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NON-NORMAL IMPACT OF EARTH PENETRATORS*

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SUMMARY

A brief literature review of the general subject of projectile penetration into soil media is presented. Particular emphasis is placed on projectiles impacting soil targets at other than normal incidence and/or at an angle of attack, for which lateral accelerations exist and can dominate the structural response. Comparisons of predicted lateral accelerations with recent earth penetrator experiments are then made using a 3 degree-of-freedom rigid-body approach developed elsewhere to determine the external penetrator loading. Agreement between experimental and calculated accelerations is favorable, but the need to include flexible-body response is indicated. Finally a scheme to incorporate a spherical-cavity-expansion analytical procedure into a detailed finite element model of the penetrator is developed to account for flexible-body response.

INTRODUCTION AND LITERATURE REVIEW

The general subject of the penetration of various media by projectiles has undergone study for over two hundred years. Several recent surveys of the field have been reported. Backman and Goldsmith (1978) review the entire field of projectile penetration, including penetration into semi-infinite targets of soil material. More recently, Anderson and Bodner (1988) survey the field of ballistic impact. Zukas (1990) focuses on the description of impact simulations utilizing two- and three- dimensional finite difference and finite element computer programs. Finally, a very recent review of projectile impact by Corbett, Reid, and Johnson (1996) contains a section on the impact of soils. Based upon the above four survey papers, it appears logical to categorize research in penetration of soil by projectiles into three fundamental areas: empirical, analytical, and numerical methods.

Empirical Methods

Early empirical studies were based on the determination of depth of penetration of projectiles striking soil. Young (1969) provides a historical perspective and presents simple empirical equations for depth of penetration in a variety of natural earth targets as a function of impact velocity, projectile weight and cross sectional area, as well as an "S-Number" to represent the influence of a given type of soil on the penetration

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depth. These empirical equations, valid for normal impact, are based on a large set of full-scale earth penetration tests. These correlations were performed over a wide range in impact velocities, nose shapes, weights, penetrator geometrical sizes, and soil types.

Projectiles impacting soil targets at other than normal incidence and/or at an angle of attack are subjected to net lateral acceleration loading as well as axial decelerations. Non-normal impact (AOI ≠90 Deg.) with angle-of-attack (AOA) is illustrated in Figure 1. These lateral loads can be very important to the structural response of the case of the projectile as well as any internal components. Extending his earlier empirical depth-of-penetration approach, Young (1991) developed a semi-empirical method called SAMPLL for calculating lateral loads on penetrators, based on the S-Number concept. The method assumes the penetrator is a rigid body undergoing planar motion with three degrees of freedom and that lateral loads are proportional to axial loads and angle of attack. Lateral forces resulting from the impact angle are also included by an empirical method. Knowing the spatial distribution of lateral forces over the penetrator, the penetrator motion is determined from rigid-body mechanics for each time step in the penetration process. The method has been empirically adjusted to give reasonable agreement with experimental data.

Analytical Methods

Analytical methods for determining penetration depth and surface pressures on penetrators are exclusively based on cavity-growth models. Hopkins (1960) first presented the solution for dynamic expansion of a spherical cavity. Yew and Stirbis (1978) generalized spherical cavity growth by modeling the penetration process and the tunnel produced by the projectile by a series of spherical cavity expansions initiated at the tip of the penetrator. Forrestal, Longcope, and Norwood (1981) estimate the forces on conical penetrators into dry porous rock targets utilizing a cylindrical cavity expansion approximation. Forrestal and Luk (1992) recently utilized the spherical cavity expansion model to develop penetration equations for ogival-nose projectiles undergoing normal impact into solid targets. Comparisons with experimental data (axial deceleration-time histories) are quite favorable.

The above analytical studies for predicting penetrator decelerations and depth of penetration have the advantage over the empirical methods cited earlier, as they are developed with classical soil mechanical properties; and therefore, provide a more fundamental understanding of the physical process than a simple empirical fit to data. However, only ideal, normal impacts are considered. Recognizing the need for lateral loads on penetrators, due to non-normal impact and non-zero angle of attack, Davie and Richgels (1983) extended the cavity-growth analytical models described above to analyze the rigid-body response of a penetrator into a soil target. The code, called GNOME, is uncoupled, as deformations of the penetrator are ignored. The rigid-body treatment of the penetrator is similar to the SAMPLL Code, except that surface loading of the rigid body is based on spherical and cylindrical cavity growth models and soil material property imputs similar to analytical approaches cited above.

