Effect of Soil Parameters on High Velocity Projectile Penetration

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SYNOPSIS A parameter analysis is performed on an analytical penetration model which has been recently developed. Figures are plotted to show how the disturbed zone size, parameters of displacement and stress fields and dynamic section pressure are dependent on soil compressibility, shear strength and mass density. Main results are presented and discussed.

INTRODUCTION

Vertical penetration of projectiles into soils has been a subject of research for a long time. Based on many field tests, empirical formulae were developed to predict penetration depth (Young, 1969). These formulae were found to yield results in good agreement with test data. Soil is represented by an empirical constant which is found by curve fitting.

Two dimensional computer codes were adjusted to analyse penetration problems (Thigpen, 1974) and results usually show good agreement with test data. The programs are very time consuming and their use is therefore limited. A new analytical model has been developed (Yankelevsky, et al, 1980) to represent soil-projectile interaction and to provide efficient calculations of projectile and soil response. Comparisons of the model predictions at low and high impact velocities show very good agreement. This paper presents a study of soil properties effects on penetration.

THE DISCS MODEL

The soil medium is represented by a set of discs, of equal thickness, being perpendicular to the projectile axis. When the nose tip reaches a disc at depth z (Fig. 1), a plastic shock wave propagates in the radial direction and an axisymmetric hole is developed, the radius of which equals to the local projectile radius.

The velocity field is assumed to coincide with the radial direction, hence the problem becomes one dimensional. Since high local volumetric strains are involved, it is assumed that plastic strains govern, and the elastic strains may be ignored. Soil is represented by the mean stress vs. the volumetric strain relationship and by the principal stress difference at failure as function of the mean stress.

The stresses in a typical disc vary with the radial coordinate and the volumetric strain varies too. An average mean stress $\bar{\sigma}$ is defined, corresponding to an average volumetric strain $\bar{\varepsilon}$ The average values are defined under the condition that they should perform the same work over strain increments as the variable stresses do (3). By using conservation principles of mass and momentum, where the average value $\bar{\varepsilon}$ is introduced, and the Rankine-Hugoniot jump conditions at the plastic front, the following interaction expression is obtained:

$$p(t) = -\frac{1}{2}\tau\cdot\ln(\bar{\varepsilon}) + \frac{1}{2}\cdot\rho_o\left[1 - \frac{\ln(\bar{\varepsilon})}{1-\bar{\varepsilon}}\right]\cdot\dot{R}^2(t) - \frac{1}{2}\rho_o\cdot\frac{\ln(\bar{\varepsilon})}{1-\bar{\varepsilon}}\cdot R(t)\cdot\ddot{R}(t) \quad (1)$$

where: $p(t)$ = interaction pressure
τ = principal stress difference at failure (corresponds to $\bar{\sigma}$)
$\bar{\varepsilon}$ = the average volumetric strain (corresponds to $\bar{\sigma}$)
ρ_o = the mass density
$R(t)$, $\dot{R}(t)$, $\ddot{R}(t)$ = the disc internal boundary values of displacement velocity and acceleration.

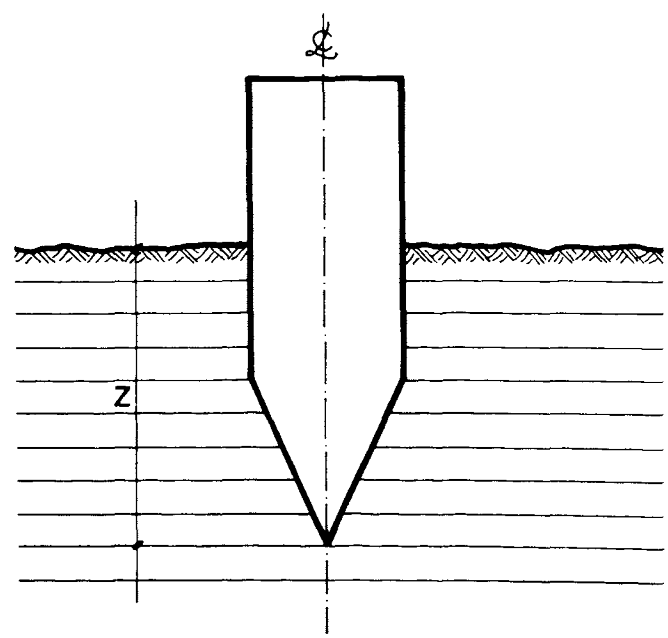

Fig. 1. The Discs Model

Other expressions for displacement and stress fields, are obtained as intermediate stages of the above derivation and will be presented in their final form.

