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PENETRATION OF CONCRETE TARGETS

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ABSTRACT

We developed penetration equations for ogive-nosed projectiles that penetrated concrete targets after normal impact. Our penetration equations predict axial force on the projectile nose, rigid-body motion, and final penetration depth. For target constitutive models, we conducted triaxial material experiments to confining pressures of 600 MPa and curve-fit these data with a linear pressure-volumetric strain relation and with a linear Mohr-Coulomb, shear strength-pressure relation. To verify our penetration equations, we conducted eleven penetration experiments with 0.90 kg, 26.9-mm-diameter, ogive-nosed projectiles into 1.37-m-diameter concrete targets with unconfined compressive strengths between 32-40 MPa. Predictions from our penetration equation are compared with final penetration depth measurements for striking velocities between 280-800 m/s.

INTRODUCTION

Brown (1986) presents a review paper on equations for penetration and perforation of concrete targets. All these equations are empirical and result from curve-fits to test data. In addition, these empirical equations are expressed in terms of specific units, so these empirical equations are dimensionally dependent. More recently, Forrestal, Altman, Cargile, and Hanchak (1993) developed a dimensionally consistent empirical equation for depth of penetration into concrete targets that contains the functional form of experimentally verified, analytical models (Forrestal, Luk, Rosenberg, and Brar, 1992, and Forrestal and Luk, 1992). Forrestal, Altman, Cargile, and Hanchak (1993) resorted to an empirical approach because current penetration studies lack the necessary material data required for input into an analytical model.

In this paper, we present work in progress on an analytical model for penetration of concrete targets, some of the experimental data required for constitutive descriptions, and depth of penetration data for striking velocities between 280-800 m/s. We compare penetration model predictions with depth of penetration data and discuss future work for an improved penetration model.

EXPERIMENTS

Concrete targets were cast in galvanized, corrugated steel culverts with approximately 1.22 and 1.37-m-diameter. Target length varied depending on the striking velocity, but all target lengths were greater than twice the depth of penetration. In addition, 152-mm-diameter, 305-mm-long cylinders were cast at the time of pour for unconfined compressive strength tests. Values of unconfined compressive strength for each target are given in Table 1. Penetration and unconfined compressive strength experiments were conducted from 30 to 60 days after the concrete was cast.

A 83-mm-diameter, smooth-bore powder-gun launched the 0.898-0.912 kg projectiles dimensioned in Figure 1 to striking velocities between 277 and 800 m/s. Projectiles were machined

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from 4340 steel rods and heat treated to a hardness of R_C 43 - 45. The projectiles were fitted with plastic sabots and obturators that fit snugly into the gun bore. Sabots and obturators were stripped aerodynamically prior to striking the targets. Striking velocities and pitch and yaw angles were measured with orthogonal streak cameras. Pitch and yaw angles were always less than one degree. Tables 1 presents a data summary for the penetration experiments.

In addition to the unconfined compressive strength tests, we conducted triaxial material experiments with 51-mm-diameter, 110-mm-long, concrete cylinders. The triaxial material experiments are conducted in two phases: isotropic compression followed by triaxial shear. Concrete cylinders were loaded with axial stress σ_a and radial stress σ_r . For isotropic compression ($\sigma_a = \sigma_r$), deformation measurements of the length and diameter changes during loading were taken and volumetric strains were calculated. Figure 2 shows pressure versus volumetric strain data. For the triaxial shear experiments, concrete cylinders are first loaded with isotropic compression, and then the axial stress σ_a is increased while the radial stress σ_r is held constant. Maximum stress difference $\tau = \sigma_a - \sigma_r$ or shear strength versus pressure $p = 1/3(\sigma_a + 2\sigma_r)$ is given in Figure 3.

Other material data required for input to our analytic model will be obtained from planar impact (Grady, 1993) and Hopkinson pressure bar experiments. This work is in progress.

PENETRATION MODEL

A projectile with an ogival nose impacts a uniform target at normal incidence with velocity V_s and proceeds to penetrate at rigid body velocity V_z . As Figure 4 shows, an ogive is the arc of a circle and is tangent to the projectile shank. The ogive is commonly defined in terms of caliber-radius-head

$$CRH = s/2a = \psi \quad (1)$$

where s and a are defined in Figure 4. For a rigid projectile, motion and final depth can be calculated when forces on the projectile are known. Thus, we first model target resistance and then calculate deceleration, velocity and depth.

To obtain closed-form penetration equations, we use the spherical, cavity-expansion approximation (Bishop, Hill, Mott, 1945). Normal stress on the projectile nose is approximated by results from spherically symmetric, cavity-expansion analyses that relate cavity-expansion velocity to radial stress at the cavity surface. In particular, normal stress on the projectile nose is taken as the stress at the cavity surface associated with the distributed expansion velocity at the nose-target interface caused by projectile penetration.

