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N. S. Fox
U.S. Army Corps of Engineers

R. A. Lohnes
Iowa State University

R. L. Handy
Iowa State University

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Depth Studies of Wisconsin Loess in Southwestern Iowa: IV. Shear Strength[1]

N. S. Fox, R. A. Lohnes, and R. L. Handy[2]

Abstract: This report is the fourth in a series of papers dealing with depth variations in the engineering properties of Wisconsin-age loess in Iowa. Previous studies have included graduation and in-place density (Davidson, et. al. 1953), clay and carbonate contents (Handy and Davidson, 1956), and organic matter, manganese and iron contents (Daniels et. al. 1960).

This paper discusses the variation of the Coulomb shear strength parameters c (cohesive shear strength) and ϕ (angle of internal friction) in the loess in a cut located in N. W. ¼ Sec. 3, T77N, R44W, Harrison County, Iowa. This cut was described in detail and proposed as a new type section for the Loveland formation by Daniels and Handy (1959). In general, the hill and cut consist of approximately 130 feet of post-Farmdale loess, over 12 feet of Farmdale loess, over 20 feet of Loveland loess, over oxidized calcareous Kansan (?) till. The upper 30 feet of loess is not cut and was not included in the description by Daniels et. al (1959). Below this, the upper 40′ of the cut has a slope of 50 per cent, and the lower 90 feet is cut into three near-vertical benches.

Review of Previous Work

Previous studies of shear strength parameters of loess sampled from the Loveland section were made by Olson (1958) using direct-shear tests and Akiyama (1963) using triaxial testing. Because of difficulties in trimming test samples and maintaining the natural moisture content, and because of the relatively arduous nature of the tests, relatively little could be concluded

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[2] Captain, U.S. Army Corps of Engineers; and Assistant Professor and Professor of Civil Engineering, respectively, Iowa State University, Ames.

regarding variations in shear strength with depth. Olson concluded that ϕ was 24.2° regardless of depth or moisture content, and that c was a function of preconsolidation and moisture content. Akiyama, running a consolidated-undrained test, found that ϕ was 28.5° and ϕ', in which correction is made for pore pressure, was 29.8°, with no apparent relation to depth, moisture content or density. Cohesion was of the order of 1 to 3 psi, depending on the moisture content.

Clevenger (1956), summarizing Bureau of Reclamation studies of Nebraska loess, indicated that ϕ varied from 31° to 33° regardless of moisture content, density, prewetting, or consolidation, but that cohesion did depend on moisture content and density.

Bore-Hole Shear Test

The present study was made possible by development of a new field test device that gives ϕ and c without the necessity for field sampling or the tedious laboratory trimming and testing of samples. The latter actually causes statistical bias because weak samples often break prior to laboratory testing. Extensive comparative studies have shown that data from the field device closely correlates with data from quick-undrained laboratory tests, ϕ usually agreeing to within 1° and c to within 1 psi (Fox, 1966). As an example of the efficiency of the new device, the tests described in this paper were completed in about 8 hours, or much less than the sampling time for comparable laboratory tests. By usual test procedures the time required would have been a matter of weeks.

The Bore-Hole Shear Test in effect performs a direct shear test on the trimmed sides of a bore hole. The device, shown in figure 1, is lowered at the end of a cable, and corrugated plates are forced outward to engage soil at the sides of the hole. The expansion pressure represents the normal pressure on the developed shear surface, or N in the Coulomb equation. After application of an expansion pressure, the device is pulled vertically up the hole at a controlled rate, and a separate measurement is made of the resistance to pull. The field set-up of the apparatus is shown in figure 2. The peak value of this resistance represents the shearing strength, S, of the soil. After the peak value is reached, the pulling force is reduced to zero, and the expansion pressure is increased to a new value of N. Application of a second pulling force enables a second value of S to be determined corresponding to the second N. A third value is similarly found, and the three points are plotted on a S vs. N coordinate system. A best-fit straight line determined by these points represents the Mohr-Coulomb shear failure envelope of

