No. E-11 CORRELATION OF SURFACE LOADING TESTS WITH UNCONFINED COMPRESSION TESTS FOR COHESIVE SOILS

(Progress Report)

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<u>Purpose of Investigation</u>. For elastic-isotropic materials the relation between the settlement in a surface loading test and the compression of an unconfined cylinder is known. Therefore it would be foolish to make expensive and time-consuming surface loading tests on such materials when inexpensive and quickly completed unconfined compression tests, together with a simple computation, will give the same result.

The purpose of this investigation is to determine the corresponding relationship for cohesive soils.

<u>The Testing Equipment</u>. The testing equipment used for all tests consisted chiefly in a loading machine built from a 1000 lb capacity Fairbanks platform scales, shown in Fig. 1 and 2. The specimen is placed on the platform with a crossbar and bearing plate suspended above it. A jack underneath the platform applies the load through the crossbar. The load is measured on the scales beam in the same way as an object is weighed on any scales. The settlement or compression is measured by an extensometer, reading to 1/10,000 inch. Fig. 1 shows the loading machine set up for a surface loading test on plasticine. Fig. 2 shows part of the test enlarged. The extensometer directly over the bearing plate measures the settlements. The other extensometers are used for measuring the deformation of the surface surrounding the loaded area, but these observations are not discussed in this paper.

Fig. 1

Fig. 2

<u>Theoretical Relation between Surface Loading Tests and Unconfined Compression Tests for Elastic Isotropic Materials</u>. Symbols used are:

p = pressure per unit area.
E = modulus of elasticity.
d = diameter of bearing plate in a loading test.
h = height of unconfined compression test specimen at beginning of test.
Δ_c = settlement in a loading test.
Δ_u = compression in an unconfined compression test.
$\delta_c = \frac{\Delta_c}{d}$ = strain index in a loading test.
$\delta_u = \frac{\Delta_u}{h}$ = strain in an unconfined compression test.
$J = \frac{\delta_c}{\delta_u}$ = strain ratio.

The formula for the settlement of a rigid circular area on the surface of an elastic-isotropic material, semi-infinite in extent, is:

$$\Delta_c = \frac{3\pi}{16} \cdot \frac{p}{E} \cdot d \qquad (1)$$

(Ref. Fröhlich, O. K., Druckverteilung im Baugrund, Vienna, 1934, p. 182.) and the arbitrarily defined strain index

$$\delta_c = \frac{\Delta_c}{d} = \frac{3\pi}{16} \cdot \frac{p}{E} \qquad (2)$$

The compression of an unconfined cylinder or prism of elastic-isotropic material is:

$$\Delta_u = \frac{ph}{E} \quad \ldots . \quad (3) \text{ , and the strain} \quad \delta_u = \frac{\Delta_u}{h} = \frac{p}{E} \qquad (4)$$

In this investigation we are particularly interested in the strain ratio $J = \frac{\delta_c}{\delta_u}$ which for an elastic-isotropic material is,

$$J = \frac{3\pi}{16} = 0.59$$

Tests on Glycerine-Gelatine. Although it is evident that results from working with a material that follows accurately Hooke's Law must check with theory, tests were conducted with a stable glycerine-gelatine mixture for two reasons, first to develop and calibrate the testing equipment; and second, to determine the minimum relative dimensions of the loaded areas and the size of the blocks of soil needed to reduce to a tolerable amount the influence of the boundaries.

The glycerine-gelatine mixture was made by heating 20% (by weight) of commercial gelatine with 80% of commercial glycerine. When cooled this makes an elastic rubbery material that is almost perfectly elastic, possessing a modulus of elasticity of about 1.5 kg./ sq cm. It is somewhat hygroscopic, taking on or giving off moisture according to the state of humidity of the surrounding air. To prevent any possible change in the physical properties of the material during the test, due to change in moisture content, the loading test block was kept covered with a thin layer of oil, and the unconfined compression test specimens (later cut from this block) were kept well covered with automobile cup grease.

Loading tests were run on different parts of the surface of a $9\frac{1}{4}$ x $9\frac{1}{4}$ x $6\frac{1}{2}$ inch block of glycerine-gelatine. Table I shows the results of 11 tests, and Fig. 3 a typical settlement curve.

At the completion of the loading tests the block of glycerine-gelatine was cut into prisms for unconfined compression tests. These were cut from the upper stratum and near the centre of the block where the loading tests were run, thereby using that part of the material which had the greatest effect on the loading tests. This was to offset as far as could be any possible lack of homogeneity in the whole block, due to uneven cooling after mixing, variation in moisture content, or what not.

