

**MERCURY-FILLED SETTLEMENT GAGE**

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Interim Report

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**Synopsis:** A description is given of a remote sensing, multiple-point, mercury-filled settlement gage designed for measuring in-place settlements. The gage consists of settlement units positioned at locations where settlement measurements are desired and a monitoring unit located outside of construction limits. Settlement readings are observed on a mercury manometer located at the monitoring site and are equal to the differences in initial and subsequent pressure head readings. Comparisons of measurements obtained at a highway construction site from mercury gage settlement units and conventional settlement platforms are presented and show very good agreement. With the mercury gage, a large amount of settlement information can be obtained per installation, and the gage does not have many of the disadvantages associated with the settlement platform.

## INTRODUCTION

Construction of certain engineering structures, highway embankments and buildings, for example, frequently results in settlements which can adversely affect the performance and even the stability of the structure. Hence, it is important to be able to measure in-place settlements and to compare observed settlements with theoretical predictions.

Since 1964, the Division of Research, Kentucky Department of Highways, has focused attention on the development of a remote sensing gage. As a result, a multiple-point, mercury-filled settlement gage has been developed. Such gages do not have many of the disadvantages associated with settlement platforms and other types of gages. Furthermore, the multiple-point gages provide much more settlement information per installation than can be obtained from a settlement platform.

## GAGE DETAILS

### Description

Components and arrangement of the multiple-point, mercury-filled settlement gage, capable of measuring several points of settlement per installation, are shown schematically in Figure 1. The gage contains two units: 1) the monitoring site located at some convenient site outside the loaded area and 2) settlement units positioned at points where settlement measurements are desired.

At the monitoring site, Tube 1 (in Figure 1) leads from a tee connector mounted on a control panel, loops through the area where measurements are desired, and returns to the monitoring site. A portion of the return end of Tube 1 is fixed in a vertical position to an aluminum pipe anchored in concrete. The middle portion is coiled and "stacked" around the pipe. Another tube (No. 2) leads from the tee connector to a mercury-filled manometer having a resolution of 0.1 inch and the capacity to measure a pressure head as large as ten feet. The third end of the tee is connected to an array of

valves, mounted on the control panel for fine control of applying and releasing nitrogen pressure, and to a bottled nitrogen supply.

Settlement units (Figure 1) consist of stainless steel tube connectors inserted into the return portion of Tube 1 at points where settlement measurements are desired. The connectors are machined in such a way that the cut ends of Tube 1 fit tightly into each end of the connector, and a constant diameter is maintained throughout Tube 1. A practical limit of settlement units is two per foot of gage length. Normally, six to ten points have been used per gage installation. In Figure 1, only two units are illustrated.

Insulated electrical wires (No. 1 and No. 2) are connected (soldered) to each stainless steel insert and extended from each settlement unit through a push-button switch to an ohmmeter located on the control panel. The settlement unit is insulated and protected by casting it in an epoxy resin of a type commonly used for splicing communication cable. At the base of the vertical portion of Tube 1, a stainless steel connector of the same construction as the settlement units is inserted. An insulated electrical wire (No. 3) leads from that point to the ohmmeter.

Toggle valve (No. 1 in Figure 1) permits an instantaneous shut-off of the release of nitrogen pressure from the gage system. The nitrogen tank is recharged through the check valve (No. 2). The metering valve (No. 3) provides an extremely fine release of nitrogen pressure from the gage system. On-off valves (No. 4 and No. 5) control the direction of flow of the nitrogen.

Mercury is introduced into Tube 1 through a detachable plexiglass reservoir. The bottom portion of the reservoir is funnel-shaped. Diameter of the stem portion of the funnel is equal to the inside diameter of Tube 1. Sufficient mercury to fill the return portion of Tube 1 reaching from the farthest settlement unit to the bottom coil at the monitoring site is first introduced into the cylinder positioned horizontally. With a quick motion, the filled reservoir is tilted vertically and the mercury is allowed to drain into Tube 1. This normally permits introduction of a mercury column into Tube 1 free of breaks. Mercury remains in Tube 1 until all settlement readings have been obtained; thereafter it is recovered. Nitrogen is used to prevent condensation of moisture in Tube 1 which, if present, could cause breaks in the mercury column. The valves, nitrogen tank and ohmmeter are housed in a portable carrying case. The manometer can either be transported or stored (mounted) at the site. By using flexible tubing, the manometer can be coiled and conveniently transported to the site.