PARAMETER ANALYSIS

1. The Plastic Zone

The width of the plastic zone is found to be solely dependent on the volumetric strain. Plotting the size of the plastic zone in projectile calibers (Fig. 2) shows that the penetration phenomenon has a very local effect and the disturbed zone size does not exceed a few projectile calibers. Experimental evidence (Byers & Chabai, 1977)which shows that zero stresses were measured at 7.25 calibers distance from the penetration axis, supports the theoretical result.

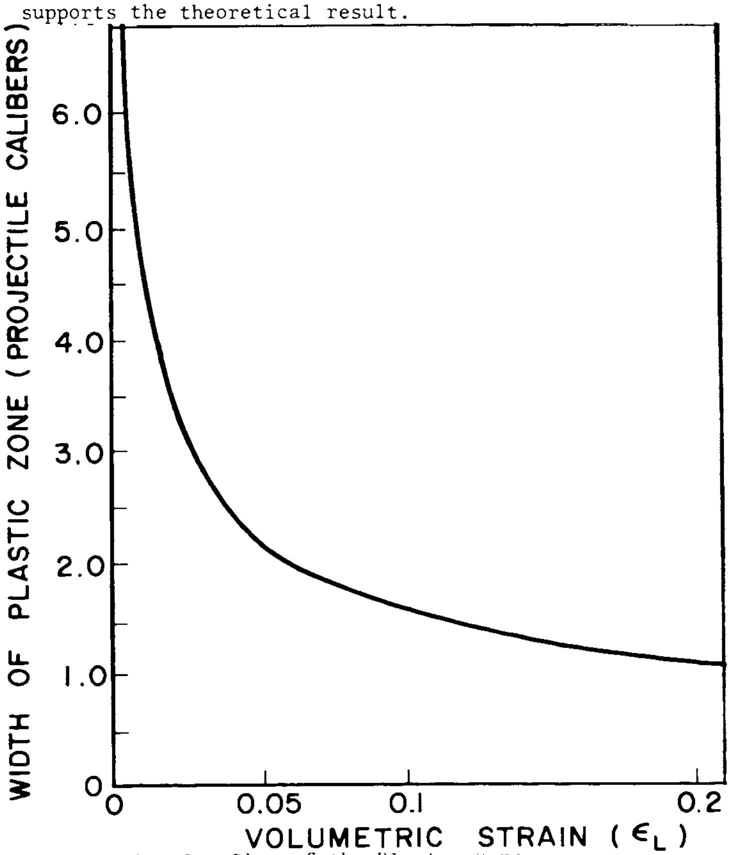

Fig. 2. Size of the Plastic Zone

2. The Displacement Field

The displacement field is found to be:

$$\frac{u(t)}{R(t)} = \left\{(1-\bar{\varepsilon})\left[\frac{r}{R(t)}\right]^2 + 1\right\}^{1/2} - \frac{r}{R(t)} \tag{2}$$

From Fig. 3 it may be seen that highest gradient is developed at the soil-projectile interface and its value is independent of the volumetric strain. At large volumetric strains the gradients change very slightly, but they decrease very rapidly for small volumetric strains. At a Lagrangeam coordinate r equal to one projectile diameter, the radial displacement is smaller than 20% of its value at the internal boundary.

