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# DYNAMICS LOAD PENETRATION FUNCTIONS FOR IMPACT ANALYSIS

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ABSTRACT

Experimentally determined penetration resistance vs. depth curves for dynamic normal penetration of rigid cylinders against ductile (lead) targets and fragile (gypsum) targets are presented in the paper. Three head types as well as three different projectile diameters were used to evaluate potential size and geometrical effects. The results are compared with similar data obtained in static experiments, described in a previous contribution.

## 1. INTRODUCTION

The study of penetration of solid media by rigid and deformable projectiles has been undertaken by means of both theoretical (Forrestal 'et al',1981;1986; Longcope 'et al',1981) as well as purely experimental procedures (Haldar & Hamieh,1984). Penetration is also a relevant aspect of the initial stages of projectile impact leading to scabbing and perforation of plates and shells.

The problem of penetration following low velocity impact has great practical importance in the design of protective structures in Nuclear Power Plants (NPP), as well as in risk analyses of NPP and other engineering applications. As a consequence of this pressing need, a number of empirical or semi-empirical equations have been proposed to predict penetration (Riera,1989), but their use is hampered by an insufficient knowledge of the importance of various factors that may also influence the target response.

In order to contribute to the development of a sound formulation, an experimental program aimed at the determination of load-penetration functions under displacement-controlled static and also under low velocity impact tests was initiated in 1989 at the LDEC (UFRGS). In a previous paper, Tamagna & Riera (1991) described the results obtained in the static tests. Herein, resistance vs. penetration curves measured under impact conditions are presented. The marked difference in behaviour of ductile and fragile target materials is discussed in conjunction with other governing factors, such as head geometry and size effects.

## 2. DESCRIPTION OF THE EXPERIMENTAL PROGRAM

Circular cylindrical penetrometers approximately 100 mm long with exchangeable heads were used in both the static and the impact experiments. The penetrometers were provided with strain gages calibrated to measure the net axial load. In order to evaluate size effects, three penetrometer diameters (7, 10 and 13 mm) were used, as well as three head types: flat, spherical and conical (1:3). To approach the ideal conditions expected in case of a perfectly rigid projectile, the heads were fabricated of heat-treated high strength steel, achieving hardness 55 Rockwell

To model the target, idealized in most theoretical approaches as a half-space, a circular cylinder with height and diameter equal to 250 mm was used. The target material was encased within a steel tube, designed to provide a static stiffness equivalent to that of the (missing portion) of the half space.

Gypsum was chosen as a typical fragile target material, and lead as representative of a target material that can undergo large plastic deformations. The mean tensile strength of gypsum, measured in diametral compression tests on 50 x 100 mm cylinders was f = 0.626 $N/mm^2$, with a CV of 4%. The compressive strength of cylinders of the same size had a mean value f'= 2.80 $N/mm^2$, with a CV of 6%. Compact tension tests led to a Gf value of approximately 50 N/m. On the other hand, the tensile strength of lead was measured in rectangular bars 400 $mm^2$ long, with a cross-sectional area of 320 $mm^2$, resulting a mean value f = 13.4 $N/mm^2$.

The driving force and penetrometer displacement were measured by means of a bridge-amplifier and piezoelectric accelerometers fed into a data acquisition system controlled by a microprocessor. In the impact tests, 8000 points per second were acquired. The penetration velocity and displacement, obtained by integration of the acceleration records, were corrected if necessary by comparison with total penetration.

## 3. EXPERIMENTAL RESULTS

The variation of the penetration stress, i.e. the total driving force referred to the penetrometer cross-sectional area, with the penetration to diameter ratio, is shown in Fig. 3.1 for the ductile (lead) target and in Fig. 3.2 for the fragile (gypsum) target. Both set of results correspond to low velocity ($V < 10$ m/s) impact conditions.