The results of six unconfined compression tests are shown in Table II, and a typical curve in Fig. 3. Several tests were run to failure. The stress strain relationship is a straight line to about 30% strain and then begins to curve slightly. The average strain ratio for all tests is $J_{ave.} = 0.57$ as compared with the theoretical value for an elastic-isotropic material $J = 0.59$.

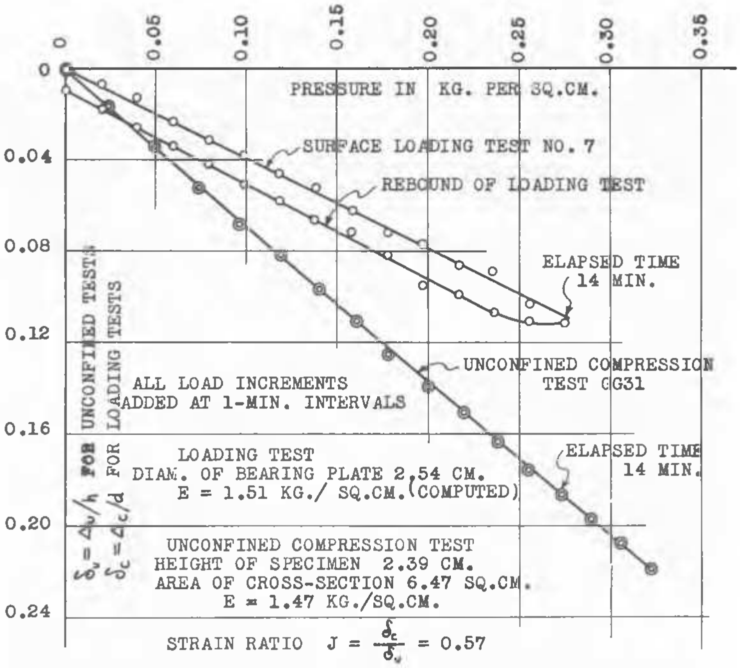

FIG. 3 TYPICAL SURFACE LOADING TEST AND UNCONFINED COMPRESSION TEST ON GLYCERINE - GELATINE.

From the close agreement of the actual with the theoretical strain ratio and from a comparison of Tables I and II it is concluded that the testing equipment is sufficiently accurate, in spite of the small dimensions of the loaded areas; and that the container is large enough to keep the boundary effects down to a tolerable amount. Furthermore, if a purely elastic material is so little affected by these boundaries, a plastic or partially plastic material, as used in the following tests, will be affected to a still smaller degree, because stresses are distributed in an elastic material to a greater distance than in materials which do not follow Hooke's Law.

Tests on Plasticine. Tests similar to those on glycerine-gelatine were run on plasticine, or modeling clay, a purely plastic material. There is a difference in the consistency of the material, depending on how long it has been remoulded. It is softest immediately after remoulding, and its consistency becomes stiffer with time. In order to reduce the influence of this change of cohesion with time, both loading and unconfined tests were run 48 hours (±1 hour) after remoulding.

Fig. 4 shows the average curves of three loading tests, and of four unconfined compression tests. None of the curves ran far from the average. The strain ratio curve is also shown.

TABLE I

Results of Surface Loading Tests on Glycerine-Gelatine with Rigid Bearing Plate

Test No.	Dia. of Bearing Plate in cm	Strain Index δ_c at p = 0.1 kg/cm^2	E in kg/cm^2 computed	Ave. E for each Bearing Plate Area
4	2.54	0.0445	1.325	1.482
5	"	0.0366	1.611	
6	"	0.0402	1.466	
7	"	0.0390	1.511	
8	"	0.0394	1.496	
9	1.88	0.0394	1.496	1.557
10	"	0.0355	1.663	
11	"	0.0390	1.511	
12	1.25	0.0352	1.675	1.529
13	"	0.0416	1.417	
14	"	0.0394	1.496	

Average of all tests E = 1.515 kg/cm^2

$$E = \frac{3\pi}{16} \cdot \frac{pd}{\Delta_c}$$

TABLE II

Results of Unconfined Compression Tests on Rectangular Prisms cut from Upper Layer of Gelatine Test-block used in Loading Tests