An effort is made to position settlement units and the coiled portion of Tube 1 at the same elevation. With this arrangement, settlements as large as ten feet can be measured. Otherwise, the maximum settlement that can be measured is ten feet minus the initial difference in elevation between the settlement unit and the coiled portion of Tube 1. Measurements can be obtained even if the monitoring site is located at an elevation below the settlement units.

### Theory and Operation

The operation of the gage is summarized in Figure 2. Figures 2(A), (B), and (C) illustrate steps necessary to obtain a pressure head reading,  $h_o$ , when the settlement unit(s) is (are) situated in some initial position. To obtain subsequent pressure head readings,  $h$ , for the settlement unit(s) in a new position (Figure 2(D)), the steps illustrated in (A), (B), and (C) are repeated.

When nitrogen pressure is applied to the two mercury columns (Figure 2) and the columns are adjusted to some static state such as shown in Figure 2(C), the difference,  $h_o^1$ , in level between the ends of the mercury column, A and B, equals the initial pressure head,  $h_o$ , observed on the manometer at the monitoring site. That is, when the columns of mercury are at rest, all velocity heads and head losses are zero and Bernouilli's equation for the system reduces to

$$h_o^1 = h_o = P_o/\gamma_m, \quad 1$$

where  $P_o$  = pressure applied to the two mercury columns,  
 $\gamma_m$  = unit weight of mercury, and  
 $P_o/\gamma_m$  = pressure head.

A change,  $h_s$ , in elevation of the settlement unit from its initial elevation (Figure 2(D)) will result in an equal change in pressure head observed on the manometer. Hence, for this new position of the settlement unit,

$$h^1 = h = P/\gamma_m \quad 2$$

and

$$h_s = h^1 - h_o^1 = h - h_o, \quad 3$$

where  $P/\gamma_m$  = subsequently applied pressure head.

Contact of the end of the mercury column in Tube 1, Figure 2(B), at each settlement unit is recognized by completion of an electrical circuit via the ohmmeter, the wire extending from the ohmmeter to the stainless steel connector (Point C) at the monitoring site, the mercury column in Tube 1, the stainless steel connector of the settlement unit, and a wire extending from the settlement unit to the ohmmeter. As nitrogen pressure is applied (Figure 2(B)), the mercury column in Tube 1 will contact the stainless steel connector at the monitoring site completing the circuit; the ohmmeter needle deflects.

Pressure application is discontinued at the instant the ohmmeter needle deflects to zero. By an extremely fine release of pressure (Figure 2(C)) through the metering valve, the column of mercury is allowed to move toward the stainless steel connector of the settlement unit. At the instant the column contacts the stainless steel connector, as signaled by a deflection of the ohmmeter needle, the toggle valve (No. 1) is closed, locking the pressure in the system. Hence, the pressure head observed on the manometer at the monitoring site can be recorded accurately and conveniently. This procedure is repeated for each settlement unit on the gage length.

Length of the mercury column in Tube 1 is affected by 1) volume change in Tube 1 due to creep or relaxation and 2) difference in temperature of mercury in Tube 1 and mercury in the manometer at the monitoring site. In the former case, the level of the end of the mercury column at B, Figure 2(C), must be referenced initially to a fixed datum. In each subsequent settlement reading, the position of the end of the column is noted with respect to the initially fixed datum. If the end of the column is below the initial point, then a correction, M, must be added to the observed manometer reading; if above the point, the correction is subtracted. Equation 3 then becomes

$$h_s = (h \pm M) - h_o. \quad 4$$

However, this correction can be practically eliminated by using tubing that is not subject to large expansion and contraction and by coiling the tubing at the monitoring site in a manner shown in Figure 1.

Since the temperature of the mercury in Tube 1 and in the manometer at the monitoring site may differ, there may be an error,  $\epsilon$ , proportional to the temperature difference and applied pressure. Consequently, the difference in the levels of the mercury column in Tube 1 will not equal the observed pressure head on the manometer at the monitoring site. The error can be computed from

$$\epsilon = h (T_g - T_m) / (9988 - T_g), \quad 5$$

where  $h$  = observed pressure head on the manometer at monitoring site,  
 $T_g$  = temperature in Fahrenheit of mercury in Tube 1, normally ground temperature, and  
 $T_m$  = temperature in Fahrenheit of mercury in the manometer at the monitoring site,  
 normally air temperature.

