Failure Mode of Soils During Static and Dynamic Penetration

by

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Introduction

Well established bearing capacity formulae are available for estimation of foundation load for static condition. Most of these formulae are derived by assuming a failure pattern based on laboratory studies and field performance. The demands of foundation that are properly designed for dynamic load have increased the need for further research effort. The proper design of foundation for dynamic load requires a clear understanding of various factors such as the strain rate effect, inertial effect, and modes of failure. The first two factors are broadly discussed by Whitman (1970) and for a particular case of low velocity penetration by Dayal and Allen (1975). The scope of the present paper is limited to third factor, i.e. modes of failure during dynamic loading.

In order to study the difference, if any, in failure pattern during dynamic loading, constant velocity penetration tests were performed on a two dimensional target. The experiments provided a means of viewing sub-surface soil movement associated with penetration of the penetrator. The tests were performed at velocities ranging from 0.0044 fps (0.13 cm/s) to 2.662 fps (81.14 cm/s) onto the soil target varied from gravelly sand through to clay of various strength and moisture content.

The Experimental Procedure

The experiments consisted of driving a penetrator in to a prepared soil target at various speeds. The penetrator was coupled to a hydraulic actuator which in turn was connected to a structural laboratory's 'Material Testing System' (M.T.S.) which provided the required velocity and controlled penetration. The velocity and penetration depth for any particular test could be adjusted from M.T.S. speed and stroke console. The maximum velocity of 2.66 fps (81.1 cm/s) and a stroke of 2 ft (61 cm) could be obtained from this system.

The target tank used for this test was 12 in. (30.5 cm) wide by 24 in. (61 cm) high and 1.5 in. (3.8 cm) thick so that either a half-sectional or a complete - rod penetrator of 1.4 in. (35.6 mm) diameter could enter with mininum friction on its front or back. The front face of the target tank was of 3/4 in. (19 mm) thick plexiglas to permit observations of the movement of the target material during penetration.

To facilitate the visual observations of the movement of the soil, a reference grid was required. Following the required compaction, the

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This paper was received in August, 1980 and is open for discussion till the end of January, 1982.

cover of the container was firmly clamped against the top surface of the soil. The container was then placed on one side, levelled, and the exposed plexiglas side removed. Two methods of marking the grid were tried. In the first method, as suggested by Peck (1962), two square frames of thin angle iron section, the same size as the plexiglas plate, were constructed. A series of cords, spaced 1 in. (25.4 mm) apart, were stretched between the opposite sides of the frame. In one frame the cords were stretched horizontally and in the other frame they were stretched vertically. To make the grid, the cords were dusted with coloured marking powder, and the frame was placed in position on the exposed surface of the soil, the cords being just clear of the soil surface. Each cord was then flicked, leaving a thin coloured line on the surface. The procedure was repeated with the other frame to draw the lines at 90° to the previous ones and thus, the grid of 1 in. (25.4 mm) was obtained on the exposed surface. The second method was that used by Selig (1961), the grid lines being formed by coloured sand sprinkled on a slotted plexiglas frame. There again, two frames were used of the same dimensions as that of the removable plexiglas, with horizontal and vertical slots.

After drawing the grid, the removable plexiglas plate was again replaced and tightened in position. The container was placed upright, ready for testing. Both procedures mentioned above have been tried and it was found that in case of dry sand and very soft clay samples, the second method was more satisfactory, whereas, for compacted and moist soils the first method gave the best results.

Each test was filmed with a high speed 16 mm movie camera. The films were later projected on the screen for sequential studies of the failure pattern during penetration.

Table 1 gives the details of defferent penetration velocities which have been used in this programme on various types of target materials. The index and strength properties of the soil targets are also included in this table. The majority of the tests were performed on target prepared from Silica Sand and pottery clay. These materials were used to simulate the clay and sand targets. A few tests were also performed on targets of gravelly sand and of mixture of silica sand and pottery clay. These materials were selected because they were readily available in large quantities and provided uniform target materials.

Test Results and Discussion

Figures 1 and 2 show typical photographs taken before and after the test on very soft clay target using half-sectional penetrator at a constant penetration velocity of 2.66 (81 cm/s). It can be seen that the particles at a distance greater than approximately $2D$ (D = penetrator diameter) away from the penetrator centre line are not affected during the penetration.

The distortion of the horizontal and veritcal grid lines indicate that within the disturbed zone the particles move downward and away from the penetrator. A uniform soil nose is formed on and around the tip of the penetrator which pushed the soil mass downward and outward.