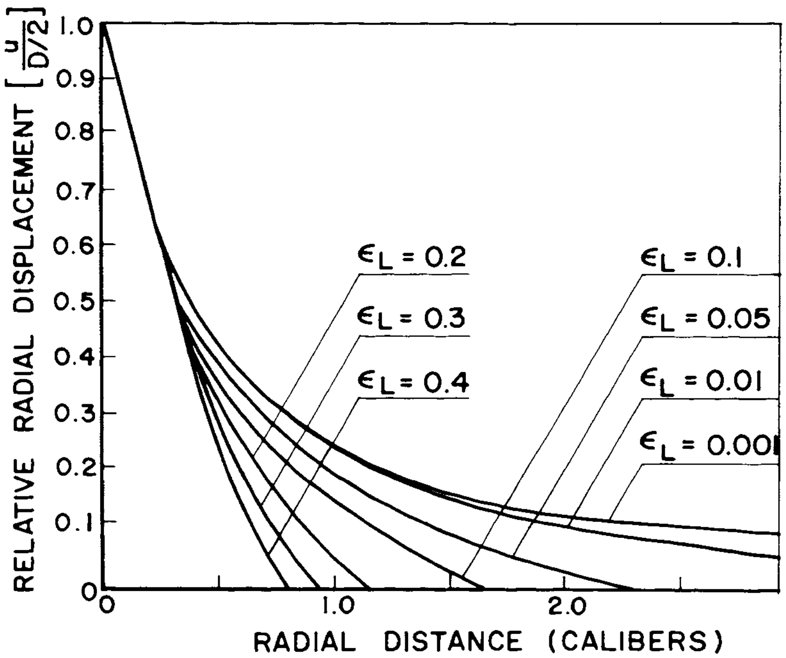

Fig. 3. Displacement Field

3. Stress Distribution in the Plastic Zone

The radial stress at the disc internal boundary equals to the interaction pressure (Eq. 1), and the stress at the Lagrangean coordinate h (the plastic front) is found to be:

$$\sigma_h = \rho_o \cdot R^2(t)$$

Between these values the radial stress is theoretically expressed as follows:

$${}_r = P_{st}(r) + A(r)\dot{R}^2(t) + B(r)R(t)\ddot{R}(t) \tag{4}$$

where:

$$\frac{P_{st}(r)}{\tau} = -\frac{1}{2}\ln\left[(1-\bar{\varepsilon})\left(\frac{r}{h}\right)^2 + \bar{\varepsilon}\right] \tag{4a}$$

$$\frac{A(r)}{\rho_o} = \frac{1}{2}\left\{\frac{2-\bar{\varepsilon}}{1-\bar{\varepsilon}} - \frac{\bar{\varepsilon}}{1-\bar{\varepsilon}}\cdot\frac{1}{(1-\bar{\varepsilon})(r/h)^2+\bar{\varepsilon}} - \frac{1}{1-\bar{\varepsilon}}\ln\left[(1-\bar{\varepsilon})\left(\frac{r}{h}\right)^2 + \bar{\varepsilon}\right]\right\} \tag{4b}$$

$$\frac{B(r)}{\rho_o} = -\frac{1}{2}\left\{\frac{1}{1-\bar{\varepsilon}}\ln\left[(1-\bar{\varepsilon})\left(\frac{r}{h}\right)^2 + \bar{\varepsilon}\right]\right\} \tag{4c}$$

The variations of $P_{st}(r)$ and $A(r)$ are shown in Figs. 4-5, for various levels of volumetric strain.