The influence of skin friction, already observed in the static experiments, is also clearly perceptible in the impact tests. The nondimensional ß factor, defined by Riera(1989) and Tamagna & Riera (1991) as the ratio between the penetration stress and the compression strength of the target material, is useful to detect the relative influence of various factors. Thus, Table 3.1 presents values of ß, computed at a penetration/diameter ratio equal to 3, for the ductile target, which is considered an adequate estimator of ß , the asymptotic tip resistance factor.

TABLE 3.1. Values of ß(3) for the ductile target

| Diameter | Cone | Bullet | Flat | Mean |
|---|---|---|---|---|
| 7 | ---- | 18.5 | 11.1 | 14.8 |
| 10 | 11.6 | ---- | 13.6 | 12.4 |
| 13 | 15.2 | 18.4 | 16.8 | 16.8 |
| Mean | 13.4 | 18.4 | 13.8 | 15.0 |

TABLE 3.2. Values of ß(3) for the fragile target

| Diameter | Cone | Bullet | Flat | Mean |
|---|---|---|---|---|
| 7 | 9.3 | 9.6 | 8.6 | 9.2 |
| 10 | 6.1 | 7.6 | 4.4 | 6.0 |
| 13 | 3.6 | 3.7 | 8.6 | 5.3 |
| Mean | 5.3 | 6.0 | 7.2 | 6.8 |

TABLE 3.3. Values of ß for fracture initiation

| Diameter | Cone | Bullet | Flat | Mean |
|---|---|---|---|---|
| 7 | 11.7 | 9.1 | 6.7 | 9.2 |
| 10 | ---- | 6.2 | 5.1 | 5.6 |
| 13 | 7.0 | 3.2 | 4.5 | 4.9 |
| Mean | 9.3 | 6.2 | 5.4 | 6.7 |

Inspection of the results given above shows that (a) in connection with the tip resistance there is no significant size effect, (b) there is no perceptible rate stress or strain rate effect, (c) the N-factor commonly used to account for the influence of head geometry is not reliable. In fact, the evidence suggests that static resistance vs. depth curves may be employed for prediction of penetration under impact conditions.

Similar information for the fragile target is given in Table 3.2. Moreover, Table 3.2 shows the ß factors corresponding to the first peak in the resistance-penetration diagrams. In almost all the tests with the gypsum target, a steep resistance increase at the beginning of penetration is followed by a sudden drop of the driving force, which is attributed to fracture. Since the speed of unstable fracture propagation, estimated at around 38% of the P-wave velocity, largely exceeds the penetration velocity, fracture may be assumed to occur instantaneously, at which point the resistance suddenly drops. For fragile materials, a very significant size effect should be expected, as confirmed by the experimental results.