Based on the sequential study of the failure patterns obtained for various penetration velocities at different depths of penetration for target materials

TABLE 1

Summary of Test Details

Test No.	Target material	Target strength	Test velocities used (in fps)				Maximum variation of velocity
			0.0044	0.0420	0.0456	2.6620	
1	Moist gravelly sand	$\gamma_t = 109$ pcf	X	—	—	X	600
2	Sand medium sand size 37 per cent fine sand size 63 per cent	Lose dry sand $\gamma_d = 85.5$ pcf $\phi = 31°$	X	X	X	X	600
3	,, ,,	Dense saturated sand $\gamma_d = 88.5$ pcf $\omega = 27$ per cent $\phi = 41°$	X	X	X	X	600
4	Pottary clay silt size 58 per cent clay size 42 per cent Plastic limit 21 per cent Liquid limit 37 per cent Plasticity Index 16	Soft clay $\gamma_d = 82.2$ pcf $\omega = 35.4$ per cent $C_u = 200$ psf	X	X	X	X	600
5	,, ,,	Medium stiff clay $\gamma_d = 90.8$ pcf $\omega = 25.4$ per cent $C_u = 960$ psf	X	X	X	X	600
6	,, ,,	Stiff clay $\gamma_d = 90.6$ pcf $\omega = 22.5$ per cent $C_u = 1670$ psf	Y	X	X	X	600
7	Sand-clay mixture medium sand size 15 per cent Fine sand size 30 per cent Clay size 35 per cent Silt size 30 per cent	$\gamma_d = 101.6$ pcf $\omega = 17$ per cent $C = 400$ psf $\phi = 15°$	X	X	X	X	600

Note: psf=47.9 Pa, 1 pcf=0.016 gm/cm^3, 1 fps=0.305 m/s, X=Test performed.

ranging from gravelly sand to clay of various strength and moisture contents, the following conclusions could be drawn :

(1) There is no significant difference in failure patterns obtained at the higher velocity (2.662 fps; 81 cm/s) or low velocity (0.0044 to 0.042 fps; 0.13 to 1.3 cm/s) penetration tests. The ratio of high (dynamic) to low velocity (static) varied between 60 and 630.

(2) In higher velocity tests, the formation of craters were generally observed up to a depth of 0.1 to 0.2 in. (2,5 to 5 mm) below the target surface.

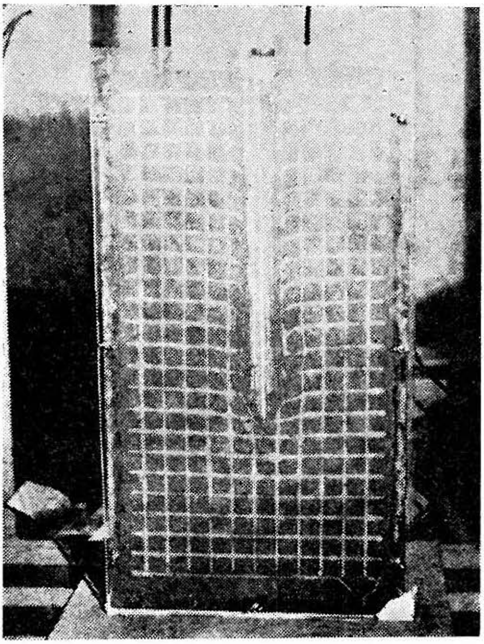

FIGURE 1 Formation of 1 inch grid on a very soft clay sample

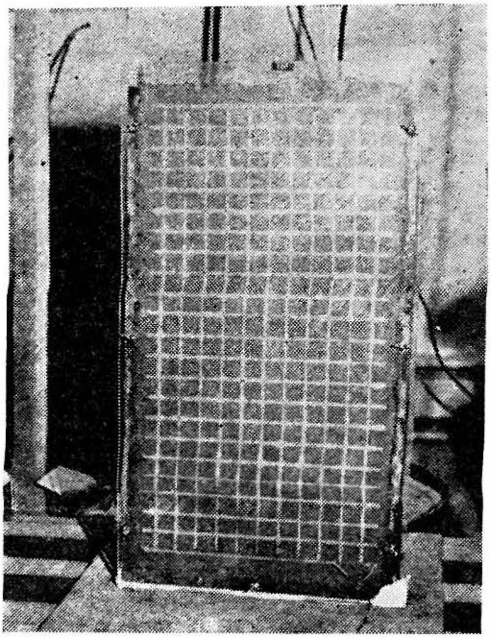

FIGURE 2 Distorted grid after higher velocity (2.66 fps) penetration.

(3) From the failure patterns observed for different types of solids at different densities and at different moisture contents, it may be inferred that the failure apparently occured principally through two mechanisms; shearing (general shear failure) and punching (local shear failure). In contrast to the general shear type of failure where a well defined shear planes are obtained, local shear failure occurs when the shear planes are not well defined. In the latter mode of failure a 'plastic' or 'sheared' zone is formed near the edge of the footing causing the punching effects. The shearing and punching failure patterns, as studied from the high speed movie are shown in a simplified form in Figure 3 (A and B), respectively. In dense, well-packed or tightly bound soils, penetration occured primarily by shearing. This is substantiated from the study of the distoration of the grids, and the fact that the radial cracks extending to the surface and the upheavel of the materials around the penetrator were generally seen in the case of the penetration of the densely packed sandy soils. In loose soils and in saturated clay, penetration was accomplished chiefly by punching as seen in Figure 2.

