Borehole Shear Test for Stiff Soil

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Introduction

The Iowa Borehole Shear Test (BST) is a rapid, direct shear test performed on the walls of a borehole in soil. The test measures in-situ soil shear strength by failing the soil along the circumference of the hole. Sharply ridged, diametrically opposed shear plates are expanded by gas pressure to apply a normal stress against sides of the hole, Fig. 1(*a*). A shearing stress is then applied by pulling the plates axially along the hole while maintaining a constant normal stress until failure occurs. By repeating the test with different values of normal stress, a series of shearing stress values are obtained from which a Mohr-Coulomb failure envelope is drawn (Fig. 2). Allowing time for drainage between successive points permits interpretation of results on a consolidated-drained basis.

Stage Testing, Soft Soils

As pointed out by Schmertman (5), the Borehole Shear Test in current use is essentially a stage test in that shearing is induced repeatedly in the same soil mass, at successively higher normal stresses. This improves precision, saves time, encourages dissipation of pore pressures, and is allowable if the consolidated, drained cohesion (c') of soil close to the test plates exceeds that of the adjacent undisturbed soil; i.e., the previously sheared soil consolidates and builds up a cake that rides with the plates. In this way, successive shear surfaces move outward to engage fresh but nearly identical soil, [Fig. 1(*a*)]. The result is exceptionally linear failure envelopes in sands or soft-to-medium consistency clays (Fig. 2).

One limitation of the present device is that, in stiff soils such as heavily overconsolidated clays and glacial tills, the shear plate teeth of Fig. 1(*a*) slide over the soil surface and only scrape deeper with each successive pull until the teeth are filled. Initial penetration of adjacent wedges as in the conventional shear plate design, should cause interference between individual failure surfaces in hard materials, preventing full penetration of the teeth. As a result, no soil cake builds up, and the test essentially measures sliding friction of disturbed

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soil against undisturbed soil. This gives an erroneously low or even negative value of cohesion and a tendency towards too high a friction angle because of the successive deepening of the "bite" and filling of the teeth with each test point.

Initial Plate Modifications

The problem of developing the BST for stiff soils initially was attacked by Yang (7) who tried several new plate designs with 40° rather than 60° symmetrical wedges, separated by intermediate "flats" equal to or slightly exceeding the

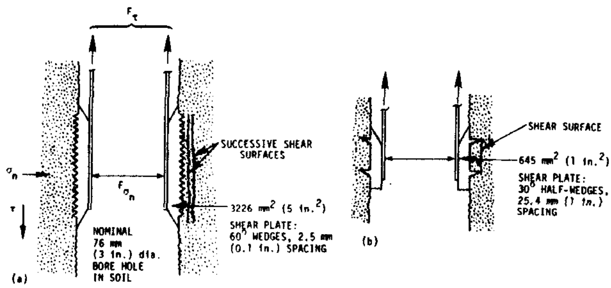

FIG. 1.—(a) Conventional Borehole Shear Test Shear Plate Design for Stage-Testing of Low-Cohesive Clays or Sandy Soils; (b) Shear Plate for Stiff Soils

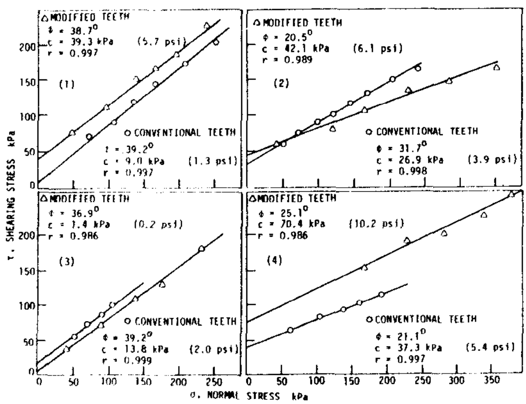

FIG. 2.—Borehole Shear Test Results with Modified and Conventional Teeth

wedge width. Cohesion as high as 120 kPa (17.5 psi) was measured by relocating the modified shear plates after each test, compared to 72 kPa (10.5 psi) for the same soil by the conventional plates with stage tests. Stage tests with the modified plates gave intermediate cohesions. This dependence of cohesion on plate design indicated that a more thorough investigation was needed (7).

Learning from Rock Tester

Substantial insight on the stiff soil problem was gained from research that successfully extended the Borehole Shear Test principle to the testing of rock, namely coal, sandstone, limestone, shale (2), and more recently, granite (unpublished communication). It was concluded that for rock it is desirable to space wedges out and rely on single tests at each rock contact position. Initial seating pressure of shear plates required for wedge penetration produces predictable rock damage, primarily a lowering of measured cohesion. A shear plate design of tooth-spacing 10 times the tooth depth leaves about 60%–80% of the enclosed surface unfractured, depending on φ (3).