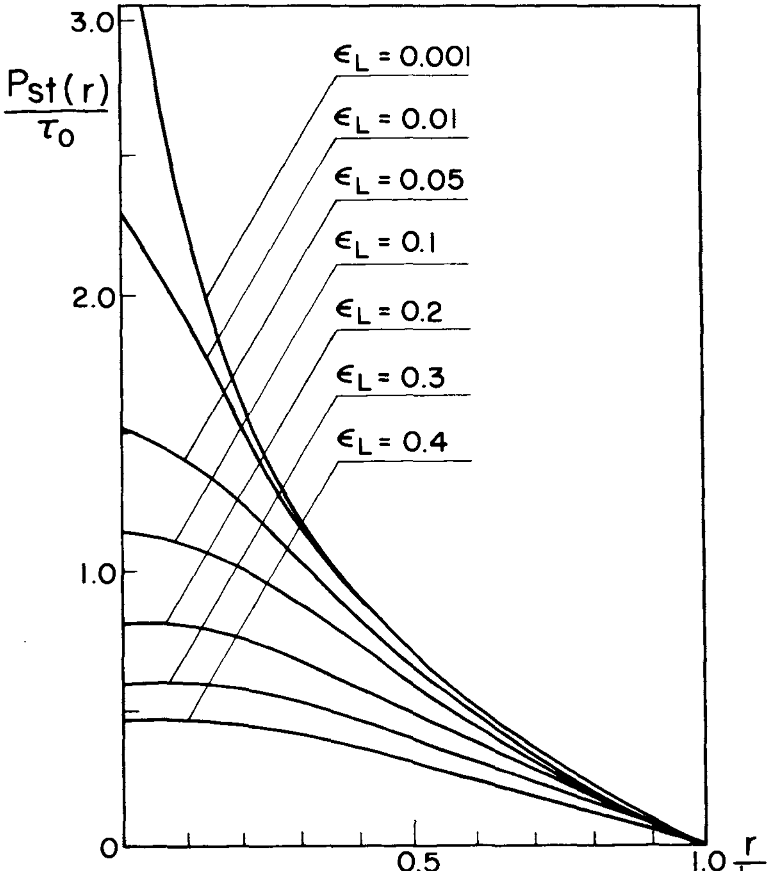

Fig. 4. Stress Field Parameter $P_{st}(r)$

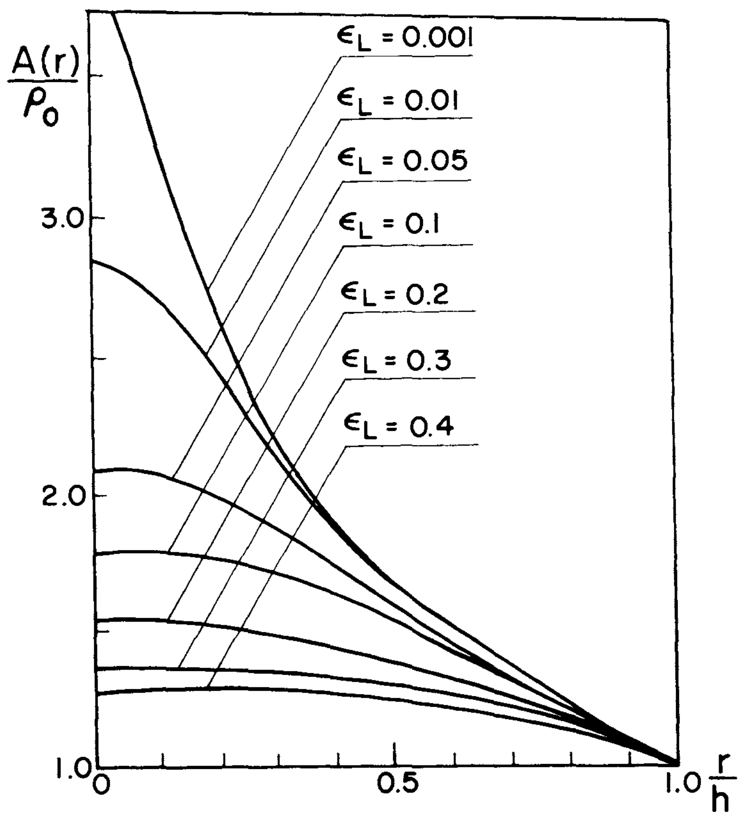

Fig. 5. Stress Field Parameter A(r)

4. Effect of Soil Parameters on Penetration Depth

to analyse some soil parameters, a projectile having an ogive nose has been chosen. Performing integration of all the vertical resistive force components yields the following expression for the resistive force:

$$P_z(t) = -\frac{\pi D^2}{4}\left[-\frac{1}{2}\tau\,\ln(\bar{\varepsilon}) + 4\alpha\rho_o\dot{W}^2(t) - 8\beta D\rho_o\frac{\ln(\bar{\varepsilon})}{1-\bar{\varepsilon}}\ddot{W}(t)\right] \quad (5)$$

where: α,β = nose shape coefficients (for CRH=9.25 their values are: $\alpha \approx 0.0336$; $\beta = -0.0272$)

D = projectile diameter

$\dot{W}(t),\ddot{W}(t)$ = the corresponding values of projectile velocity and acceleration.