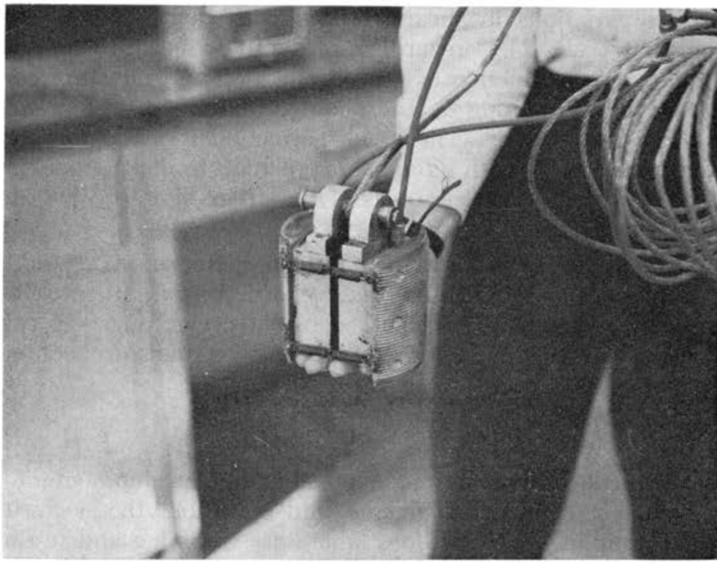

Figure 1. Expanding cylinder for bore hole test device.

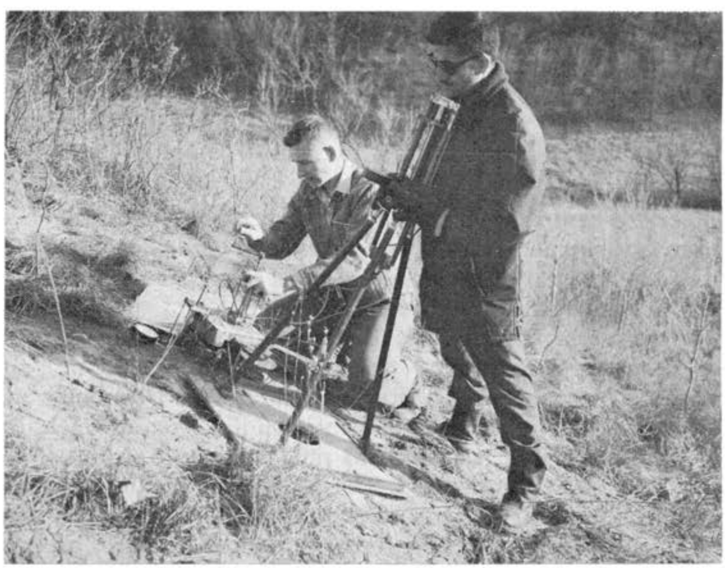

Figure 2. Field set-up for shear test.

the soil under the conditions of test, with the equation S = C + N tan ϕ. The slope of the line is the angle of the internal friction ϕ, and the intercept with zero normal pressure is cohesion c. Once c and ϕ values are known, the relationship may be used to predict the shearing strength under any normal pressure, for evaluation of stability of cuts, retaining walls, foundations, etc.

RESULTS

The shear strength parameters c and ϕ shown in Table 1 compare favorably with previously reported laboratory values, ϕ in most cases varying from 24 to 35°, and c varying from 0.7 to 4.3 psi. In addition several systematic relationships are shown.

Table 1. Field Test Data

Test No.	Vert. dist. from top of hill, ft.[a]	Depth in Hole, in.	c, psi	ϕ, deg.	Moisture Content, %	Remarks
1	0	2-9	0.7	24.0	17.2	
2	3	36-43	1.6	15.2	17.2	
3	33	27-34	1.7	31.3	16.0	31° from vert.
4	77	27-34	1.0	25.4	14.6	
5	99	27 34	1.4	29.5	16.0	
6	131	19-26	4.3	28.5	23.7	Farmdale
7	33	29-36	3.0	24.3	—	Repeats of
8	33	72-79	3.0	24.3	—	test 3, run
9	33	132-139	3.0	24.3	—	vertically
10	33	30-44	2.3	34.0	—	45° from vert.
11	33	30.44	2.6	35.1	—	Horizontal

[a]Equivalent depths of Daniels and Handy (1959) are 30′ less since they were measured from top of the cut rather than top of the hill.

Figure 3 shows a gradual increase in ϕ with depth. Two tests did not plot on this curve: Test 2, conducted a low-density loess at the top of the hill, and Test 3, which was not run vertically. Test 2 gave a low value for ϕ, probably relating to the loose loess structure. A similar value of ϕ at low normal pressures was reported by Akiyama (1963) for a higher clay content loess. The discrepancy of Test 3 led us to repeat it three more times vertically, tests 7, 8, and 9, all of which gave identical and more reasonable values of ϕ, 24.3°.

Cohesion also appears to vary somewhat with depth, as shown in figure 4. The repeats of Test 3 gave an even higher value of cohesion, but were probably influenced by a low soil temperature; tests 7, 8, and 9 were made on 11 March 1966, when the soil was near the freezing temperature. This would of course increase c significantly.

Test 6 of the Farmdale loess gave $\phi = 28.5°$, which is in line with other values, and $c = 4.3$ psi. The latter is higher than other values, and probably relates to density or percent clay.

