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Experimental Investigation of Pipeline Stability In Very Soft Clay

By

Osman I. Ghazzaly, McClelland Engineers, Inc. and Sung Joo Lim, Brown & Root, Inc.

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ABSTRACT

The stability of pipes embedded in clay at water content above the liquid limit was investigated. Pipe sections remain stable within a weight range depending on the clay moisture content. Soil resistances to flotation and settlement decrease, with the increase in clay water content, to zero at about twice the liquid limit. Soil resistances can be estimated as the clay strength times one-half the pipe surface area. A pullout test is proposed to determine the yield strength of clay. The flotation force is considered equal to the buoyancy calculated using the saturated unit weight of clay.

Introduction

Significance. Pipelines are essential means of transporting a wide range of products. Long sections of pipe are buried under various soil conditions, in different environments. These pipelines must be stable against any flotation or settlement leading to costly damage. Stability of buried pipelines is influenced by several factors which have not been fully investigated.

Objectives and Scope. The main objectives of this paper are to analyze the stability of pipe sections embedded in very soft clay, and to

Nomenclature, references and illustrations at end of paper.

consider the effects of pertinent soil and pipe characteristics. Laboratory flotation and settlement tests were performed in which short pipe sections of different diameters were embedded in two clays prepared at four water contents above the liquid limit. Pullout tests were performed as a means of determining the yield strength of the experimental clays for use in pipeline stability analysis. The experimental research was conducted to study the short-term response of buried pipe; the effect of clay thixotropy was not considered. Criteria for pipeline stability were developed on the basis of experimental results and theoretical considerations.

Review of Earlier Research. An ASCE task committee (1) reported that flotation of a pipe buried in clay is potential at a moisture content which can be determined from the results of liquid limit tests by extending the straight line relationship between number of blows and water content to 0.01 blows. Tests performed by the ASCE research council (2) indicated that flotation and settlement of buried pipe depend on the difference between the unit weights of soil and pipe, and the shear strength and liquid limit of soil.

Reese and Cosbarian (3) studied the stability of pipe immersed in uniform suspension of soil grains in water, and of pipe buried in consolidated soil with shear strength. Bonar and Ghazzaly (4) proposed a pipeline stability analysis as a result of their laboratory investigation of the flotation of pipe sections embedded in cohesive soils.

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The concepts described in this section are used in connection with the flotation and settlement tests, to determine flotation and resistance forces.

Experimental Soils

Index Properties. Two clays were used in the laboratory study. Soil 1 is a stiff, light gray silty clay with a liquid limit of 46, plastic limit of 23, and specific gravity of solids of 2.69. Soil 2 is a very stiff, tan clay with a liquid limit of 76, plastic limit of 21, and specific gravity of solids of 2.83.

Soil Preparation. The layout of equipment used in soil preparation and subsequent testing is shown in Fig. 3. The preparation procedure followed is generally similar to the one adopted by Bonar and Ghazzaly (4). Samples of the two clays were prepared at four different moisture contents above the liquid limit, and ranging up to about 2.3 times the liquid limit for Soil 1, and 1.6 times the liquid limit for Soil 2.

Flotation and Settlement Tests

The main purpose of the tests was to measure the resistance of cohesive soils to flotation and settlement of buried pipe sections at water contents above the liquid limit, and hence, to determine the flotation force acting on the pipe.

Test Equipment. The equipment is generally similar to that used in earlier research (4). A sketch of the test setup is given in Fig. 4. The pipe sections were 8-in. and 12-in. diameter and 27 in. long. Each pipe was sealed at both ends, with plastic tubing at top and bottom connected to compressed air and to a water container placed on a platform scale; see Fig. 3.

Two steel rods were attached to the ends of each pipe section and extended vertically to guide pipe movement. A dial indicator was connected to these rods to measure vertical pipe displacement. The rods could be prevented from movement by a locking device built across the testing tank.

Test Procedure. When the soil-water mixture attained the desired consistency and uniformity in the mixing tank, the liquid clay was pumped into the test tank. A pipe section with known characteristics was locked in position and covered with soil to a depth of one diameter above its top. The pipe was emptied completely and the weight of the water container was determined on the platform scale. The weight of the pipe was then increased by filling it with water from the container, to a level estimated to stabilize the pipe in initial equilibrium, and the locks on the rods were released slowly to check if the pipe would move. If pipe movement occurred, the water in the pipe was adjusted to equilibrium

and its weight measured.

With the locks completely released, water was removed from the pipe and directed into the container, using air pressure, until upward pipe flotation started. The weight of water removed from the pipe was determined.

Water was directed back to the pipe from the container to reestablish initial equilibrium. More water was then added into the pipe until downward settlement started. The weight of water added from the container to the start of pipe settlement was measured. Test results were reduced to the form in Fig. 2.

Measurement of Soil Strength

Two methods were employed to determine the strength of liquid clays for use in pipeline stability analysis. Test equipment and procedure are described by Lim (7) and are summarized in the following two sections.

Pullout Tests. Test equipment and setup are sketched in Fig. 5. The test is a modification of the approach proposed by Boardman and Whitmore (6). The equipment included a loading frame with a pulley and a winch connected to a spring balance to which a small plastic tube section was suspended. The tube was buried in liquid clay placed in a container and its movement was measured by a dial indicator. Hollow tube sections 2.5-in. and 4.5-in. diameter, and 12 in. long were used in the tests. The weight of a tube could be increased by placing lead shot inside and sealing the ends with fitted caps.

Tests were performed on both tube sizes embedded in the two experimental clays at each of the four moisture contents. In the test the weight of the suspended tube was increased to a known magnitude above the estimated buoyancy force at a particular moisture content. The tube plus content was pushed in the liquid clay and its movement monitored until initial equilibrium was reached. At that point the initial tension in the spring, T_0 in equation {1}, was read off the balance scale, and checked by calculation. A known force increment, T in equation {2}, was applied to the tube by the winch and was maintained constant while the displacement of the tube was measured at certain time intervals. When the displacement-time relationship (Fig. 1-a) was established, the force increment was increased and the process repeated to obtain a relationship between soil resistance, R in equation {3}, and average rate of displacement for each force increment (as in Fig 1-b), to enable determination of the yield strength, τ , of the liquid clay.