With aid of Newton's second law and Eq. 5, the acceleration is expressed as follows:

$$\ddot{W}(t) = -\frac{\pi D^2}{4}\cdot\frac{-\frac{1}{2}\tau\,\ln(\bar{\varepsilon}) + 4\alpha\rho_o\dot{W}^2(t)}{m_p - 8\beta D\rho_o\frac{\ln(\bar{\varepsilon})}{1-\bar{\varepsilon}}\cdot\frac{\pi D^2}{4}} \quad (6)$$

where: m_p = the projectile mass.

The dynamic section pressure Q is defined as the value of the instantaneous dynamic resistive force divided by the projectile cross section area:

$$Q = \frac{m_p\ddot{W}(t)}{\pi D^2/4} = \frac{\frac{1}{2}\tau\,\ln(\bar{\varepsilon}) - 4\alpha\rho_o\dot{W}^2(t)}{\frac{4m_p}{\pi D^2} - 8\beta F\frac{\ln(\bar{\varepsilon})}{1-\bar{\varepsilon}}} \quad (7)$$

where F is a non dimensional mass parameter:

$$F = \frac{\rho_o\,\pi D^3}{4\,m_p}$$

The expression for the dynamic section pressure is analysed for a wide range of parameters and the following major results are obtained:

a. At low impact velocities penetration is insensitive to soil density and is strongly dependent on the volumetric strain (Fig. 6).

At higher impact velocities the density is more effective. At very high velocities the section pressure is proportional to the soil density (hydrodynamic regime). The higher is the velocity, the less effective is the volumetric strain (Fig. 7).

b. At low impact velocities the section pressure is strongly dependent on the principal stress difference at failure and it becomes less effective at higher velocities (Fig. 8).