Test No.	Height of Specimen in cm	Area of cross-section of specimens in cm^2		E in kg/cm^2
GG17	2.81	2.75 x 2.76	7.59	1.32
GG23	2.91	2.65 x 2.71	7.18	1.50
GG29	2.65	2.32 x 2.75	6.38	1.49
GG30	2.60	2.40 x 2.89	6.94	1.48
GG31	2.39	2.55 x 2.97	7.57	1.47
GG33	2.70	2.53 x 2.60	6.58	1.50

$$E = \frac{ph}{\Delta_u}$$

Average 1.46

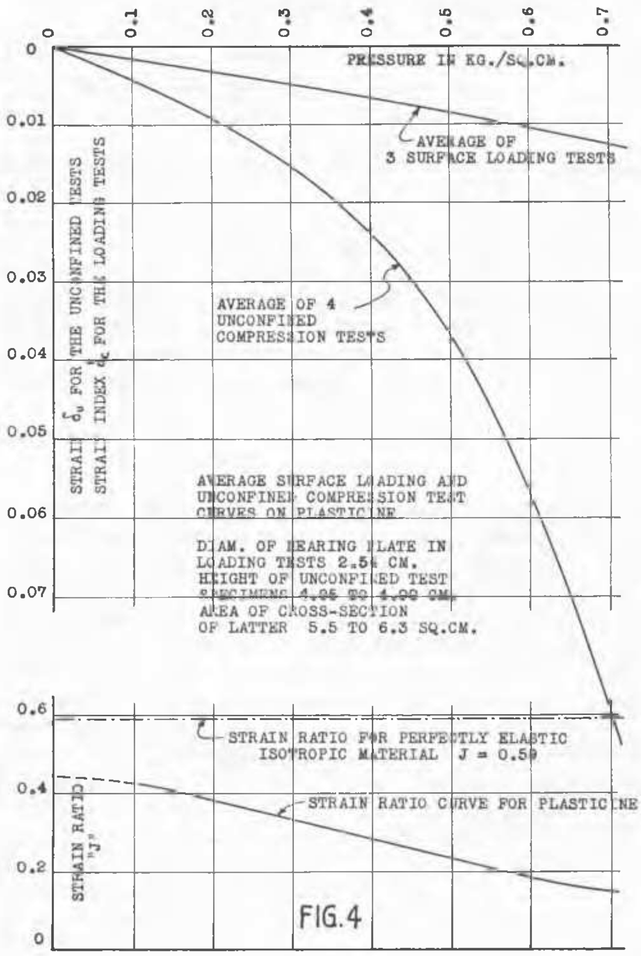

FIG.4

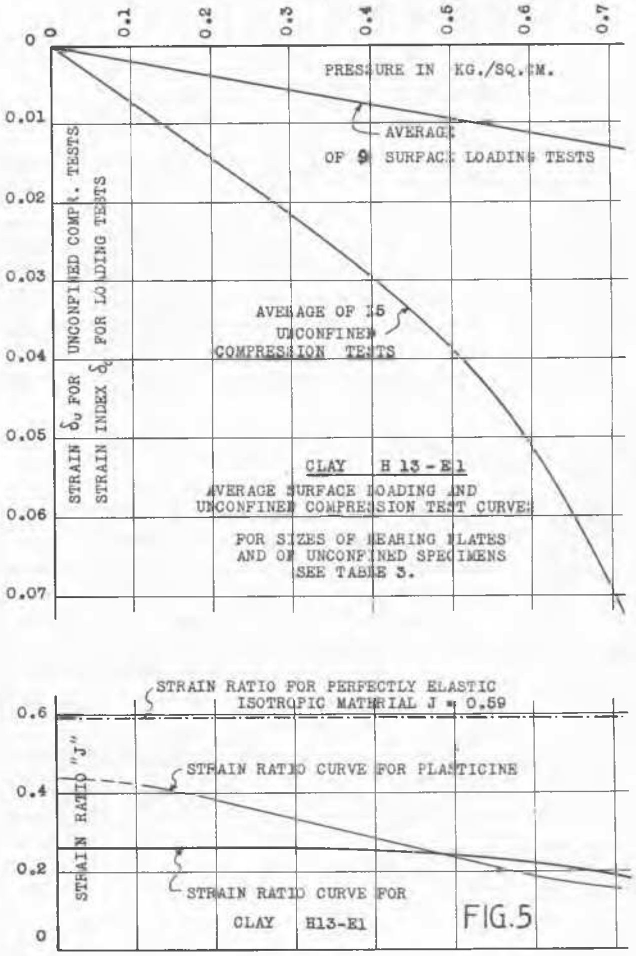

FIG.5

As shown before, the strain ratio, $J = \delta_c/\delta_u$, for an elastic-isotropic material is equal to 0.59. For plasticine J is a variable running from 0.45 down to 0.15 as the pressure increases. The first dotted part of the curve is but an estimate and the last part is not considered too reliable.