Equation 4 then becomes

$$h_s = (h \pm M + \epsilon) - h_o. \quad 6$$

The error,  $\epsilon$ , can be minimized and usually ignored. If settlement readings are obtained when ground and air temperatures are nearly equal, the error can be ignored. The computed error for an observed pressure head of 40 inches is 0.04 inches per 10° F temperature difference. In cases where large settlements and temperature differences are anticipated, the error could be significant.

This temperature differential problem can be resolved by monitoring the ground and air temperatures, computing the error, and correcting the readings or by coiling the tubing as shown in Figure 1. When the gage is read initially, ground and air temperatures may differ. Thus an initial error,  $\epsilon_0$ , is introduced. Generally, ground temperature is constant; therefore, the density of mercury in Tube 1 is constant. Since all subsequently observed pressure heads are referenced to the initially observed pressure head, the problem reduces to one of noting the air temperature at the time of the initial reading and in each subsequent reading and computing the initial and subsequent errors. Equation 6 becomes

$$h_s = (h \pm M + \epsilon) - (h_0 + \epsilon_0). \quad 7$$

Consequently, all settlement readings can be readily corrected in a simple manner by merely observing air temperatures (or by measuring directly the temperature of the mercury in the manometer at the monitoring site) during each reading. However, it can be eliminated completely by coiling the tubing (No. 1) as shown in Figure 1. Since the largest expected error is on the order of 0.6 inch, the end of the mercury column will remain in the initially marked coil of Tube 1. This coil is essentially in a horizontal plane and thus the elevation of the initial reference does not vary significantly. Therefore, no accuracy is lost due to the effects of temperature differences and applied pressures.

In the event the vertical position of the monitoring site is changed, thereby disturbing the initially marked point (B in Figure 2(C)), a correction C must be applied to Equation 7 so that finally

$$h_s = (h \pm M \pm C + \epsilon) - (h_0 + \epsilon_0). \quad 8$$

### FIELD PERFORMANCE

Fourteen mercury-filled settlement gages have been used during the period 1966-1972 at ten highway construction sites primarily to investigate settlements of compressible foundations located beneath highway bridge approach embankments. Field reliability of the mercury gage system at four of those sites is being checked by positioning settlement units of the mercury gage as close as practical to settlement

platforms and comparing measurements obtained from the two devices. Results obtained to date (April 1972) from one of the construction sites are discussed below.

The site involved major construction of the Bowling Green - Owensboro Parkway bridges across the Green River in Kentucky. Two settlement platforms were located on the southern foundation and one was situated on the northern foundation. The risers were not encased and therefore were subjected to negative friction. A multiple-point, mercury-filled settlement gage was installed on each approach foundation (see Figure 3). The mercury gage on the north side measured 270 feet in length and contained six settlement units. On the south side, the mercury gage contained five settlement units and was 225 feet in length.

The most useful check of the reliability of the mercury gage was made on the north side where Settlement Unit 2 (M2) was positioned within three feet of a settlement platform (SP1 in Figure 3). Settlement-logarithm time curves obtained from the settlement platform and mercury gage Unit 2 are compared in Figure 4. Fill height-logarithm time curve and a typical soil profile of the northern foundation are also shown in Figure 4.

All individual settlement measurements obtained from the settlement platform (SP1) and mercury gage Unit 2 (M2) were within  $\pm 0.25$  inches of the mean of the two measurements. For 80 percent of the measurements, the differences were within  $\pm 0.14$  inches. Half of the readings were within  $\pm 0.08$  inches of the mean. The largest differences occurred during the time periods of about 50 to 90 days and 105 to 160 days (Figure 4). During those periods, when there was a pause in loading, consolidation of the fill apparently exerted sufficient negative frictional forces on the pipe risers to overload the settlement platform, resulting in measurements of greater settlements than had actually occurred. The settlement platform curve dipped noticeably during each of those periods.

Settlement- and fill height-logarithm time curves for mercury gage points located on the northern foundation are shown in Figure 5. Gage Units 5 and 6 were located within three feet of each other. The height of fill over Unit 5 was slightly larger than that over Unit 6. Settlement-logarithm time curves in Figure 5 are approximately parallel. In 80 percent of the settlement measurements obtained from those two points, variations of the differences of the two readings from the initial difference of 0.34 inch was within 0.10 inch.

