d^2 \rho N} \ln\left[1 + \frac{\rho N}{S f_c} V_1^2\right] + 2d \qquad H > 2d \qquad (6)$$

$$H = \frac{M}{2\beta} \log\left[1 + \frac{\beta}{\alpha} V_0^2\right] \qquad (7)$$

where H the penetration depth. Other variables correspond to those in references, respectively. Each equation is deduced based on different theories as shown in Fig.1
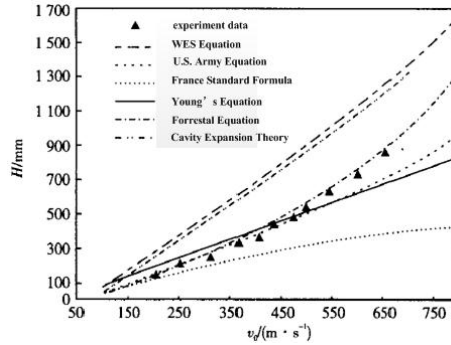

Figure 1. The relationships between entry velocity and the penetration depth based on various equations. [3]

Testing Techniques for Measuring the Penetration Depth of Projectile

Pre-buried Method. The empirical equation based on the pre-buried method is of high accuracy since the equation is fitted to the experiment data. Direct measurement is often used for a small-value DOP measuring. While for projectile penetrating deeply into the medium, it could hardly travel along a straight. In this case, the pre-buried method is often applied. Sensors like probes [7], photosensitive fiber [8], and strain gages [9] are pre-embedded in the target. When a projectile reaches sensors, they will trigger the measuring system and the system will record the trigger time. With the positions of sensors, the penetration track and the real-time penetration depth of a projectile can be determined. First introduced by Eichelberger [10], this technique was applied in multi-layer metal target tests and then was applied in soil body tests by Allen [11]. Some studies measured the DOP with a multi-layer electric grid with arranged and numbered wires pre-embedded in the testing target (see Fig.2). However, this method has several difficulties in practical applications. The dimensions of electric wires should be uniform and they need to be homogenously distributed, otherwise will influence the testing data. Another technique is to pre-embed several acceleration sensors on the one lateral side of the target, and each two sensors are separated by a constant distance, as shown in Fig.3. The penetration depth will be obtained by relating the characteristic responses of a projectile during penetration to the signal responses detected from the sensors. The characters of acceleration impulses should be detected and the entry position of projectile should be well located, otherwise the acceleration sensors will not be triggered.
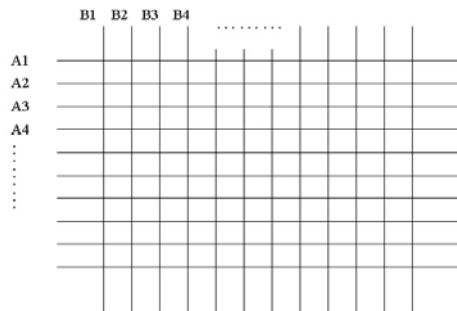

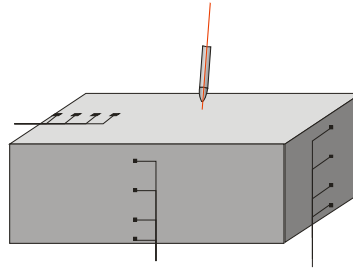Figure 2. A multi-layer electric grid with arranged and numbered wires.

Figure 3. Detection target pre-embedded with acceleration sensors.

The DOP of a projectile during penetration is accessible with the techniques mentioned above. However, high costs hinder the pre-buried method from engineering applications. Since there is no direct measurement system available for measuring DOP, let alone a system with high accuracy, it is essential to develop a simple but high-accuracy technique for DOP measurement.

Detection Method. Detection Method is widely used in various depth measurements, such as radar detection, supersonic wave detection and X-ray detection. The effectiveness of measurements by supersonic wave and X-ray detection method will be influenced by a limited probing depth. An effective way is to implement ground penetration radar. The ground penetration radar (GPR) technique emits high-frequency electromagnetic waves in broad band and short impulse, and obtains the characteristic information of the objective by receiving and analyzing the reflected waves. Once the electromagnetic waves travel inside the material, some part of waves will be reflected. By analyzing the reflected waves through time-frequency or amplitude characters, GPR will work out the characteristic information of the target. Present GPR techniques include reflection method (Fig.3) and transmission method (Fig.4).
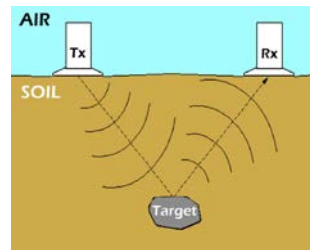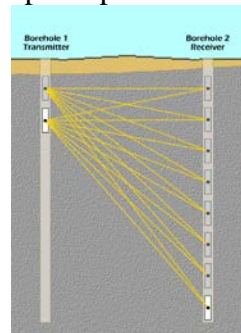

Figure 4. The principle of reflection method.

Figure 5. The principle of transmission method.

Since first explained in 1910, applying radar technique to ground detection was limited in detecting medium with weak wave absorption such as ice layers and salt mine. GPR was applied in a larger range after 1970s with higher noise-signal-ratio instruments. The ground penetration radar is mostly applied to test the mass of steel reinforced concrete. GPR is also able to detect defects, steel distribution, steel erosion, and steel network defects inside concrete [12]-[23]. But the equipment has difficulties in testing concrete target in which distance between steels is small or target having multi-lateral steel network with defects inside. Testing the diameters of steels in target is also difficult [24]-[27]. Wu [26] studied the effect of distance between steels and defects on the detecting ability of GPR, showing that the detecting ability increases with the distance between steels.

Compared with a typical GPR method, steel reinforced concrete target detected in projectile penetration is much thicker. Defects produced around the projectile, changes in dielectric constant of the target as well as the signal screening and attenuation caused by steel network lead to some extent

of error when measuring penetration depth. Therefore issues on signal screening or attenuation and change in dielectric constant should be considered before DOP measurement by the detection method.

Summary

This paper reviews the empirical equations for predicting penetration depth of a projectile into steel reinforced concrete and explores the advantages and disadvantages of two typical measuring techniques – the pre-buried method and the detection method. The high cost and nonrepeatability of the pre-buried method limits its application to practical engineering aspects. The detection method has difficulties in signal processing, but this method is less time-costing and can be used repeatedly once the detection system is set up. As a result, the detection method is of great potential in the future.

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