The anomalous data from the non-vertical test at site 3 led to two additional tests, numbers 9 and 10, with shear planes inclined at 45° and 90° from the vertical. Results are plotted in figure 5, and indicate a gradual change in ϕ depending on orientation of the shear plane. Other materials are being tested to

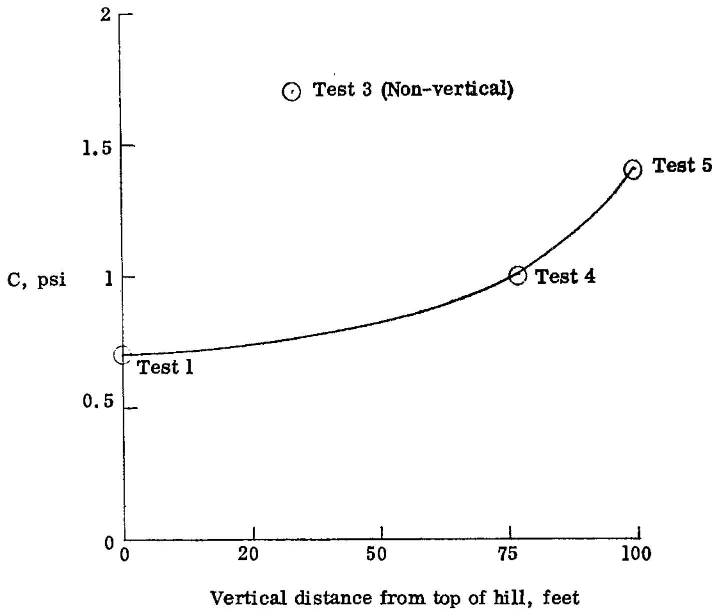

Figure 3. Relation between loess angle of internal friction ϕ and depth below top of the hill.

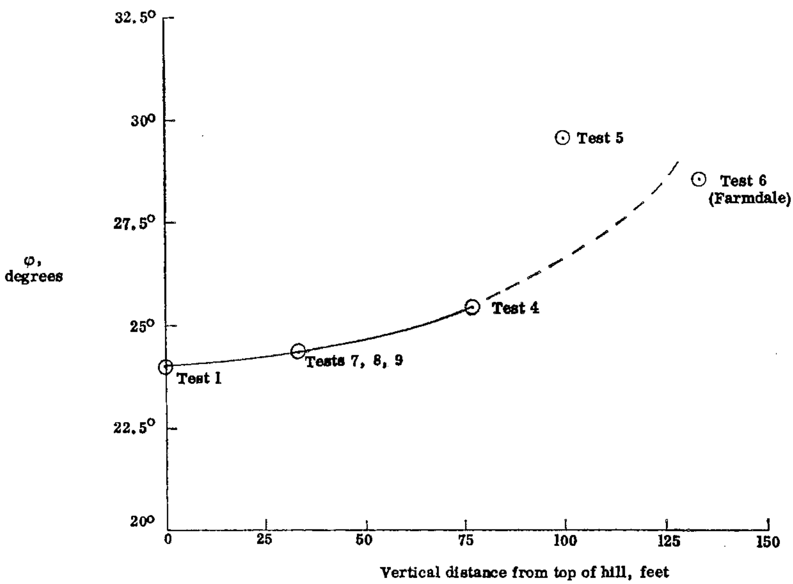

Figure 4. Relation between loess cohesion c and depth below top of the hill.

ascertain whether this is a characteristic of loess or of the shear apparatus. The implication of the data is that the shear strength of loess may be least in a vertical direction, which could explain the tendency to form vertical shear planes.

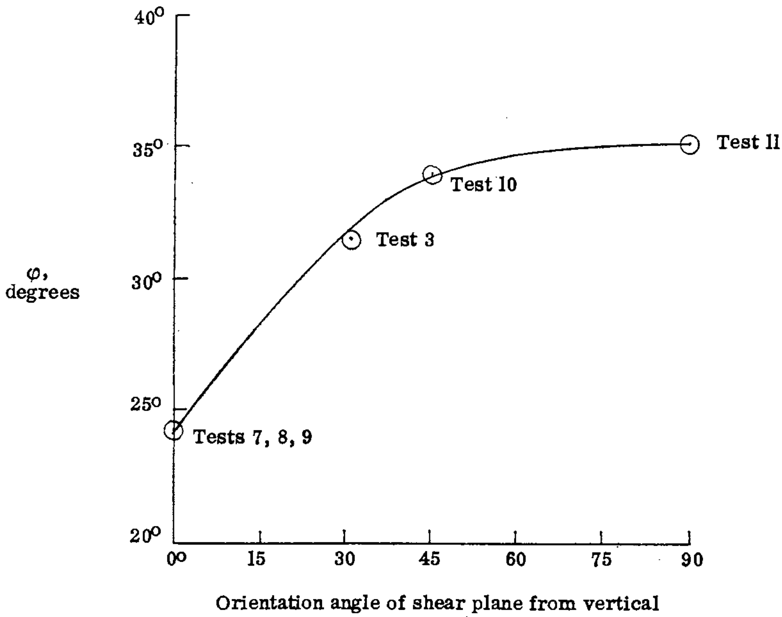

Figure 5. Effect of orientation of the shear plane on loess angle of internal friction ϕ at a depth of 33 feet, Loveland type section.

