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Low speed penetration in solids

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ABSTRACT: This work presents a study of penetration in solid media by rigid bodies. Experimental results, empirical and theoretical equations for fragile and ductile material are showed, comparing the tip influence of penetrometers and target material.

1 Introduction

The study of penetration of solid media by deformable and rigid bodies at low velocity has a great importance in the the design of NPP and others structures. A number of empirical or semi-empirical equations have been proposed to predict the penetration depth for engineering purposer, with variable degree of success.

In order to contribute to the study of this problem, an experimental program was planned to determinate the load-penetration functions for low velocity impact (up to 4 m/seg). In previous papers [2] [3] Tamagna and Riera described the results of the first static and impact tests. In this work all the experimental data collected is presented. It is shown that a simple theoretical model fits weel the experimental results.

2 Experimental program

A circular cylinder with diameter and height equal to 250 mm was used to model the target. Gypsum was chosen as a typical fragile material and lead as a ductile material. The characterization of gypsum was made by means compression tests [1]. On the other hand, the compression strength of lead was measured in rectangular bars in flexure [1]. In all cases the target material was encased within a steel tube , designed to provide a static stiffness equivalent to that of the half space.

Circular cylindrical penetrometers approximately 100mm long with exchangeable heads were used in both static and dynamic experiments. The penetrometers with 7, 10 and 13 mm diameter were used with calibrated strain gages to measure the net axial load. Three types of head were used: conical, spherical and flat, fabricated using heat-treated high strength steel, and achieving hardness 55 Rockwell C.

The penetrometer displacements were measured by means of accelerometers fed into a data acquisition system controlled by a microcomputer.

3 Experimental results

The experimental results are presented as penetration functions, that is normalized-stress vs. adimensional penetration. The normalized stress is the penetration force divided by

the transversal area of penetrometer times a reference stress. The reference stress used for lead was 2 KN/cm² [1] and for gypsum 0.28 KN/cm² [1]. The general expression for the penetration function is:

$$\beta\left(\frac{x}{d}\right) = \frac{F}{A \cdot Y} \quad (1)$$

where: x: tip penetrometer displacement, A: penetrometer area, Y: reference stress, β : penetration function.

3.1 Static tests in lead

The figure 1 shows the curve of average values of the function beta. The tip influence is very clear, the initial concavity in the cone tip curve, the intermediate position of the spherical tip and the strong inclination of flat tip curve. The friction coefficient is the same in all curves because the ending slope of the curves are the same.

Figure 2 presents the average values for each kind of penetrometer tip without the influence of the lateral friction. It is possible to conclude that the asymptotic normalized stress is similar in all cases.

3.2 Dynamic lead tests

The results of the dynamic lead tests are given in the form of average curves that represent the penetration function for each type of head, as shown in figure 3. The influence of the tip, as in static tests is clear. If the dynamic and the static tests results are compared, the friction influence is lower in the dynamic tests.

3.3 Static test in gypsum

Figure 4 shows the averages curves that represent the function β for each type of head.

3.4 Dynamic gypsum tests

Figure 5 shows the penetration function for three heads: conical, spherical and flat. It is observed that the function beta for the conical head penetrometer is lower than in the spherical and flat head penetrometer.

4 Regression analysis

In this section, functions obtained by nonlinear regression analysis on the experimental data are presented. The choice of the function is based in the following facts: 1) The typical behavior of the penetration curves for the different tips, 2) when the friction is not considered all the curves are asymptotic to an horizontal line. The regression technique is applied with the average values of the normalized stress for each type of tip.

FIGURE 1 - STATIC TESTS IN LEAD

FIGURE 3 - DYNAMIC LEAD TESTS

FIGURE 2 - STATIC TESTS IN LEAD

FIGURE 5 - DYNAMIC GYPSUM TESTS

FIGURE 4 - DYNAMIC LEAD TESTS

FIGURE 6 - STATIC TESTS IN LEAD, CONICAL HEAD WITH FRICTION

FIGURE 7 - STATIC TESTS IN LEAD, SPHERICAL HEAD WITH FRICTION

FIGURE 8 - STATIC TESTS IN LEAD, FLAT HEAD WITH FRICTION

The functions selected are:

spherical and flat penetrometer heads

$$\beta(\zeta) = A_1(1 - e^{-A_2\zeta}) + A_3\zeta \quad (2)$$

conical head

$$\beta_1(\zeta) = A_4\zeta^2, \quad \beta_2(\zeta) = A_1(1 - e^{-A_2\zeta}) + A_3\zeta$$

$$\beta(\zeta) = \frac{\beta_1(\zeta) \cdot \beta_2(\zeta)}{\beta_1(\zeta) + \beta_2(\zeta)} \quad (3)$$

where: A_i : adjustable parameters, $\zeta = x/d$

The parameters for all cases are given in the following tables

Table 1. Static lead tests.