Miniature Vane Tests. Standard test equipment was used to determine the cohesive shear strength, c , of several specimens of the

Theoretical Considerations

Clay Consistency and Rheology. Problems of instability are more likely to be associated with pipelines buried in weaker clays. The strength of a clay is a function of its water content. Clays with water content above the liquid limit, referred to as liquid clays in this paper, flow upon application of external forces and their mechanical properties can, therefore, be investigated on the basis of rheology.

As the moisture content is reduced from a state of liquid suspension, the clay properties change from those of Newtonian fluids to those of non-Newtonian paste-like materials (5). When the liquid limit is reached, the clay enters a plastic state which ranges to the plastic limit where the soil hardens to a semi-solid state.

Strength of Liquid Clays. A body which initially hangs suspended in liquid clay, with no movement or corresponding soil resistance, is subjected to a tension force, T_0 , a flotation force, F , which can be equal to the buoyancy, and the pipe weight, W , such that:

$$T_0 = W - F \quad \{1\}$$

If the body is pulled upward with a force, T , to produce a displacement, s , in a time period, t , and with soil resistance, R , developed, the stability equation is:

$$T = W - F + R \quad \{2\}$$

subtracting equation {1} from {2} gives:

$$R = T - T_0 \quad \{3\}$$

Repeating the pullout of the body with larger forces will result in a displacement-time response schematically represented in Fig 1-a, from which the average rate of displacement, $\frac{s}{t}$, for each applied force (T_1, T_2, T_3) can be determined. Extrapolating the curve giving the relationship between soil resistance to pullout, R , in equation {3}, and the rate of displacement, to zero displacement rate gives the soil yield resistance, R_y (6), as shown in Fig 1-b. Dividing this resistance by the surface area gives the yield strength, τ , of the liquid clay.

The above reasoning represents the basic concept behind the pullout test. Another approach to determine the strength of liquid clays was proposed by Bonar and Ghazzaly (4) through the use of miniature vane test results. The cohesive shear strength determined by the miniature vane for specimens of a clay at water content within the plastic range, can be extrapolated beyond the liquid limit on the straight line semi-logarithmic plot of shear strength versus water content.

Pipe Soil Interaction. If a pipe is embedded in a clay medium, initially with no displacement or soil resistance developed, the equilibrium equation is:

$$W - F = 0 \quad \begin{matrix} F - \text{flotation force} \\ W - \text{pipe weight} \end{matrix} \quad \{4\}$$

A change in the weight of the pipe from that in equation {4} will cause mobilization of soil resistance, and the equilibrium equation becomes:

$$W - F \pm R = 0 \quad \{5\}$$

where,

W = volume of pipe x unit weight of pipe plus contents, γ_p

F = volume of pipe x equivalent unit weight of soil, γ_{se}

Expressing the forces in equation {5} at the start of flotation and settlement, per unit volume of pipe, results in the following two equilibrium equations:

$$\gamma_{pf} - \gamma_{se} + R_f = 0 \quad \begin{matrix} \text{flotation up} \\ \text{flotation} \end{matrix} \quad \{6-a\}$$

$$\gamma_{ps} - \gamma_{se} - R_s = 0 \quad \begin{matrix} \text{settlement down} \\ \text{settlement} \end{matrix} \quad \{6-b\}$$

Consider a pipe embedded in liquid clay at the initial equilibrium position, where the unit weight of pipe plus contents, γ_p , is equal to the equivalent unit weight of soil, γ_{se} .

If the unit weight of pipe is decreased to γ_{pf} or increased to γ_{ps} , the pipe will start flotation or settlement, respectively. If a range of pipe equilibrium exists (analogous to Coulomb's concept of solid friction) which decreases as the soil moisture content increases, a plot similar to Fig. 2 is possible. Subtracting equation {6-a} from {6-b} will yield the pipe equilibrium range as the sum of the soil resistance to flotation and settlement, i.e.,

$$\gamma_{ps} - \gamma_{pf} = R_s + R_f \quad \{7\}$$

If soil resistances to flotation and settlement are equal, i.e.,

$$R_f = R_s = R_v \quad \{8\}$$

the flotation force per unit volume of pipe (or the equivalent unit weight of soil), γ_{se} , is given by either:

$$\gamma_{se} = \gamma_{ps} - R_v \quad \{9-a\}$$

or

$$\gamma_{se} = \gamma_{pf} + R_v \quad \{9-b\}$$

It should be noted that Bonar and Ghazzaly (4) concluded that γ_{se} is equal to the saturated unit weight of soil, γ_s .

two experimental clays formed at different moisture contents ranging within the plastic state of the clay. Extrapolation of the straight line semi-logarithmic relationship between cohesive shear strength and water content beyond the liquid limit, made possible the estimate of cohesive shear strength of liquid clay specimens, which could not be tested directly (4).

Test Results and Analysis

Pullout Tests. Typical test results are presented in Fig. 6, in which shear strength was calculated as the soil resistance to pullout, R , divided by the cylindrical surface area of the tube. The displacement rate, $\frac{s}{t}$, was computed as the average rate for the initial, more or less, straight line portion of the displacement-time curve for each force increment.

Fig. 6 shows that there is no difference in the results of the two sizes of tubes used. The semi-logarithmic relationship between clay shear strength, or resistance to pullout, and displacement rate is a straight line for any water content between one and two times the liquid limit. This suggests that a rheological model analogous to the Bingham model (5) can represent the force-displacement response of liquid clays with water content in this range.

Extending the straight lines in Fig. 6 to zero displacement produces what will be termed the yield strength of the liquid clay, τ . If these yield strengths are plotted against the ratio of water content to liquid limit, on a semi-logarithmic plot, a straight line relationship will result, as shown in Fig. 7.

Miniature Vane Tests. Fig. 8 shows a semi-logarithmic plot of the clay cohesive shear strength, τ , determined by miniature vane tests, and water content within the plastic range. The relationships appear to be fairly linear, and can be extended beyond the liquid limit (4).

Flotation and Settlement Tests. Figs. 9 and 10 show the unit weights of 8-in. and 12-in. diameter pipe plus content, at the start of flotation and settlement in the two clays with four different moisture contents above the liquid limit. There was no significant difference in the results of the two pipe sizes.