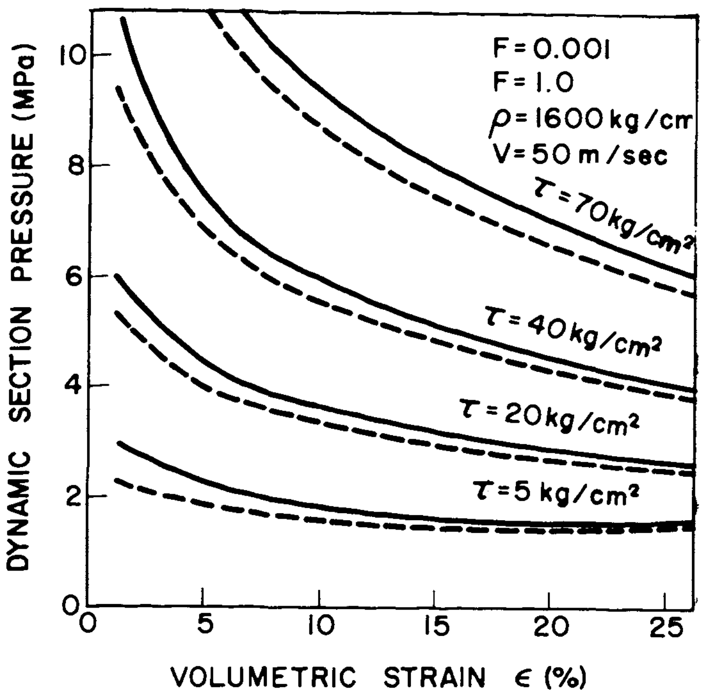

Fig. 6. Dynamic Section Pressure at Low Velocity

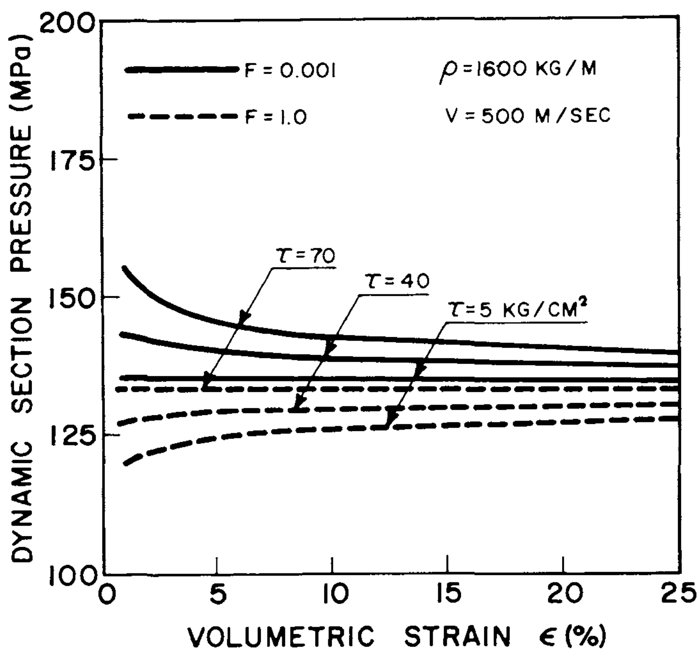

Fig. 8. Dynamic Section Pressure at High Velocity

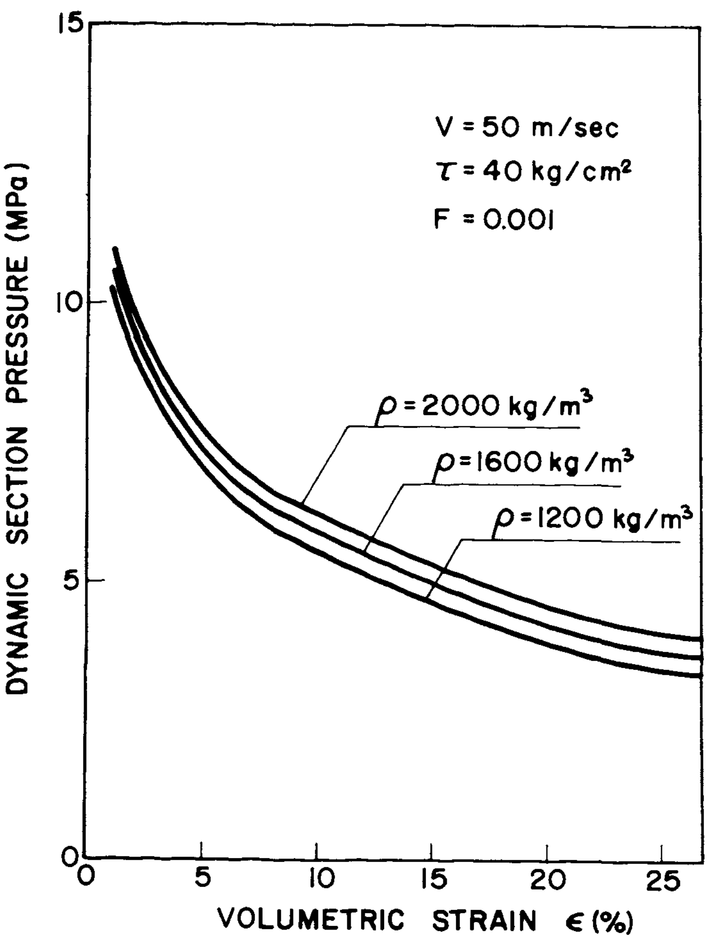

Fig. 7. Effect of Mass Density at Low Velocity

c. The dynmaic section pressure is not sensitive to the mass parameter except for very high velocities.

CONCLUSIONS

Parameter study has been performed with aid of a new penetration model. Penetration is found to cause a local disturbance which is limited to a few projectile diameters. The size of the projectile zone is strongly dependent by the columetric strain. The displacement gradient near the projectile boundary is independent of the volumetric strain, but at increasing radial distance the gradients decrease when the volumetric strain is smaller.

At low velocities the dynamic section pressure is strongly dependent on the principal stress difference at failure and the magnitude of the volumetric strain, and is insensitive to the magnitue of the soil density.

An opposite trend is observed at high velocities.

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