Comparisons of settlement-logarithm time curves obtained from settlement platforms (SP1 and SP2 in Figure 3) and from mercury gage units (M1 and M2) on the southern foundation are presented in Figure 6. Meaningful comparisons of readings obtained from the mercury gage and settlement platforms could not be made because pipe risers of the platforms were damaged on several occasions by the contractor's equipment. Figure 7 shows settlement-logarithm time curves for mercury gage Units 3, 4,



and 5.

### CONCLUSIONS

Experience with the mercury gage since 1966 at ten highway construction sites has shown that settlements as large as three feet can be measured with no difficulties; however, the gage has the capacity to measure settlements as large as ten feet, if properly positioned. The monitoring unit can be located either above or below the settlement units. Errors occurring in the measurements due to volume changes of the tubing and to effects of temperature on the unit weight of mercury can be corrected or made small and ignored, depending on the accuracy required.

Thus far, length of gage has not been a factor in limiting its use. Readings from gages as long as 370 feet have been obtained successfully for as long as two years. An almost continuous settlement profile can be obtained with the mercury gage. Two settlement measurements per foot of gage can be obtained. Thus far, six to ten units have been installed per gage.

Generally, settlement measurements obtained from a mercury gage unit and a settlement platform were within a range of  $\pm 0.14$  inch of the mean of the two measurements. Field studies show that at any given time, readings can be repeated within an accuracy of 0.1 inch, the resolution of the manometer used to obtain the readings.