As shown previously by equation [7], the difference between the unit weight of pipe plus content at start of settlement, γ_{ps} , and that at the start of flotation, γ_{pf} , gives the sum of the soil resistances to settlement and flotation per unit volume of pipe, i.e., $R_s + R_f$. This combined soil resistance is represented by the vertical ordinate between the flotation and settlement curves at any moisture content in Figs. 9 and 10.

Assuming equal soil resistances to flotation and settlement above the liquid limit, as indicated by equation [8], this resistance, R_v , is equivalent to one-half the vertical ordinate between flotation and settlement curves in Figs. 9 and 10. The mid-point of the vertical ordinate between these two curves represents the unit weight of pipe plus content equivalent to the flotation force per unit volume of pipe, γ_{se} , as shown by equation [9].

Test results show that a range of stability of a pipe embedded in clay exists which is analogous to Coulomb's concept of solid friction. The upper and lower boundaries of this range, in terms of the unit weight of pipe plus content, signify the start of pipe settlement and flotation. This range, at any water content, represents the combined soil resistances to pipe flotation and settlement, and decreases as the water content of the clay increases. The soil resistances approach zero at a water content between two to three times the liquid limit, as estimated from the convergence of the curves in Figs. 9 and 10. To be on the conservative side, however, soil resistances to flotation and settlement of pipes embedded in clay can be considered zero at twice the liquid limit.

Comparison of Computed and Measured Results. Theoretical computations of soil resistances to pipe flotation and settlement were made and are summarized in Table 1. Soil resistances were computed using both the yield strength, τ , determined by the pullout test, and the cohesive shear strength, c , of the liquid clay estimated from the results of miniature vane tests. Multiplying the soil strength by one-half the surface area of the buried pipe gives the resistance to flotation and settlement in liquid clays. Thus, the soil resistance, R_c , per unit volume of pipe of diameter D , was computed as:

$$R_c = \frac{2\tau}{D} \quad \tau - \text{pullout test yield strength} \quad [10-a]$$

or,

$$R_c = \frac{2c}{D} \quad c - \text{shear strength of liquid clay} \quad [10-b]$$

The theoretical flotation force was considered equal to the buoyancy acting on the pipe. Therefore, the flotation force per unit volume of pipe at any water content, w , was calculated as the saturated unit weight of the liquid clay, γ_s , such that (4):

$$\gamma_s = \frac{G\gamma}{1 + Gw} \quad w - \text{water content} \quad [11]$$

As shown in Table 1, comparison of computed and measured values of soil resistances and flotation forces shows generally good agreement. The ratio of computed to measured soil resistances ranges from 0.61 to 1.63 for resistances computed

using the yield strength determined by pullout tests, and ranges from 0.32 to 2.45 for resistances computed using the cohesive strength estimated by the miniature vane test. The ratio of computed to measured flotation forces varies from 0.84 to 0.99.

CONCLUSIONS

1. Soil resistances to flotation and settlement of buried pipes decrease with the increase in the water content of the surrounding clay, to a zero value at about twice the liquid limit.
2. Embedded pipes remain stable within a weight range depending on the clay water content, a concept analogous to Coulomb's solid friction.
3. Soil resistances to flotation or settlement of pipes buried in clay at water content above the liquid limit (i.e., liquid clay) are equal and can be estimated by multiplying one-half the cylindrical surface area of the pipe by the yield strength of clay. The ratio of computed to measured soil resistances ranged from 0.61 to 1.63.
4. The yield strength of liquid clay can be determined by a proposed pullout test.
5. The flotation force acting on pipes embedded in liquid clay is equivalent to the buoyancy calculated on the basis of the saturated unit weight of the surrounding clay at any water content. The ratio of calculated to measured flotation forces varied from 0.84 to 0.99.
6. The cohesive shear strength of liquid clay may be estimated by the miniature vane test, and used in computing soil resistances. The ratio of computed to measured soil resistances ranged from 0.32 to 2.45 in this case.

NOMENCLATURE

- c = cohesive shear strength of clay
 D = pipe diameter
 F = flotation force
 G = specific gravity of solid soil particles
 γ = unit weight of pipe plus content
 γ_{pf} = unit weight of pipe plus content at start of flotation
 γ_{ps} = unit weight of pipe plus content at start of settlement
 γ_s = saturated unit weight of soil
 γ_{se} = equivalent unit weight of soil
 γ_w = unit weight of water, i.e., 62.4 pcf
 R^w = soil resistance to flotation or settlement
 R_c = computed soil resistance to flotation or settlement per unit volume of pipe

- R_f = soil resistance at start of flotation per unit volume of pipe
 R_s = soil resistance at start of settlement per unit volume of pipe
 R_v = soil resistance at start of flotation or settlement per unit volume of pipe
 R_y = yield resistance of liquid clay
 s_y = displacement
 T = pullout force (T_1, T_2, T_3)
 t = time period
 T = initial tension force
 τ_o = yield strength of liquid clay
 W = weight of pipe
 w = soil water content

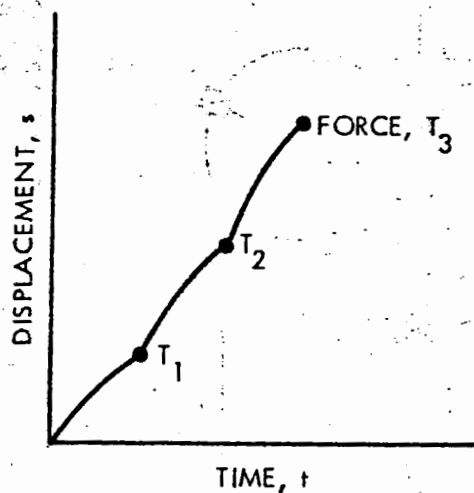
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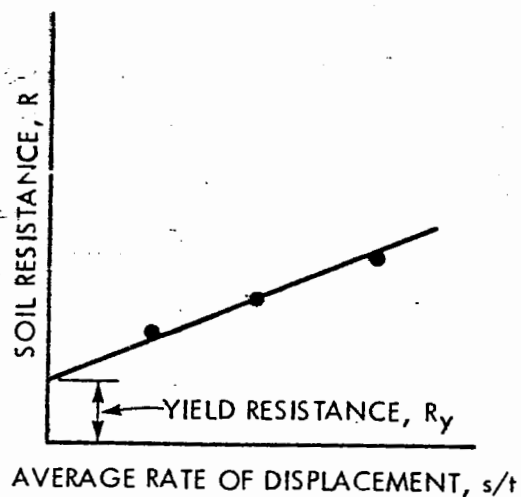
TABLE 1 - COMPARISON OF COMPUTED AND MEASURED RESULTS