Vertical and horizontal bore-hole shear tests at five additional locations in western Iowa now indicate that horizontal shear strength is not consistently different from vertical, but averages about the same. The horizontal shear strength is more variable, probably relating to faint sandy stratification observable on weathered faces of the bluff-line deposits. These shear data are included in an article accepted for publication in the Journal of Geology, Vol. 76, 1968.

Discussion

The increase in ϕ with depth probably relates to an increase in density. Field measurements by Davidson et. al. (1953) indicate that loess density increases from about 70 to 90 pcf as depth increases from 0 to 100′, due to the consolidating pressure.

Similarly the increased cohesion may relate to density, although this parameter is more variable because of transitory influences of moisture content and temperature.

The apparent change in shear strength depending on orientation shear plane needs further checking.

Conclusions

1. The angle of internal friction of friable Wisconsin loess

exposed at the Lovland Type Section increases with depth, particularly below 90 feet.

2. Cohesion also tends to increase slightly with depth, probably due to the increased density.

3. For purposes of design, most ϕ values for depths 0-50 were in the range 24-26°, although a value of 15.2° was obtained for extremely porous loess at a depth of 3 feet. Cohesion was more variable, the lowest value being 0.7 psi.

Sample Slope Calculations

As an example of usefulness of these data, by use of appropriate equations one may predict the maximum height of cuts:

According to Spangler (1960, p. 296).

$$H = \frac{4\ c \sin i \cos \phi}{w[1 - \cos (i - \phi)]}$$

where i is the angle of the slope with the horizontal, w is the moist unit weight of the soil, and H the maximum height of the cut. Failure is assumed to take place along a plane with a critical angle θ,

$$\theta = \frac{i + \phi}{2}$$

If we substitute c = 1.5 psi (or 216 psf) and w (wet density) = 93 pcf, the maximum height of a cut is

$$H = 9.3 \frac{\sin i \cos \phi}{1 - \cos (i - \phi)}$$

For a vertical cut i = 90°. Since θ will be about 45 + 16 = 61°, from Fig 5, ϕ would be about 31°. Therefore

$$H = 9.3 \frac{1\ (0.859)}{1 - 0.515} = 16 \text{ feet}$$

Actually, relatively few natural or artificial loess cuts are truly vertical. A common cut slope is ¼ - on - 1, or i = 76°. With θ = 38 + 16 = 54°, from Fig. 5, ϕ = 33°, and H equals 29 feet.

Similarly if i = 55°, H = 115′, which is approximately the maximum loess thickness. The stable hillslope angle should therefore be of the order of 55° from the horizontal. Field comparisons indicate that this is not an unreasonable estimate.

These height estimates are proportional to cohesion, which as we have seen is rather variable. Previous research has shown that upon saturation, cohesion of loess becomes zero, in which case the stable height also should be zero. The tendency of loess to stand in steep cuts therefore depends in part on the continual lack of saturation. After saturation, loess structure collapes, a phenomenon utilized by the Bureau of Reclamation to densify loess deposits. The sensitivity of loess cohesion to moisture content indicates it is an "apparent cohesion", relating to clay and water tensions, with little or no influence from carbonates.

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Ground Water Geology of the U.S. Gypsum Company, Sperry Mine

Lyle V. A. Sendlein[1]

Abstract. The geology relating to the U. S. Gypsum Company Sperry Mine, Des Moines County, Iowa, is discussed. Maps of the bedrock configuration, structure, and bedrock geology are presented and reviewed in light of the ground water condition existing in the area. Criteria which could cause mine flooding are investigated and evaluated.

The occurrence of an undesirable amount of water in an entry to a planned mining block in 1951 in the U.S. Gypsum Company Sperry Mine prompted this study. The amount of water encountered was small, approximately 10 gpm, but its presence pointed to a potential hazard. The flooding of U.S. Gypsum's Shoals, Indiana, mine, in 1960, caused the management to move cautiously.

[1] Assistant Professor, Earth Science, Iowa State University, Ames.