Spherically Symmetric Cavity Expansion. A spherically symmetric cavity is expanded from zero initial radius at constant velocity V . This expansion produces plastic and elastic response regions. For slow enough V , there are three regions of response: an elastic region, a region with radial cracks (the material reaches its tensile strength), and a plastic region (the material reaches its shear strength). As V increases, the radially cracked region diminishes and is eliminated eventually. That is, for large enough cavity-expansion velocity, the response is elastic-plastic. The plastic region is bounded by $r=Vt$ and $r=ct$, the cracked region is bounded by $r=ct$ and $r=c_1t$, and the elastic region is bounded by $r=c_1t$ and $r=c_d t$ where r is the Eulerian coordinate, t is time, c and c_1 are interface velocities, and c_d is the elastic, dilatational velocity.

The material description in the plastic region is.

$$p = K(1 - \rho/\rho_0) = K\eta \quad (2a)$$

$$p = (\sigma_r + \sigma_\theta + \sigma_\phi)/3 ; \quad \sigma_\theta = \sigma_\phi \quad (2b)$$

$$\tau = \lambda p + \tau_0 ; \quad \tau_0 = [(3 - \lambda)/3]Y \quad (2c)$$

where p is the pressure; ρ_0 and ρ are densities in the undeformed and deformed material respectively; η is the volumetric strain; K is the bulk modulus; σ_r and σ_θ are radial and circumferential Cauchy stress components (positive in compression); λ and τ_0 define the pressure dependent shear strength; and Y is the uniaxial compressive strength.

The material in the radially cracked region is taken as linearly elastic with $\sigma_\theta = 0$. For the elastic region $\sigma_\theta \geq -f$, where f is the tensile strength, E is the Young's modulus, and ν is Poisson's ratio.

Tzou, Forrestal, and Longcope, 1993, developed analytical and numerical solutions for these spherical, cavity-expansion problems. As previously discussed, we develop these cavity-expansion analyses for input to our penetration models. The penetration equations (Forrestal and Luk, 1992 and Forrestal, Luk, Rosenberg, and Brar, 1992) use the relationships between radial stress at the cavity surface σ_r and the cavity-expansion velocity V . For the concrete target studied in this paper, we take $K = 7.5$ GPa, $\nu = 0.23$, $\tau_0 = 150$ MPa, $Y = 164$ MPa, $\lambda = 0.25$, $f = 16.2$ MPa, and $\rho = 2310$ kg/m³. Figure 5 shows σ_r versus V for the elastic-cracked-plastic and elastic-plastic models. In addition, Figure 5 shows that the radially cracked region is eliminated for $(\rho/Y)^{1/2} V > 1.5$.

To obtain closed-form penetration equations, we curve-fit the elastic-cracked-plastic numerical results in Figure 5 with

$$\sigma_r/Y = A + B[(\rho/Y)^{1/2} V]^2 \quad (3)$$

In equation 3 and Figure 5, A is the value of σ_r/Y for $V \rightarrow 0$. Forrestal and Longcope, 1990, present a closed-form equation for A , so only B is adjusted to fit the curve in Figure 5. The cavity-expansion results in Figure 5 are curve-fit accurately with $A = 2.80$ and $B = 1.37$.

Depth Of Penetration. Post-test observation of concrete targets show that the cavity after penetration is a conical region with length about two projectile diameters, $4a$, followed by a circular cylinder with diameter nearly equal to the projectile shank diameter, $2a$. Thus, the cavity length $0 < z < 4a$ is called the crater region and the cavity length $4a < z < P$ is called the tunnel region, where z is measured from the target surface and P is final penetration depth. Both the crater and tunnel regions must be taken into account in penetration analyses of concrete targets.

From Forrestal, Altman, Cargile, and Hanchak, 1993, final penetration depth is given by

$$P = \frac{m}{2\pi a^2 \rho B N} \ln \left(1 + \frac{B N \rho V_1^2}{\tau_0 A} \right) + 4a, \quad P > 4a \quad (4a)$$

$$V_1^2 = \frac{m V_s^2 - 4\pi a^3 \tau_0 A}{m + 4\pi a^3 B N \rho} \quad (4b)$$

$$N = \frac{8\psi - 1}{24\psi^2} \quad (4c)$$

where m , a , ψ are the projectile mass, shank radius, and caliber-radius-head; V_s is the striking velocity; A and B are obtained from the spherically symmetric cavity-expansion analysis; and τ_0 is given by equation 2c.

RESULTS AND DISCUSSION

For target constitutive modeling, we use linear curve-fits to the triaxial test data. Pressure p versus the volumetric strain η data (Figure 2) are curve-fit by equation 2a with $K = 7.5$ GPa.

Calculations with our penetration model predict a peak pressure of $p = 1100$ MPa for a penetration velocity of $V_z = 800$ m/s; however, the data in Figure 2 are limited to 600 MPa.