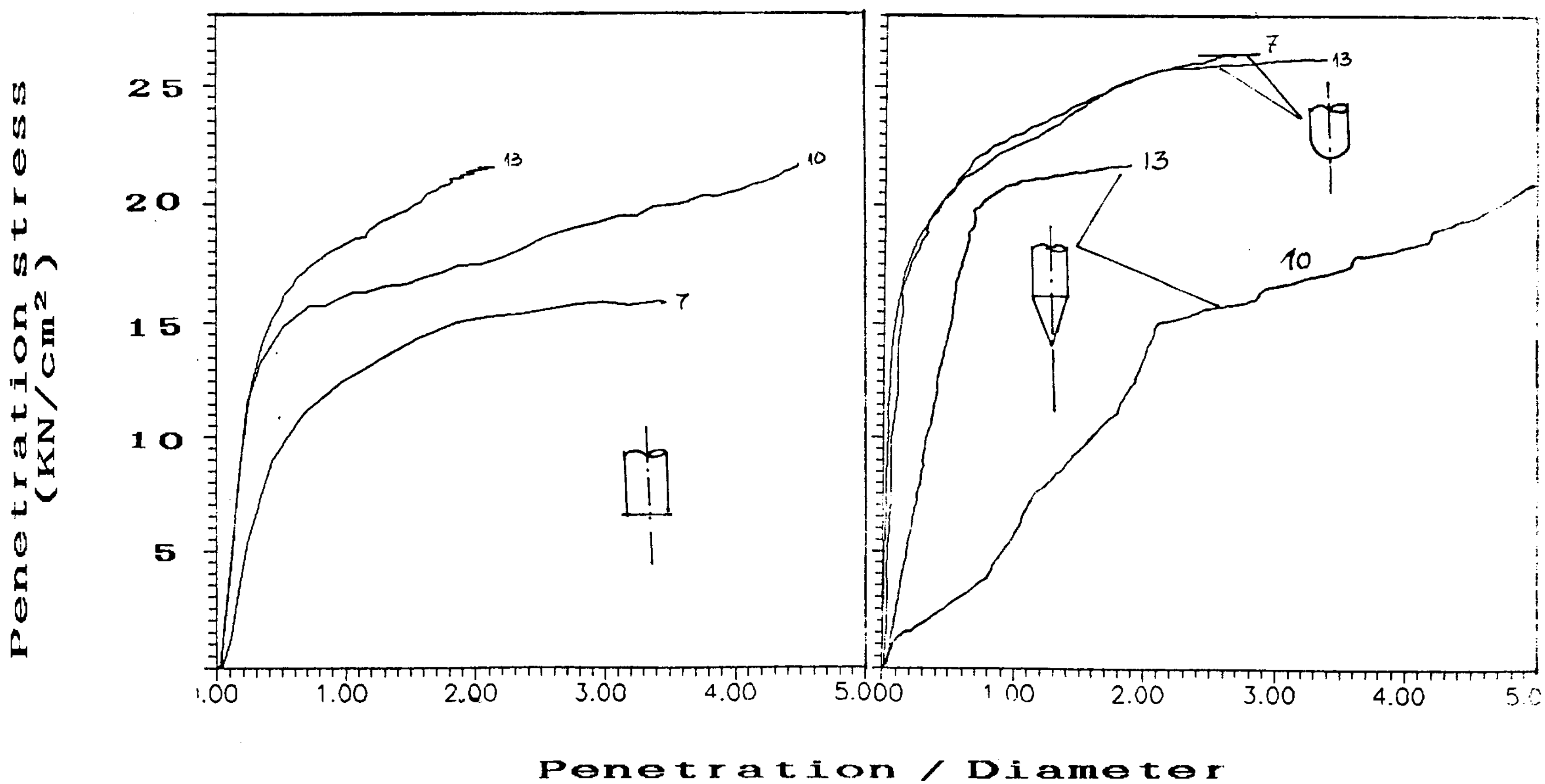


**FIG. 3.1** Penetration stress vs. penetration depth in ductile targets (lead) for different head geometries.

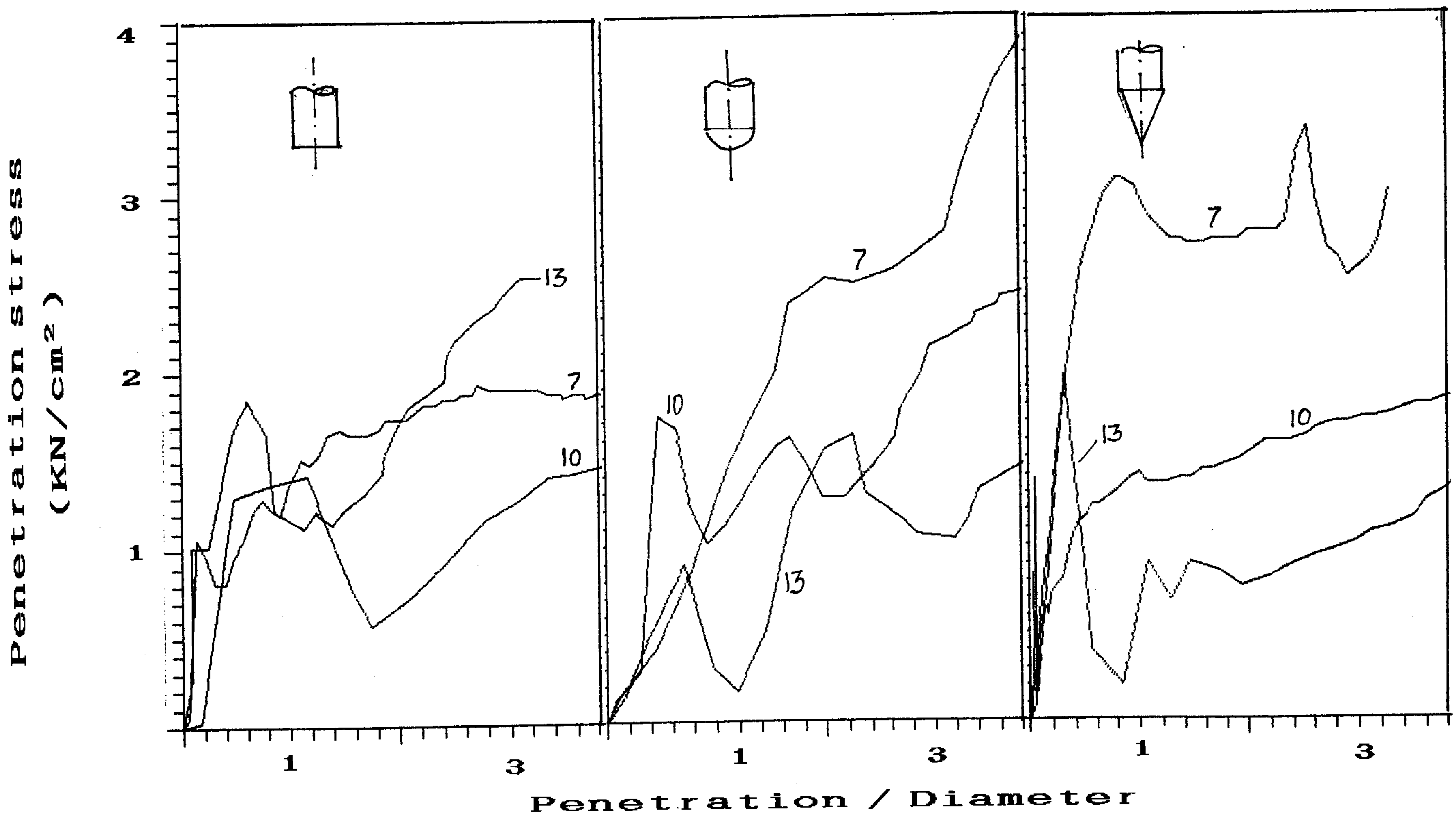


**FIG. 3.2.** Penetration stress vs. penetration depth in fragile targets (lead) for different head geometries

In addition, the resistance under impact is somewhat lower than in the static tests. It is likewise verified that the N-factors recommended in the literature to account for the influence of the head geometry are not meningful at all in case of low fracture resistance and require a complete revision. It is finally noted that the contribution of the skin friction to the total force responds to a scaling law that differs from that applicable to the tip resistance.

## 4. CONCLUSIONS

The mechanics of penetration in solids is a very complex phenomenon that precludes the use of simple prediction equations except under very restricted conditions. On the basis of the experimental results discussed above it may be concluded that:

(a) The tip resistance in fragile targets presents a pronounced size effect, which negligible in ductile targets.
(b) The resistance due to skin friction is governed by a different scaling law.
(c) The influence of head geometry cannot be quantified by means of a single N-factor.
(d) The ß factors given in Tables 3.1 and 3.2 may be used to compute approximate values of the asymptotic tip resistance.

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