Numerical Methods

Thigpen (1974) numerically investigated the penetration of a projectile into a half space of earth-type material, modeled as elastic-plastic. Calculations were performed using the Lagrangian TOODY II Code, which performs numerical integration of the conservation equations (mass, momentum and energy). The calculation was two-dimensional (axisymmetric), treating normal impact only. Close agreement of the numerical to experimental results was obtained. Rosinsky (1985) reports results for normal and oblique impacts into soil using the DYNA series of two- and three-dimensional codes (oblique impacts require a 3-D code). Both non-zero angles of incidence and non-zero angles of attack are included in three-dimensional calculations. His work is the first reported fully three-dimensional Lagrangian penetration analysis and utilizes the "pilot hole" technique to surmount problems of large mesh distortions. Logan (1991) subsequently introduced a related method which does not require iteration for oblique impact. A recent review of terminal effect codes (Kimsey and Randers-Pehrson (1992)) describes current Eulerian and Lagrangian codes and addresses other approaches to the computational difficulties associated with severe mesh deformations in Lagrangian codes. Smoothed Particle Hydrodynamics (SPH) methods have also recently been successfully utilized in high velocity impact problems by Johnson (1994).

APPLICATIONS TO PENETRATOR PREDICTIONS

Two approaches were used for correlation with experimental data in this paper: An uncoupled and a coupled approach. In both cases, a detailed finite element model of the penetrator outer case, as well as internal components, was used as a basis for which soil-penetrator interactive external loads due to the impact/penetration process were determined.

In the uncoupled case, external loads were determined using the SAMPLL rigid body program and appropriately applied to surface elements of the penetrator finite element model as time-dependent pressure histories. In this case, deformations, e.g., bending of the penetrator, are uncoupled from the soil loads. With this approach only one number, an S-number, is needed to define the penetrability of a homogenous geologic media. Furthermore, an extensive data base of test and corresponding S-numbers exists for many media. For these reasons, this approach was initially chosen. However, for the penetrator data selected, it was necessary to use significantly larger AOA than was calculated from aerodynamics to achieve agreement with this empirical approach. The most plausible reason for this is that the penetrator flexes during penetration. While satisfactory agreement between SAMPLL and experiment can be had in this case by arbitrary adjustment in the AOA input parameter, a more predictive coupled approach was sought.

In the coupled case, a spherical cavity expansion model is developed and implemented in the penetrator finite element model to locally calculate the pressure-time histories due to soil-penetrator interactions. From the previously mentioned literature on cavity expansion, a rather simple normal velocity- dependent pressure expression is evident:

$$P = A + BV_n + CV_n^2 \tag{1}$$

In this equation, P is pressure and V_n is the velocity normal to the penetrator surface, while A, B, and C are constants that only depend on the material properties of the geological medium. In addition, the pressure is assumed to be zero when the penetrator surface is moving away from the soil (V_n<0). This pressure expression has been remarkably accurate in predicting axial deceleration for vertical impacts but, as one might expect from the infinite medium simplification, it lacks the capability to accurately capture surface effects, which are more important for oblique impacts. To overcome this limitation, the above pressure expression was modified to account for near-surface effects in a manner similar to that utilized in SAMPLL. Two surface relief factors are applied; one reduces the pressure based on the depth of the point beneath the surface, while the other asymmetrically reduces the pressure, based on the distance to the free surface along a normal to the penetrator surface. Further, for soil targets, a flow-separation pressure reduction factor along the cylindrical body of the penetrator is employed. The material constants (A, B, and C) are derived (for a given penetrator and target) by equating vertical depth of penetration computed from the cavity expansion pressure relation to that computed using the S-number approach, providing a convenient link to a large experimental data base for earth penetrators. This is done for three different impact velocities to uniquely define A, B, and C. To determine the surface relief factors for the cavity expansion approach, **rigid-body** penetration simulations of the experiments were performed with both SAMPLL and the cavity expansion algorithm for impact and target conditions representative of the actual drop tests. After several iterations, suitable factors were obtained. A comparison of rigid-body lateral accelerations from SAMPLL and the cavity expansion method is shown in Figure 2 for unfrozen soil (results for frozen soil were similar). As is evident, very reasonable comparisons were obtained; in fact the differences (10% to 20%) are probably less than the scatter in SAMPLL's data base. Impact and target conditions more remote from the above calibration points were also checked and found to agree well with SAMPLL.