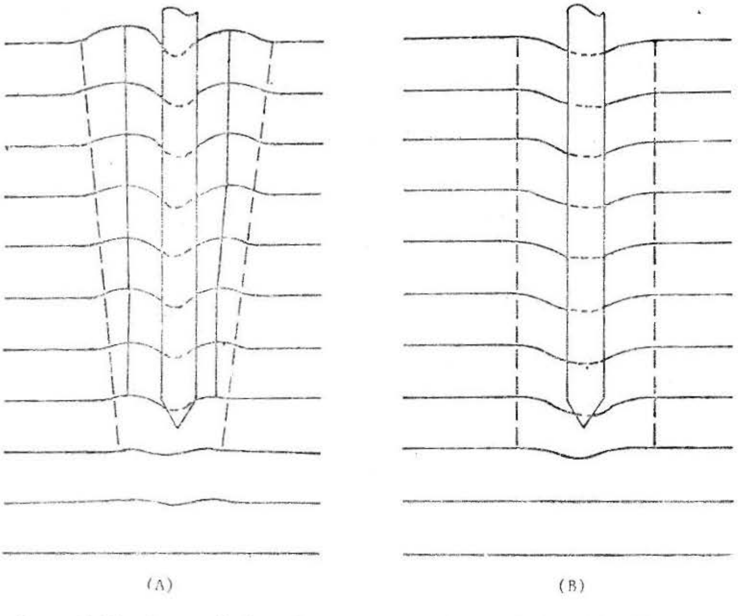

FIGURE 3 Failure patterns

(4) The movement of the soil beneath the penetrator was predominatly downward and outward.

(5) The soil nose formed on and around the conical-tip of the penetrator was clearly visible in all the cases. Both for low and higher velocity penetration the size and shape of the soil nose, for any particular target, was more or less constant for all depths of penetration. There appears to be a shear front, defined as the line bounding the zone in which no shearing of the medium has occur-

red, travelling with the penetrator at a constant depth (1.5 *D* to *D*) from the tip of the penetrator.

Various investigators have studied the modes of failure durig dynamic loading and the findings of several are briefly discussed here. Seling and McKee (1961) found that failure modes are different in dynamic loading than in the static loading for sand. The dynamic test resulted in a local shear failure rather than the classical general shear type failure. Cunny and Sloan (1962) have also observed local shear failure while Shenkman and McKee (1961) observed general shear failure for dynamically loaded footings.

Jackson and Hadala (1964) performed some static and dynamic load tests on footings resting on clay. The visual observations of the failure patterns indicated that the static and dynamic failure modes were significantly different. In the dynamic tests there appeared to be a slight heave of the soil surface around the footing where the soil surface around the statically loaded footing experienced upward movements and crack developed from the four corners of the footing and extended outward. The slightly heave around the dynamically loaded footing was characteristic of local shear failure.

Thomson (1966) performed two-dimensional constant velocity penetration tests on needle bearing rollers for velocities ranging from 0.15 to 0.367 fps (4.57 to 11.19 cm/s) and also two-dimensional impact penetration tests on Ottawa sand for impact velocities ranging from 106 to 478 fps (3231 to 1457 cm/s). Based on the distorations of the grids, obtained by a high speed movie camera, he concluded that the deformation patterns observed for penetration tests were quite similar to those seen in constant velocity penetration tests and the displacements of the particles was very similar to the displacement initially approximated by Prandtl for the identation of an infinitely long footing or punch into half space of rigid plastic weightless material. Similar observations can be interpreted from constant velocity penetration test results obtained by Clop (1965) and Chou (1972) for simulated and cohesionless and cohesive soils, respectively.

The overall results of the various investigators somewhat confusing in that some observed the general shear type and others found punching shear type of failure for dynamically loaded footings. The reasons for discrepancies in the results are legion. Besides the variation in soil type, the shape and size of footings, the various investigators used different testing systems such as, controlled stress device, controlled displacement device, and the dropping of weights, to achieve dynamic conditions.

In fact, it is difficult to conceive a unique applicable to all problems pertaining to dynamic loadings because each problem is constrained by different boundary conditions. However, based on the previous studies and present experimental investigations, it is implied as a first approximation that in the case of densely packed target the general shear failure criterion can be adopted, while in loosely packed sandy samples and soft clay samples, the local shear failure criterion can be adopted for the dynamic penetration of the soil media.

Conclusions

The modes of failure during static and dynamic penetration was studied by viewing the failure the patterns in two-dimensional penetration tests performed at velocities ranging from 0.0044 fps (0.13 cm/s) to 2.66 fps (81 cm/s).

It is noted that even the 600 fold increase in penetration velocity does not cause any significant difference in failure patterns. From previous studies and present experimental investigations it is inferred as a first approximation that local and general shear failure criteria as used in case of static loading can be adopted for the dynamic penetration of soil media.

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