PIPE DIA. (IN.) (1)	SOIL NO. (2)		MEASURED SOIL RESISTANCE R_v (PCF) (4)	MEASURED FLOTATION FORCE γ_{se} (PCF) (5)	COMPUTED FLOTATION FORCE γ_s (PCF) (6)	COMPUTED SOIL RESISTANCE (PCF)		RATIO OF COMPUTED TO MEASURED RESULTS		
								SOIL RESISTANCE (R_c/R_v)		FLOTATION FORCE γ_s/γ_{se} COL. (6) COL. (5) (11)
8	1	74.0	15.80	98.70	97.66	10.80	15.00	0.68	0.95	0.99
		83.0	9.95	97.15	95.02	8.16	6.90	0.82	0.69	0.98
		92.4	5.60	95.90	92.66	5.97	2.70	1.07	0.48	0.97
		106.0	2.25	96.60	89.78	3.66	0.90	1.63	0.40	0.93
	2	80.3	46.20	116.40	97.29	56.16	90.00	1.22	1.95	0.84
		93.1	24.30	96.10	93.82	29.58	58.50	1.22	2.41	0.98
		110.1	12.90	94.20	90.15	9.72	24.00	0.75	1.86	0.96
		120.4	8.80	93.60	88.31	5.40	16.50	0.61	1.88	0.94
12	1	74.0	11.20	99.10	97.66	7.20	10.00	0.64	0.84	0.99
		83.0	5.33	95.68	95.02	5.44	4.60	1.02	0.86	0.99
		92.4	3.17	94.84	92.66	3.98	1.80	1.26	0.57	0.98
		106.0	1.90	92.60	89.78	2.44	0.60	1.28	0.32	0.97
	2	80.3	29.10	106.50	97.29	37.44	60.00	1.29	2.06	0.91
		93.1	15.90	105.10	93.82	19.72	39.00	1.24	2.43	0.89
		110.1	8.30	96.00	90.15	6.48	16.00	0.78	1.93	0.94
		120.4	5.10	92.80	88.31	3.60	11.00	0.71	2.16	0.95

NOTE THAT FLOTATION FORCES AND SOIL RESISTANCES ARE EXPRESSED PER UNIT VOLUME OF PIPE.



(a) DISPLACEMENT - TIME
RELATIONSHIP



(b) SOIL RESISTANCE - RATE OF
DISPLACEMENT RELATIONSHIP

Fig. 1 - Yield strength of liquid clay.

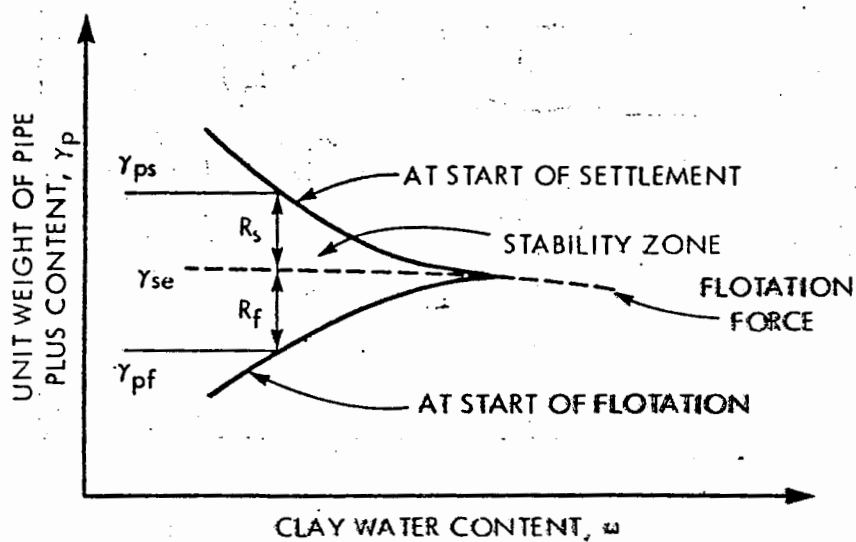


Fig. 2 - Forces at flotation and settlement.