Due to the fact that the first part of the settlement and compression curves are practically straight lines, one should theoretically expect the J curve for plasticine to start at the same value as for an elastic material. It is possible that more accurate tests will indicate an intersection of the J curve with the vertical axis closer to 0.59.

Tests on an Undisturbed Block of Clay. One of the samples of Chicago clay, Lab. No. H 13-E1, discussed in Paper No. C-6 by P. C. Rutledge in this volume, was used for this investigation. This material showed slight stratification with thin silt partings occurring occasionally. The Atterberg Limits for the upper layer of the test block are as follows:

Liquid Limit = 51.5
Plastic Limit = 28.4
Plasticity Index = 23.1

The variations in the character of the clay are reflected by the range of natural water content, 37.5% to 46.0%, average 41.4%. Precautions were taken at all times to prevent evaporation.

The surface of the test block on which the loading tests were applied was cut parallel to the stratification. At the completion of the loading tests, cubes were cut out from about 2 mm below the surface down to a depth about equal to the diameter of the loaded area, and as far as possible a pair of cubes was cut on opposite sides of each loaded area.

The average curves of 9 loading tests, of 15 unconfined compression tests, and the curve for the strain ratio J are shown in Fig. 5. In Table III are assembled strain indices for each loading test, and for comparison the corresponding strains for the unconfined compression tests on the adjacent samples. The last column in the table contains the strain ratios J for corresponding loading and unconfined tests. The average strain ratio curve for all tests is $J_{ave.} = 0.26$.

TABLE III

Results of Surface Loading Tests and of
Corresponding Unconfined Compression Tests on Clay H13-E1

Loading Tests				Unconfined Compression Tests			
Test EL1	Dia. of Loaded Area in cm	Area in cm²	Strain Index = δ_c at p = 0.25	Test Nos.	Area of cross-section of specimens in cm²	Strain = δ_u at p = 0.25 Ave.	$\frac{\delta_c}{\delta_u} = J$
EL1	5.05	20.03	0.0027	E12T, E3, E14 & E15T	15.63, 18.46 14.88 & 14.84	0.0152	0.18
EL2	"	"	0.0044	E2T and E12T	21.16 & 15.63	0.0139	0.32
EL3	"	"	0.0036	E3 and E13	18.46 & 17.33	0.0188	0.19
EL4	"	"	0.0058	E4T and E14T	20.16 & 14.88	0.0172	0.34
EL5	"	"	0.0045	E5T and E15T	20.54 & 14.84	0.0170	0.26
EL6	2.54	5.07	0.0060	E6T and E16T	8.97 & 7.70	0.0172	0.35
EL7	"	"	0.0056	E7 and E27T	9.48 & 7.51	0.0171	0.33
EL8	"	"	0.0042	E8 and E18	7.15 & 8.40	0.0216	0.19
EL9	"	"	0.0050	E9T	7.40	0.0241	0.21
	Average		0.0040			0.0180	0.26

Discussion. At first the author was surprised to find that the strain ratio for the clay tested is less than one-half of the strain ratio for elastic-isotropic materials, in spite of the fact that the stress-strain curves for the loading and unconfined compression tests on the clay show straight line relations over a considerable range. These test results make it apparent that the stratification of the material and the presence of a few silt partings introduce anisotropic conditions of a marked degree. In a recent publication by Prof. K. Wolf (Zeitschrift für Angewandte Mathematik und Mechanik, Vol. 15, Oct., 1935. See also Paper No. E-10 by H. Gray in this volume, equation 12.) the theoretical stress and strain conditions for anisotropic elastic materials were developed for the simplest cases of surface loading.

The strain conditions under a line load are represented by the following equation:

$$\delta'_z = \left(\frac{1}{E_v} - \frac{1}{m^2 \cdot E_h} \right) \cdot \frac{2\bar{p}}{\pi} \cdot \frac{kz^3}{R^2 R'^2} - \frac{m+1}{m^2 E_h} \cdot \frac{2\bar{p}}{\pi} \cdot \frac{kx^2 z}{R^2 R'^2} \qquad (5)$$

Symbols used are:

δ_z = strain under line load in a vertical direction when $E_h = E_v$.
δ'_z = strain under line load in a vertical direction when E_h is not = to E_v.
$\bar{p}$ = pressure per unit length of line.
m = Poisson's figure.
E = modulus of elasticity.
E_v = " " " in a vertical direction.
E_h = " " " " " horizontal direction.