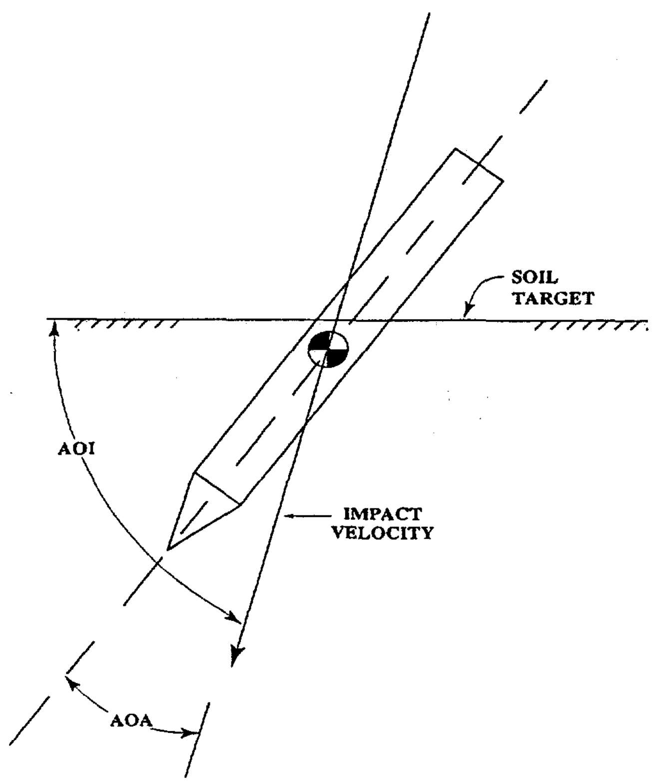

Figure 1. Non-normal angle of incidence with angle of attack.

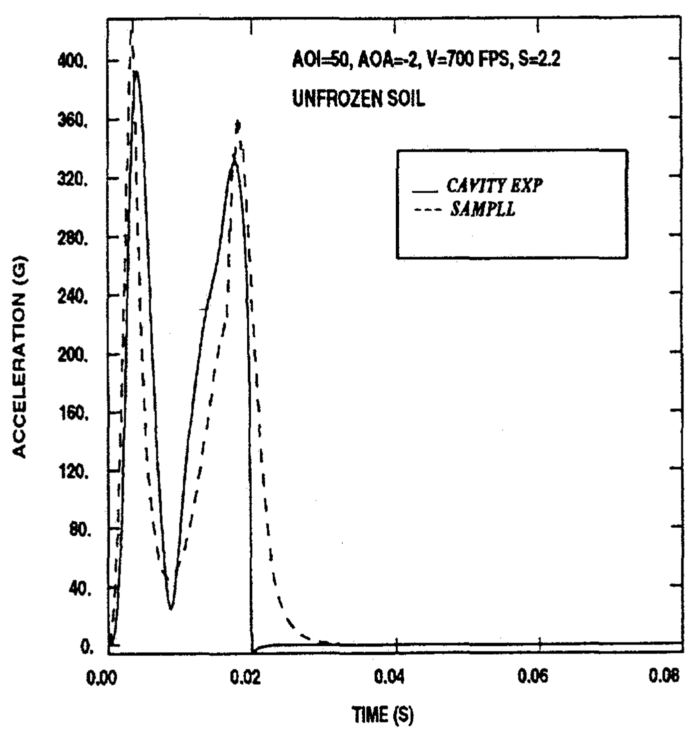

Figure 2. Comparison of SAMPLL and rigid cavity expansion lateral accelerations.

COMPARISONS WITH EXPERIMENTAL DATA

Recent experiments on earth penetrators impacting frozen and unfrozen soil have been reported for which acceleration-time histories were recorded. The tests were performed at a non-normal AOI with non-zero AOA. AOI and AOA values are inferred from trajectory analyses.