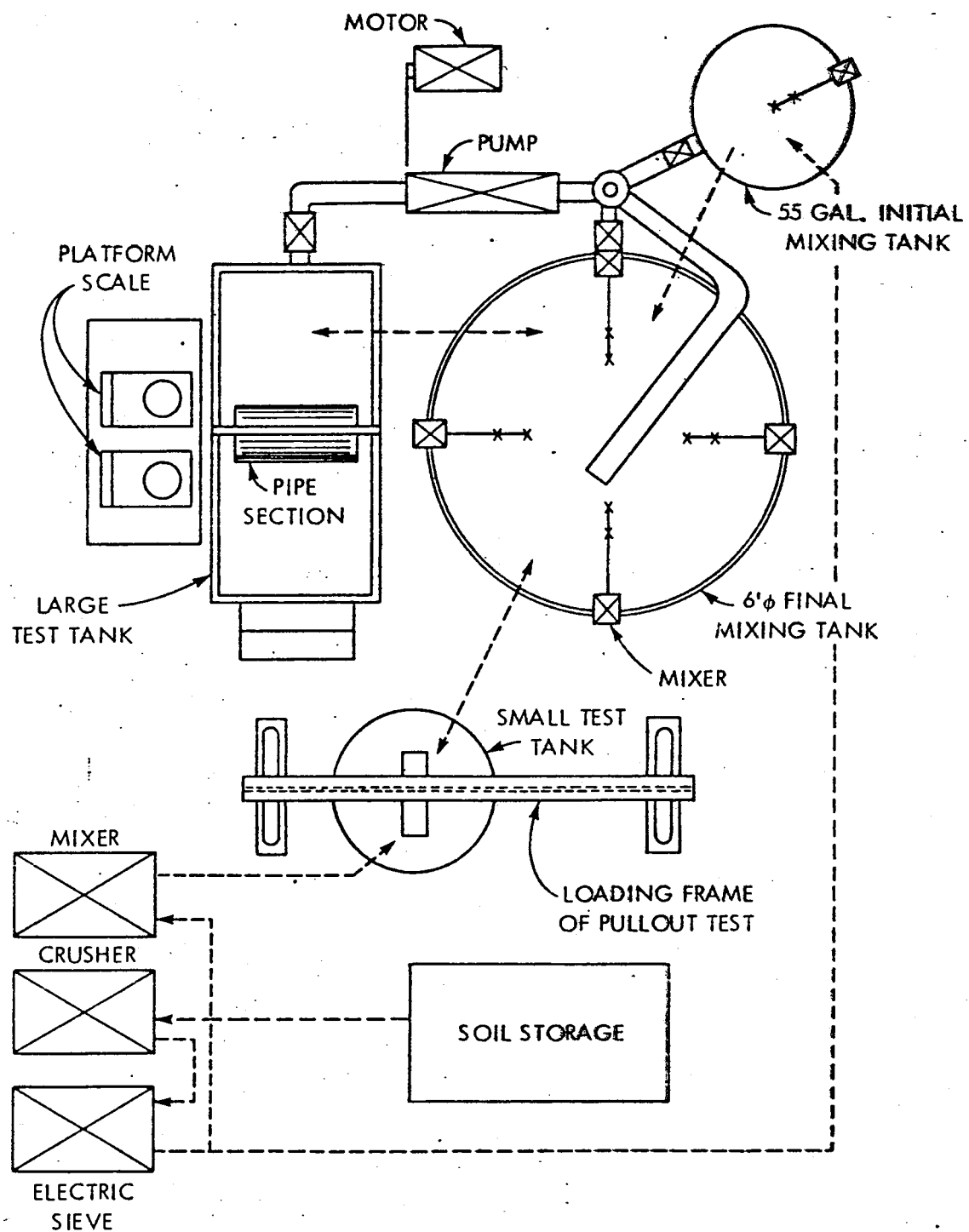


Fig. 3 - Layout of test equipment.

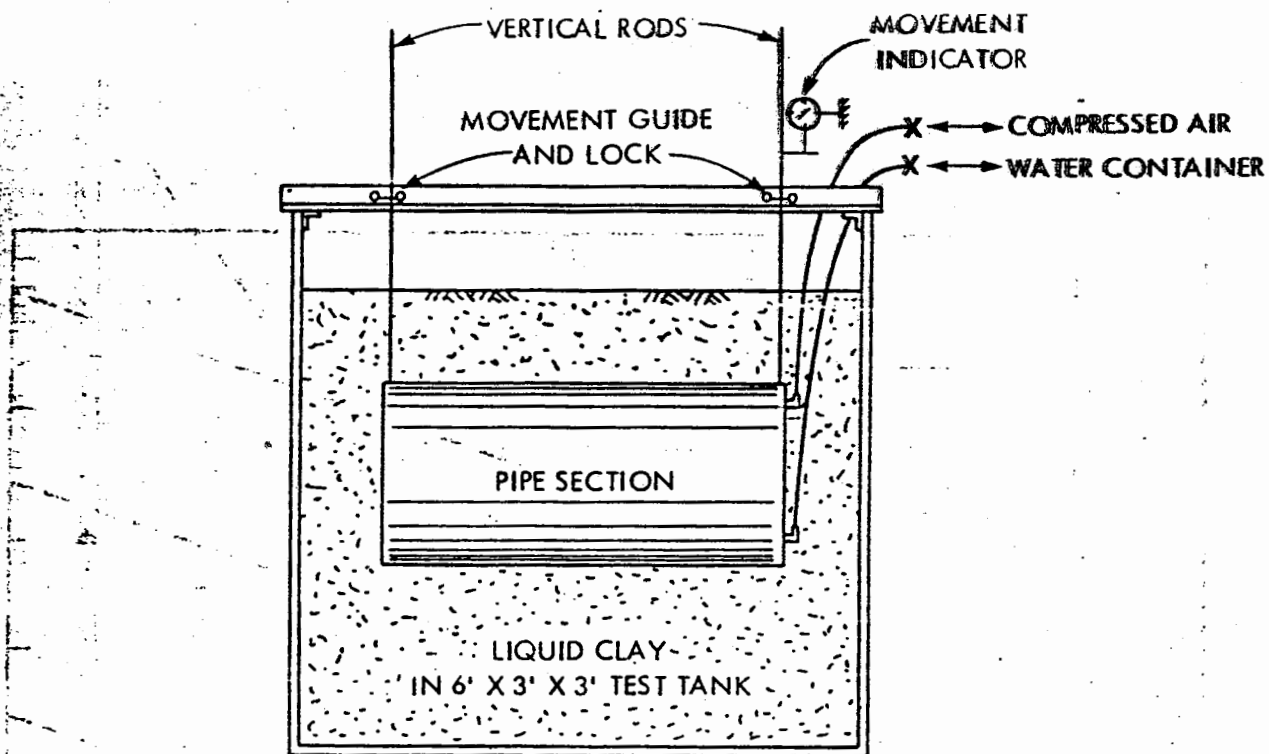


Fig. 4 - Flotation and settlement test setup.