TABLE 1.—Material Properties

Test (1)	Field density, in grams per cubic centimeter (pounds per cubic foot) (2)	Field moisture, as a percentage (3)	L.L., as a percentage (4)	P.I., as a percentage (5)	Sand >74 μm (6)	Silt 74 – 2 μm (7)	Clay < 2 μm (8)
1	2.20 (137.3)	18.4	25.0	11.0	48.9	35.3	15.8
2	2.25 (140.4)	14.4	26.0	12.0	47.7	36.1	16.2
3	1.91 (119.2)	26.8	31.7	4.6	0.7	80.2	19.1
4	2.08 (129.8)	16.4	35.0	17.0	33.6	39.0	27.4

TABLE 2.—Modified BST Versus Triaxial Test Results

	φ, in degrees		c, in kilopascals (pounds per square inch)	
Test (1)	BST (2)	Triaxial (3)	BST (4)	Triaxial (5)
1—Glacial till	38.7	26.8 (CD)	39 (5.7)	29 (4.2)
2—Glacial till	20.5	20.8 (CU) 25.0 (CD)	42 (6.1)	55 (8.0) 52 (7.6)
3—Loess	36.9	34.1 (CU)	1.4 (0.2)	0.0 (0.0)

Since for in-situ rock testing, wedge penetration is induced by preseating to a pressure that in many instances exceeds the normal stress selected for the individual test, the procedure was not directly applicable for soil because of the potential for preconsolidation at higher-than-test normal pressures.

For stiff soil, therefore, a half-wedge was adopted to allow a "slide-in" wedge penetration during shear in order to avoid the use of preseating pressures. The modified plates were reduced in area by a factor of five, allowing application of up to five times the normal and shearing stresses with the same expansion and pulling apparatus. The 30° half-wedge plate has a wedge spacing equal to 5.8 times the wedge depth [Fig. 1(*b*)]. The use of this new design requires a new position for each successive application of normal stress.

Results and Analysis

Borehole Shear Tests were performed at three sites in dense glacial till and at a fourth site in a much softer material (loess), using both conventional and modified shear plates. Characteristic properties are given in Table 1. Examination of the soil core aided in selecting zones of uniform material for testing. Results of four comparison tests are presented in Fig. 2. The value r is the correlation coefficient of a linear regression of the individual data points. In all cases, excellent linearity is indicated.

Results of the three glacial till tests using modified teeth all gave more cohesion than with the conventional teeth, while the test on the loess actually indicated slightly lower cohesion. The angle of internal friction, ϕ, was affected only at site 2 (see Fig. 2).

Comparative studies of BST and triaxial shear results have been made (1,4,6) with generally very close agreement. In some cases, the degree of drainage near shear plates was in question and BST results correlated more closely to consolidated-undrained triaxial test. This did not eliminate or include the possibility of incomplete drainage in triaxial tests.

For this preliminary study, undisturbed samples were taken from boreholes for triaxial comparison of tests 1, 2, and 3. Both consolidated-drained (CD) and consolidated-undrained (CU) tests were performed. The results given in Table 2 indicate the familiar ambiguities stated previously. In test 1 drained triaxial results gave a ϕ value lower than BST probably because of the development of undetected pore pressure. In tests 2 and 3, BST results were closer to the consolidated-undrained triaxial test.

By selecting adjacent positions for each shearing measurement, the effects of stage testing are eliminated; i.e., new stresses and strains are directly applied to a fresh soil shearing zone. The assumption now must be made that the material is homogeneous. As with all shear tests, judgment based on material characteristics and anticipated site conditions is still necessary for interpretation of results.

Conclusions

Where the BST has been used in soft materials, results have been successfully used for analysis of landslides and design of footings. However, borehole shear tests using standard conventional shear plates do not appear to give reasonable results in all materials, particularly in stiff soils, where low values of cohesion accompanied by high values of friction angle are commonplace. The modified shear plates give more realistic results in firm materials, adding a much needed improvement in the device and increasing its versatility. The plates and pulling strap are readily exchangable with the conventional plates, and the rest of the apparatus remains unchanged. The conventional plates should continue to be used for routine testing in soft to medium soils because of the larger plate area (and thus better sensitivity) and the time advantages in stage testing. Error from low cohesion is on the safe side for design. Where both types of plates are tried, the higher of the two shear envelopes should be used. Results should not be extrapolated beyond the pressure range tested and should be assumed to be on an effective stress, i.e., drained, basis.

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