A comparison of recorded axial and lateral accelerations for impact into the frozen soil is shown in Figure 3. The soil was taken as a uniform frozen layer (S=2). Impact velocity was 735 ft/sec, with an AOI of 48 deg. and AOA of -2 deg. Three curves are shown, all of which were filtered at 1 Khz: Test data, uncoupled (FEA/SAMPLL), and coupled (FEA/CAVX) cavity expansion model. It is seen that the coupled predictions are in reasonable agreement with experimental data and are a significant improvement over the uncoupled calculation. Similar observations are made in the case of penetrator oblique impact into unfrozen soil (Figure 4). This experiment occurred at an impact velocity of 780 ft/sec, an AOI of 40 deg. and AOA of -1 deg. The soil consisted of a 2.8 ft deep soft layer (S=4.8) over a thin medium layer (S=2.5) with hard soil below (S=1.8).

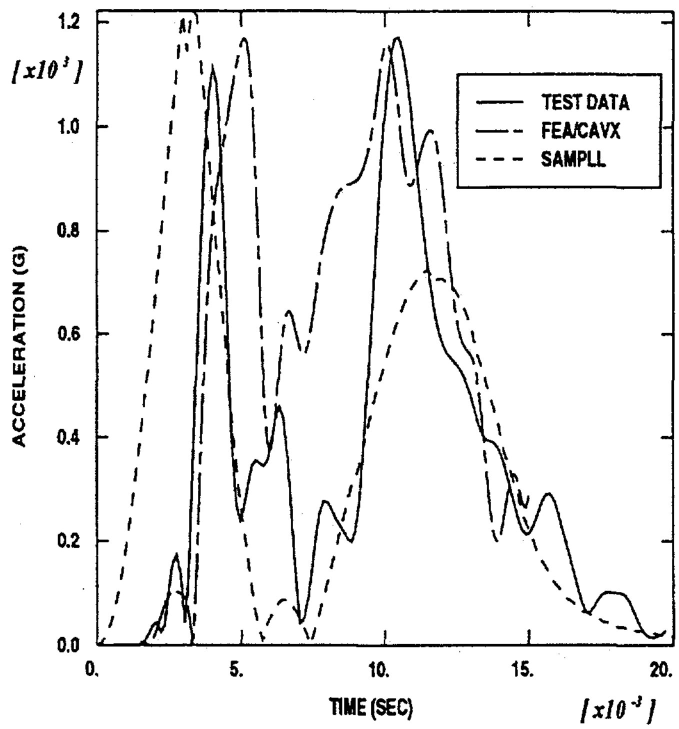

Figure 3. Frozen soil test/analysis comparison - lateral mid acceleration.

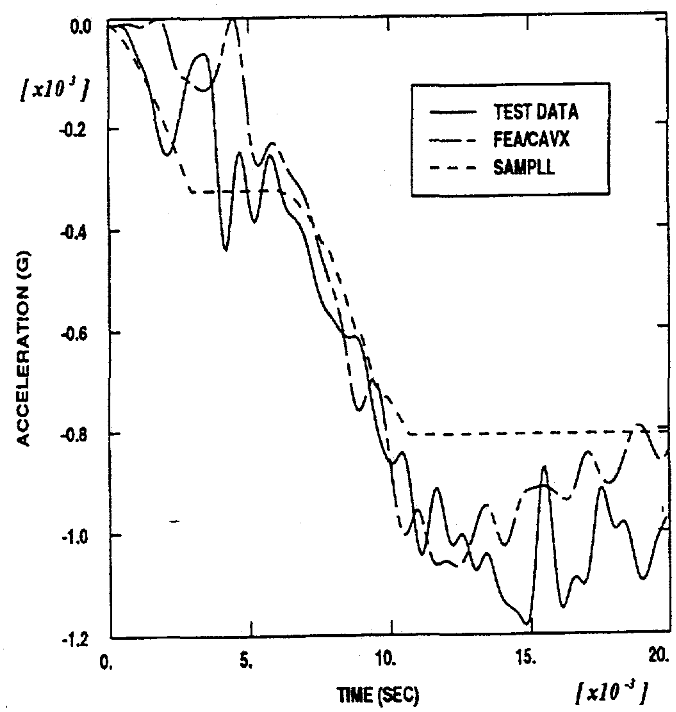

Figure 4. Layered soil test/analysis comparison - axial forward acceleration.

RESULTS AND CONCLUSIONS

Two methods of determining and applying oblique earth-penetration loading pressures to a detailed finite element model of the penetrator are developed: An uncoupled and a coupled treatment of the soil-penetrator interaction process. Resulting predictions from the two methods are favorably compared to available transient accelerometer experimental data from non-normal penetrator impacts into frozen and unfrozen soil. Results indicate that inclusion of coupling effects can be important.

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