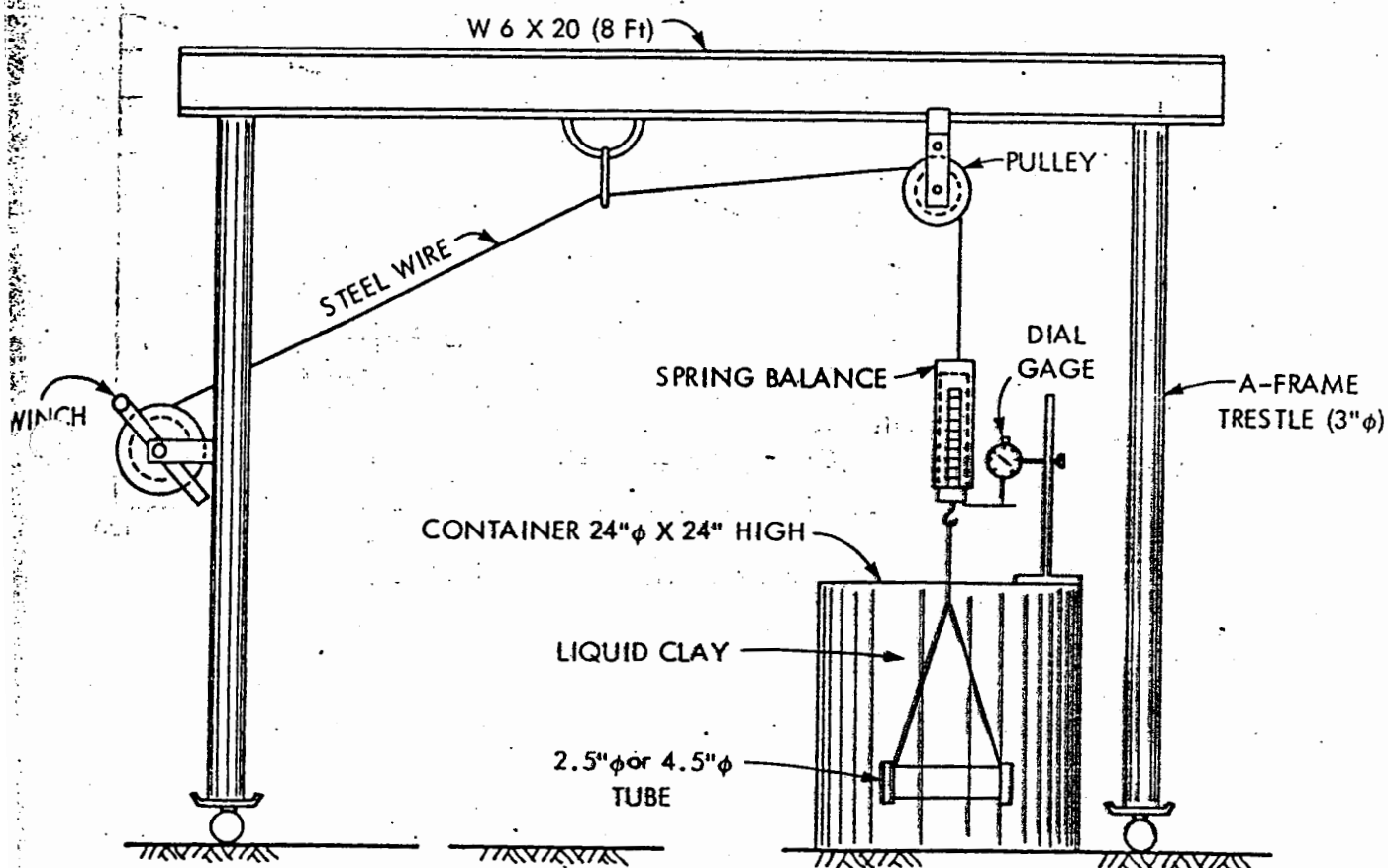


Fig. 5 - Pullout test setup.

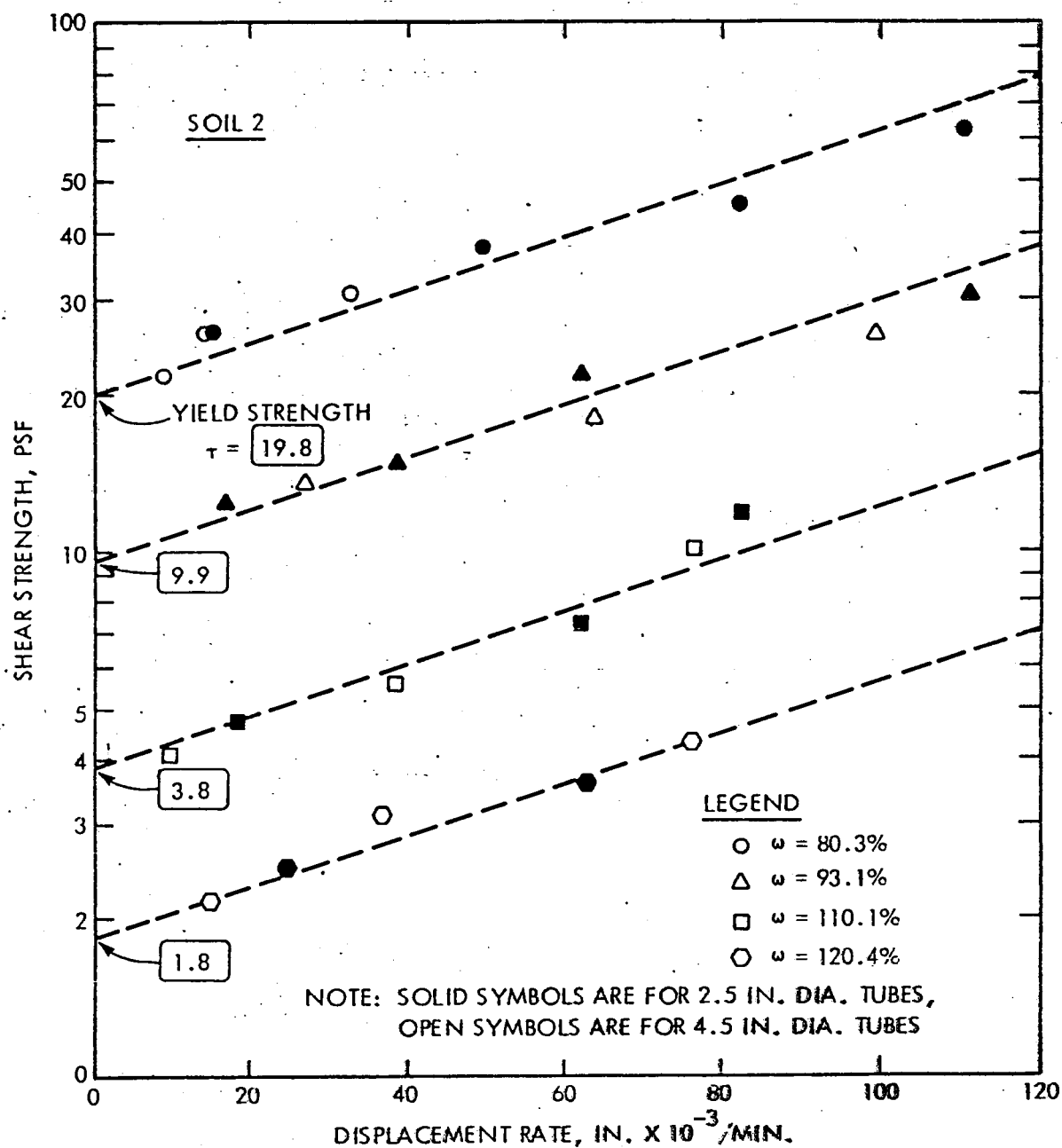


Fig. 6 - Shear strength - displacement rate relationship by pullout test.