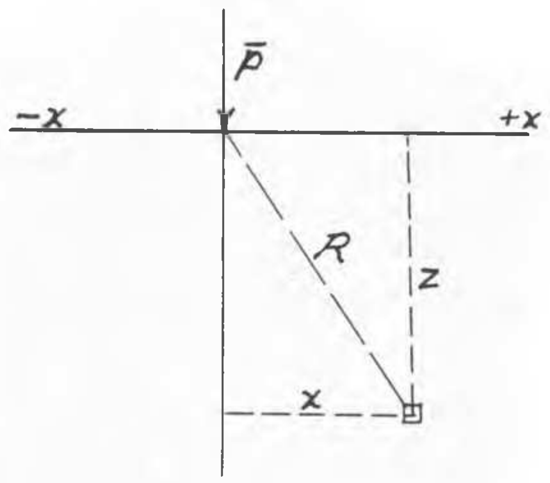

Fig. 6.

$$k = \sqrt{\frac{E_v}{E_h}}$$

$$R^2 = x^2 + z^2$$

$$R'^2 = k^2x^2 + z^2$$

For x, z, & R see Fig. 6.

Taking $m = 2$, which corresponds to rapid loading of clay, in which case practically no volume change takes place, and $x = 0$, the equation simplifies into the following:

$$\delta'_z = \left(\frac{1}{E_v} - \frac{1}{4E_h}\right) \cdot \frac{2\bar{p}k}{\pi z} \qquad (6)$$

By comparing this formula with the corresponding formula for an elastic-isotropic material,

$$\delta_z = \frac{2\bar{p}}{\pi E z} \qquad (7)$$

it is possible to compute the ratio $\frac{E_h}{E_v}$ for any given ratio of $\delta_z \div \delta'_z$.

In the absence of a theoretical solution for a circular rigid loaded area we may use the above relationships for determining approximately how much larger the modulus of elasticity in a horizontal direction must be than in a vertical direction.

The tests on clay presented above indicate a ratio of $\frac{\delta_z}{\delta'_z}$ somewhat larger than 2. For a ratio equal to 2, the corresponding ratio $\frac{E_h}{E_v} = 3.47$

At first it was considered possible to determine this ratio by simple unconfined compression tests. However, the results from a series of tests on cubical specimens about 3 to 5 cm on a side showed the average E_h practically equal to the average E_v.

Further considerations made this result appear not surprising. This clay is not an anisotropic, homogeneous material, but a stratified material consisting of individual clay layers which, within themselves, may be considered isotropic, but which are separated by very thin layers or partings of silt. These silt partings have a negligible influence on the compressibility of unconfined specimens, regardless of whether loaded parallel or perpendicular to the direction of stratification. However, when a loading test is applied on to a large mass, then pressure is exerted upon these partings mobilizing friction to such a degree that they become much less extensible than the clay itself. Consequently the mass acts as if it had been reinforced in a horizontal direction, thus producing a much wider distribution of stresses, and consequently smaller settlements, than if these silt partings were not present. Therefore, the proper way to test the influence of the silt partings on the average modulus of elasticity in a horizontal direction would be by tri-axial compression tests, which are unconfined compression tests with a lateral pressure applied through a surrounding liquid medium. These tests will be carried out during the continuation of this investigation.

Also during the continuation of this research project it is planned to investigate the mechanics of the unconfined compression test, particularly all factors which influence the test results. However, it is believed that any disturbing influences will affect chiefly the compressive strength, that is the behavior of the specimens near the end of the test, and not the first portion of the stress-strain relationship in which we are chiefly interested in this investigation of the Strain Ratio. Furthermore, it is planned to investigate the strain ratio for loaded areas at various depths beneath the surface.

Conclusions. The most important result of this investigation to-date is the demonstration that the results of loading tests on clays can be predicted from inexpensive unconfined compression tests if the strain ratio is known.

In the absence of exact knowledge of the strain ratio for a particular case one can assume the strain ratio for an elastic-isotropic material which assumption seems to be always on the safe side.

It is urgently recommended for all cases when loading tests are carried out on clay soils, to extract from the same elevation undisturbed cylindrical or prismatic specimens and to submit them to unconfined compression and soil identification tests. The information which thus would be accumulated would eventually serve to permit a reliable estimate of the strain ratio for the majority of clay soils encountered in foundation engineering.

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