Head	A_1	A_2	A_3	A_4
Conical	6,4	1,4	1,4	8,6
Spherical	4,7	3,1	1,8	-
Flat	7,2	5,1	1,0	-

Table 2. Static lead tests without friction.

Head	A_1	A_2	A_3
Conical	8,1	2,6	7,1
Spherical	6,3	2,3	-
Flat	7,3	4,5	-

Table 3. Dynamics lead tests.

Head	A_1	A_2	A_3	A_4
Conical	10,8	47,2	0,3	0,6
Spherical	10,1	1,9	1,2	-
Flat	8,1	3,2	0,6	-

Table 4. Static gypsum tests.

Head	A_1	A_2	A_3	A_4
Conical	17,1	1,1	0,0	5,6
Spherical	14,4	0,7	1,1	-
Flat	5,4	2,6	1,8	-

Table 5. Dynamics gypsum tests

Head	A_1	A_2	A_3	A_4
Conical	6,5	1,0	1,1	17,8
Spherical	9,1	1,3	0,1	-
Flat	4,1	5,0	1,4	-

The figures 6 to 13 show the comparison between the regression and experimental curves.

5 Theoretical results

The theoretical expressions are obtained considering the following hypotheses: 1) the penetrometer is indeformable 2) the target is made of an elastic-plastic material, then the problem is axisymmetric. It is considered that the solid is divided by layers. When the penetrometer tip crosses a layer the expansion of cylindrical cavity is considered [3],[1]. The final penetration force is obtained integrating the contribution of each elementary layer. The static adimensional penetration force for the conical penetrometer head is:

$$\beta\left(\frac{z}{d}\right) = \frac{d^2}{\sqrt{3}\ell^2} \left[1 + \ln \frac{\sqrt{3}E}{(5-4\nu)Y} \right] \left(\frac{z}{d} \right)^2 \quad (4)$$

It is also possible to calculate the penetration function for spherical tip considering an equivalent conical tip replacing the real spherical head [1]. In other words, one can substitute the final ratio of the conical head by the variable spherical ratio. Then the static adimensional penetration force for the spherical penetrometer heads results:

FIGURE 9 - DYNAMIC LEAD TESTS, CONICAL HEAD

FIGURE 11 - DYNAMIC GYPSUM TESTS, CONICAL HEAD

FIGURE 10 - DYNAMIC LEAD TESTS, SPHERICAL HEAD

FIGURE 12 - DYNAMIC GYPSUM TESTS, SPHERICAL HEAD

FIGURE 13 - DYNAMIC GYPSUM TESTS, FLAT HEAD

FIGURE 14 - STATIC LEAD PENETRATION, WITHOUT FRICTION

FIGURE 15 - STATIC LEAD PENETRATION, CONICAL HEAD, WITHOUT FRICTION

FIGURE 16 - STATIC LEAD PENETRATION, SPHERICAL HEAD, WITHOUT FRICTION

$$\beta\left(\frac{z}{d}\right) = \frac{4}{\sqrt{3}} \left[1 + \ln \frac{\sqrt{3} E}{(5-4\nu)Y} \right] \left(\frac{z}{d} - \frac{z^2}{d^2} \right) \quad (5)$$

Figure 14 shows the penetration functions calculated with eqs. 4-5. Figure 15 compares theoretical and experimental results for static lead tests. For conical head penetrometers, the correlation is considered good taking into account the simplifications of the theoretical model. Figure 16 presents a comparison of results for spherical tip penetrometers, it is considered a good agreement between the curves.

6. Conclusions

The empirical functions proposed, for each case, show good correlation with the experimental results. That functions take into account the head influence.

Theoretical model, despite of its simplicity, leads to satisfactories results for static penetration in elastoplastic solid media.

Ductile dynamic penetration forces result larger than ductile static penetration forces, especially for the conical head.

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