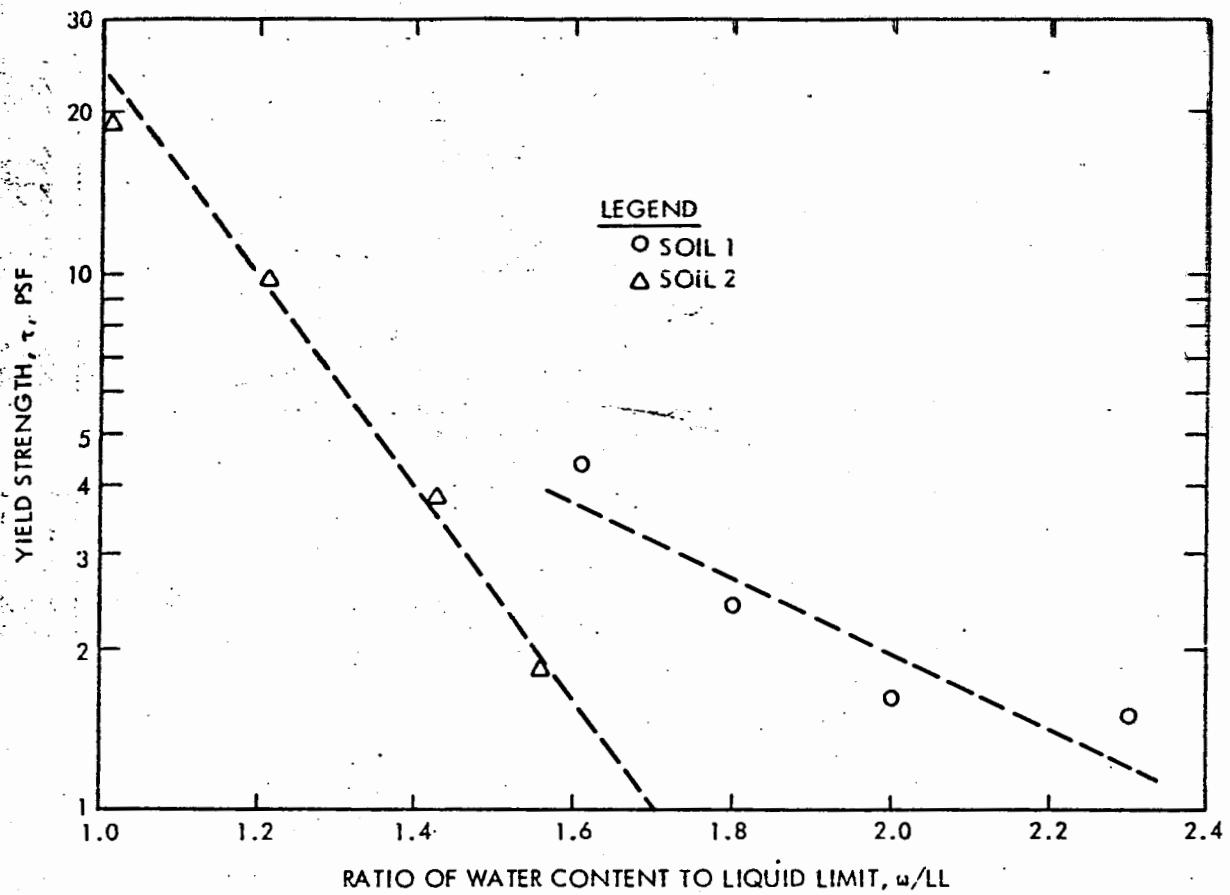


Fig. 7 - Yield strength - water content relationship for liquid clay by pullout test.

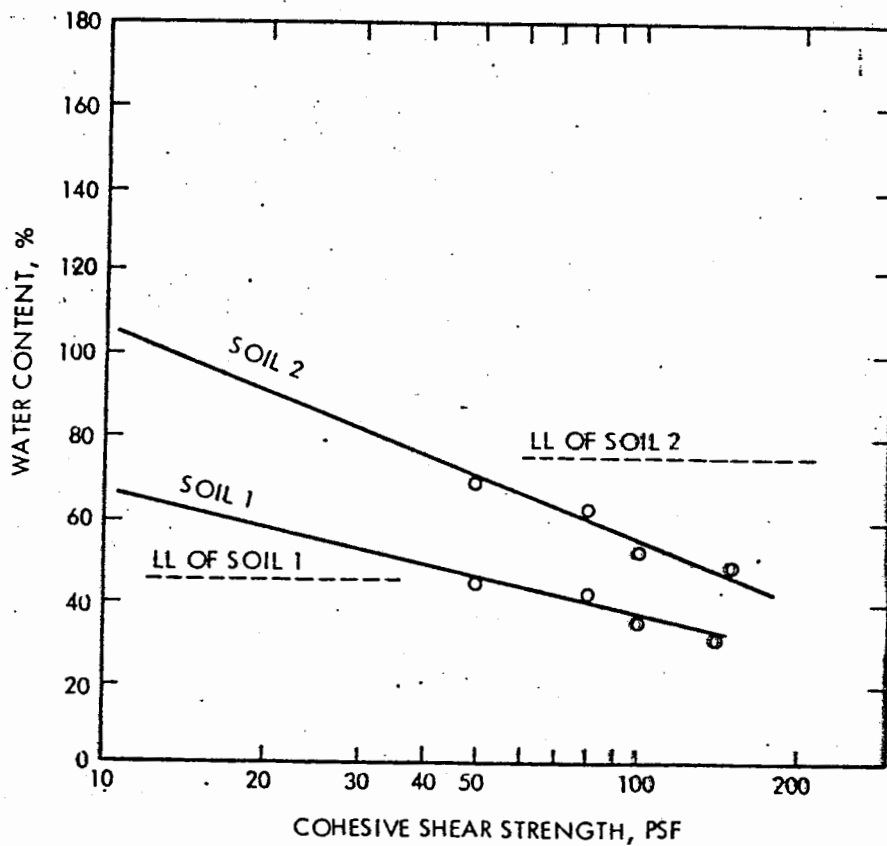


Fig. 8 - Cohesive shear strength - water content relationship from miniature vane test results.