Shear strength τ versus pressure p data (Figure 3) are curve-fit by equation 2c with $\tau = 150$ MPa, $Y = 164$ MPa, and $\lambda = 0.25$. The unconfined compressive strength $f'_c = Y$ from quasi-static tests is $Y = 35$ MPa ($f'_c = 5$ ksi); however, work in progress with split Hopkinson bar experiments gave dynamic unconfined compressive strength of about $Y = 164$ MPa.

We have planned other material tests for this concrete target with planar impact (Grady 1993) and Hopkinson bar experiments. Planar impact experiments will be conducted to axial stresses of 2.5 GPa to examine material response at higher pressures and higher loading rates. Hopkinson bar methods will be used to better define dynamic unconfined compressive strength and tensile strength.

We performed scoping calculations with our material model using the currently available material data. Figure 6 shows depth of penetration P versus striking velocity data and a model prediction. For input to the penetration model we used $K = 7.5$ GPa, $\nu = 0.23$, $\tau = 150$ MPa, $Y = 164$ MPa, $\lambda = 0.25$, $f = 16.2$ MPa, and $\rho = 2310$ kg/m³ for the target material properties. The projectile had a 2.0 caliber-radius-head nose ($\psi = 2.0$), nominal mass 0.90 kg, and the geometry is shown in Figure 1.

SUMMARY

We present work in progress on an analytical model for penetration of concrete targets. Predictions from the current model using available material data are in reasonably good agreement with penetration data.

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REFERENCES

- Bishop, R. F., Hill, R., and Mott, N. F., 1945, "The Theory of Indentation and Hardness Tests," The Proceedings of the Physical Society, Vol. 57, Part 3, pp. 147-159.
- Brown, S. J., 1986, "Energy Release Protection for Pressurized Systems. Part II. Review of Studies Into Impact / Terminal Ballistics," Applied Mechanics Reviews, Vol. 39.
- Forrestal, M. J. and Longcope, D. B., 1990, "Target Strength of Ceramic Materials for High-Velocity Penetration," Journal of Applied Physics, Vol. 67, pp. 3669-3672.
- Forrestal, M. J. and Luk, V. K., 1992, "Penetration Into Soil Targets," International Journal of Impact Engineering, Vol. 12, pp. 427-444.
- Forrestal, M. J., Luk, V. K., Rosenberg, Z., and Brar, N. S., 1992, "Penetration of 7075-T651 Aluminum Targets with Ogival-Nose Rods," International Journal of Solids and Structures, Vol. 29, PP. 1729-1736.
- Forrestal, M. J., Altman, B. S., Cargile, J. D., and Hanchak, S. J., 1993, "An empirical Equation for Penetration Depth of Ogive-Nose Projectiles Into Concrete Targets," Proceedings of the Sixth International Symposium on Interaction of Nonnuclear Munitions with Structures, Panama City Beach, Florida, pp. 29-32.

Grady, D. E., 1993, "Impact Compression Properties of Concrete," Proceedings of the Sixth International Symposium on Interaction of Nonnuclear Munitions with Structures, Panama City Beach, Florida, pp. 172-175.

Tzou, D. Y., Forrestal, M. J., and Longcope, D. B., 1993, "Dynamic Spherical Cavity-Expansion for Mohr-Coulomb Materials with a Tension Cutoff," work in progress.

Table 1. Data summary for the penetration experiments into targets with nominal unconfined compressive strength $f'_c = 36 \text{ MPa}$ (5 ksi) and density $\rho = 2310 \text{ kg/m}^3$.

Shot Number	Striking Velocity (m/s)	Penetration Depth (m)	Target Diameter (m)	Target Length (m)	Compressive Strength (MPa)	Projectile Mass (kg)
14	277	0.173	1.37	0.76	35.2	0.906
13	410	0.310	1.37	0.91	37.8	0.910
15	431	0.411	1.37	0.91	38.1	0.907
11	499	0.480	1.37	0.76	33.5	0.912
12	567	0.525	1.37	1.07	38.4	0.910
2	590	0.729	1.22	1.83	36.9	0.905
1	591	0.513	1.22	1.83	40.1	0.901
3	631	0.607	1.22	1.83	35.4	0.903
4	642	0.620	1.22	1.83	34.7	0.905
5	773	0.866	1.22	1.83	36.0	0.901
6	800	0.958	1.22	1.83	32.4	0.904

Figure 1. Projectile with mass 0.90 kg and caliber-radius-head nose $\Psi = 3.0$.

Figure 2. Pressure versus volumetric strain.

Figure 3. Shear strength versus pressure.

Figure 4. Ogival nose geometry.

Figure 5. Radial stress at the cavity surface versus cavity expansion velocity.

Figure 6. Depth of penetration data and model prediction.

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