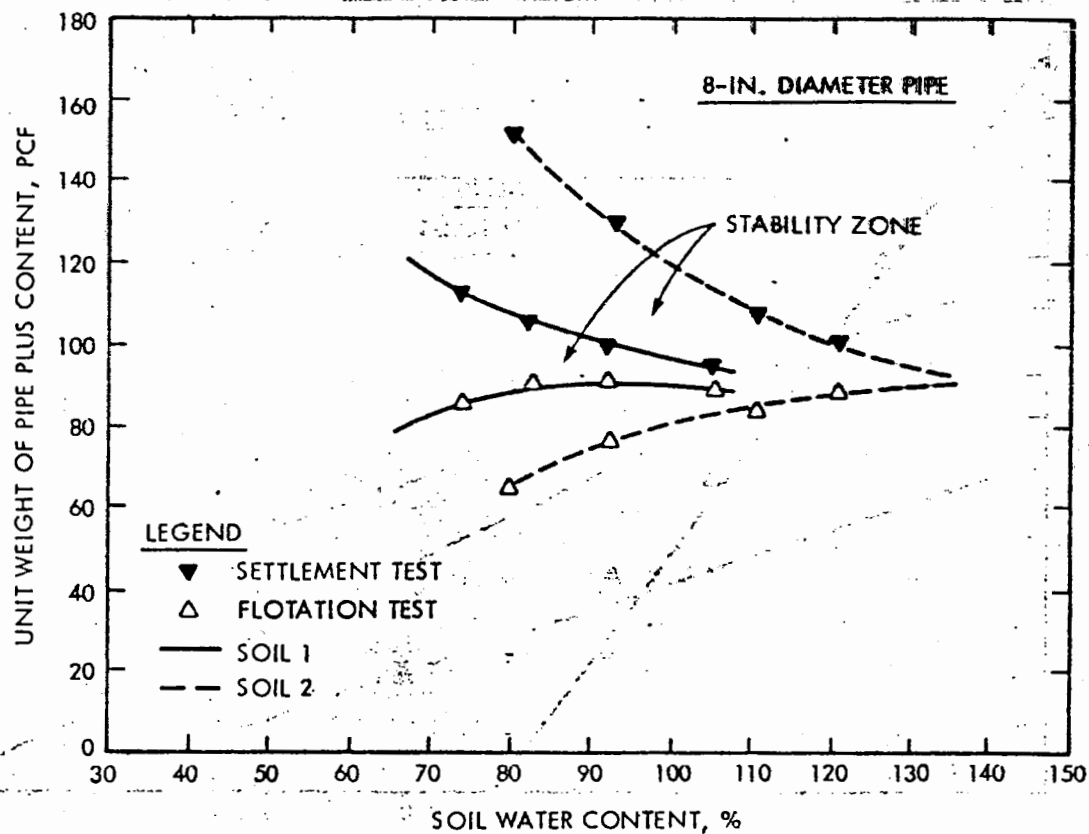


Fig. 9 - Unit weight of pipe at start of flotation and settlement.

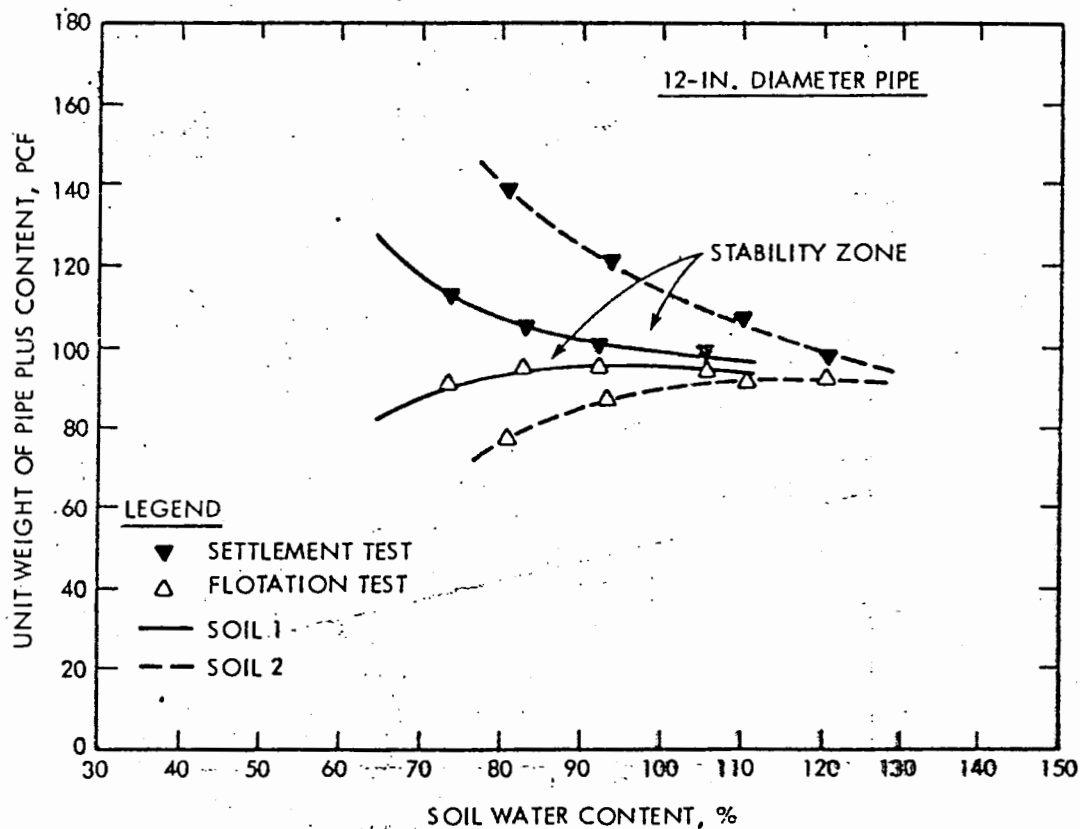


Fig. 10 - Unit weight of pipe at start of flotation and settlement.