# SETTLEMENT UNITS

# MONITORING SITE

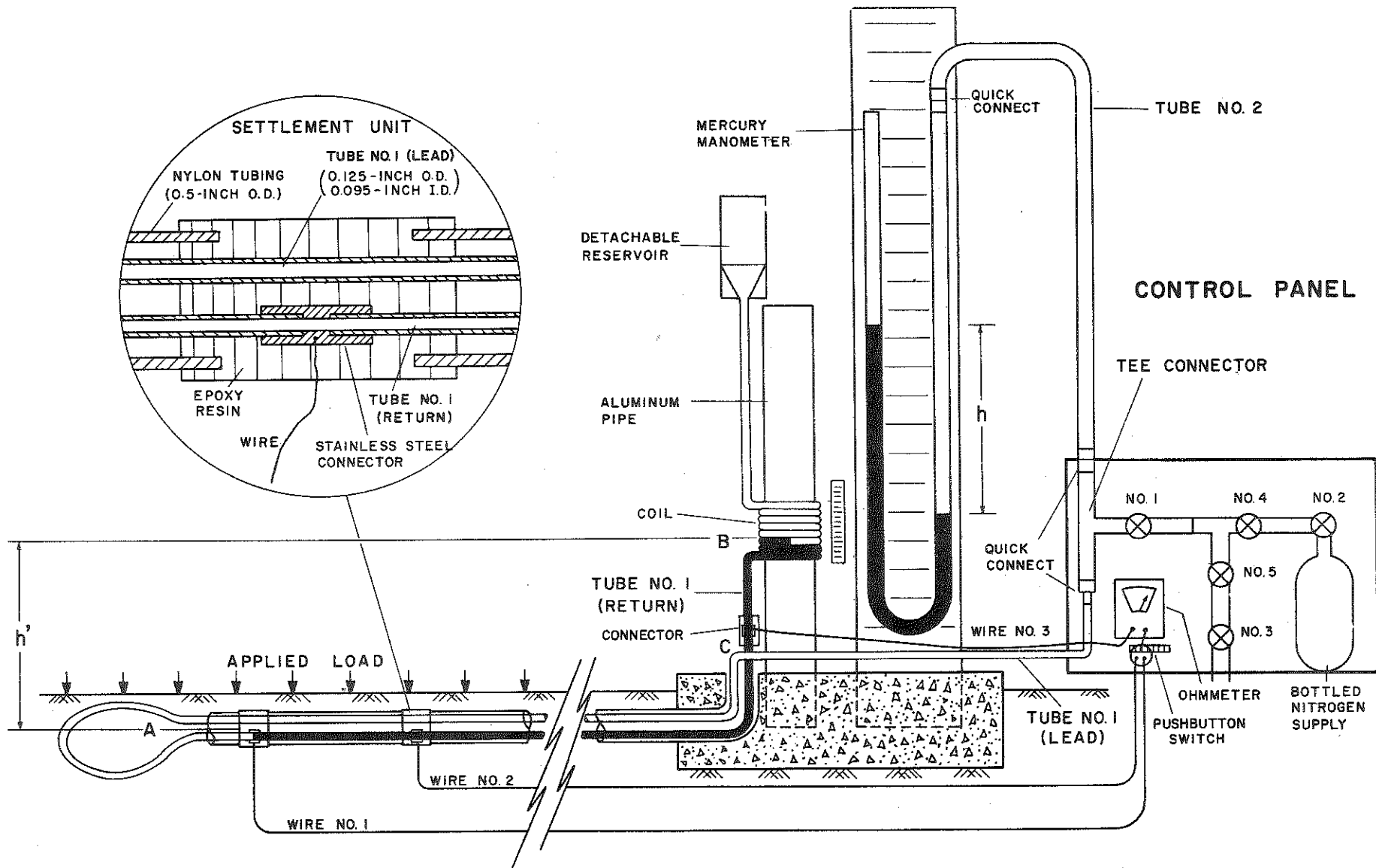


Figure 1. Components of Multiple-Point, Mercury-Filled Settlement Gage.

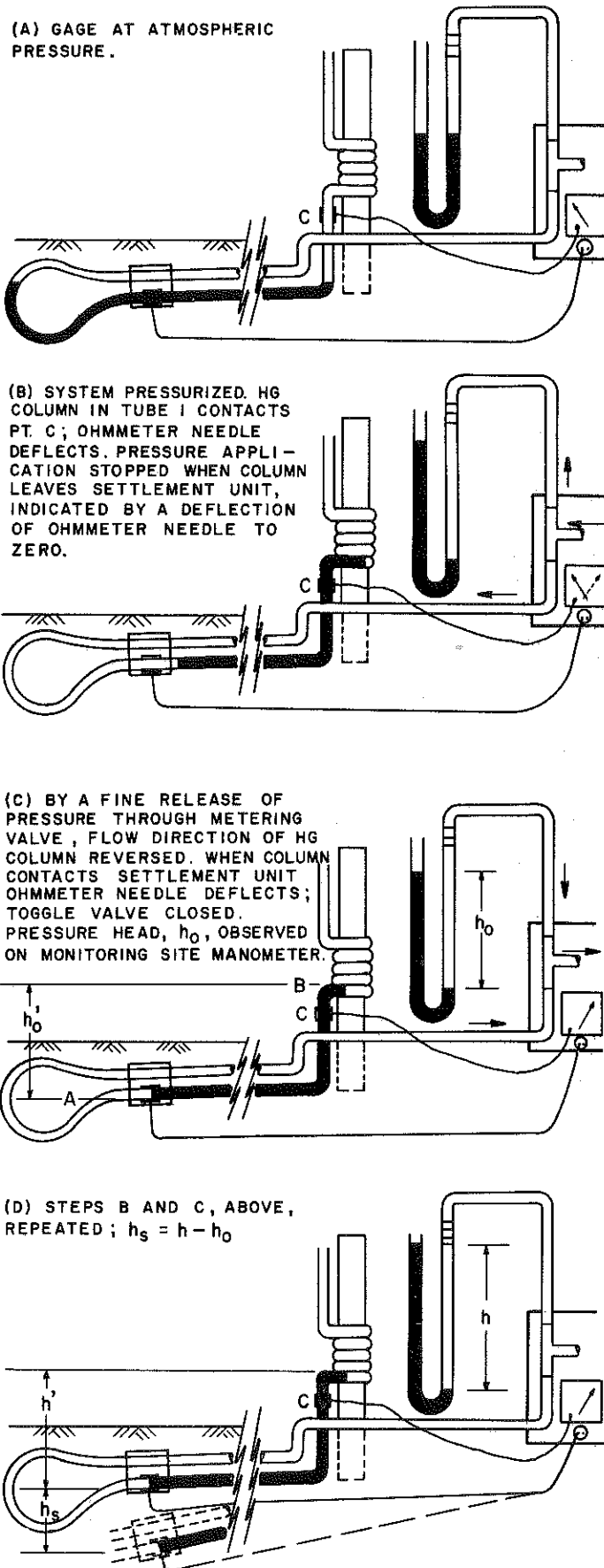


Figure 2. Operation of Multiple-Point, Mercury-Filled Settlement Gage.

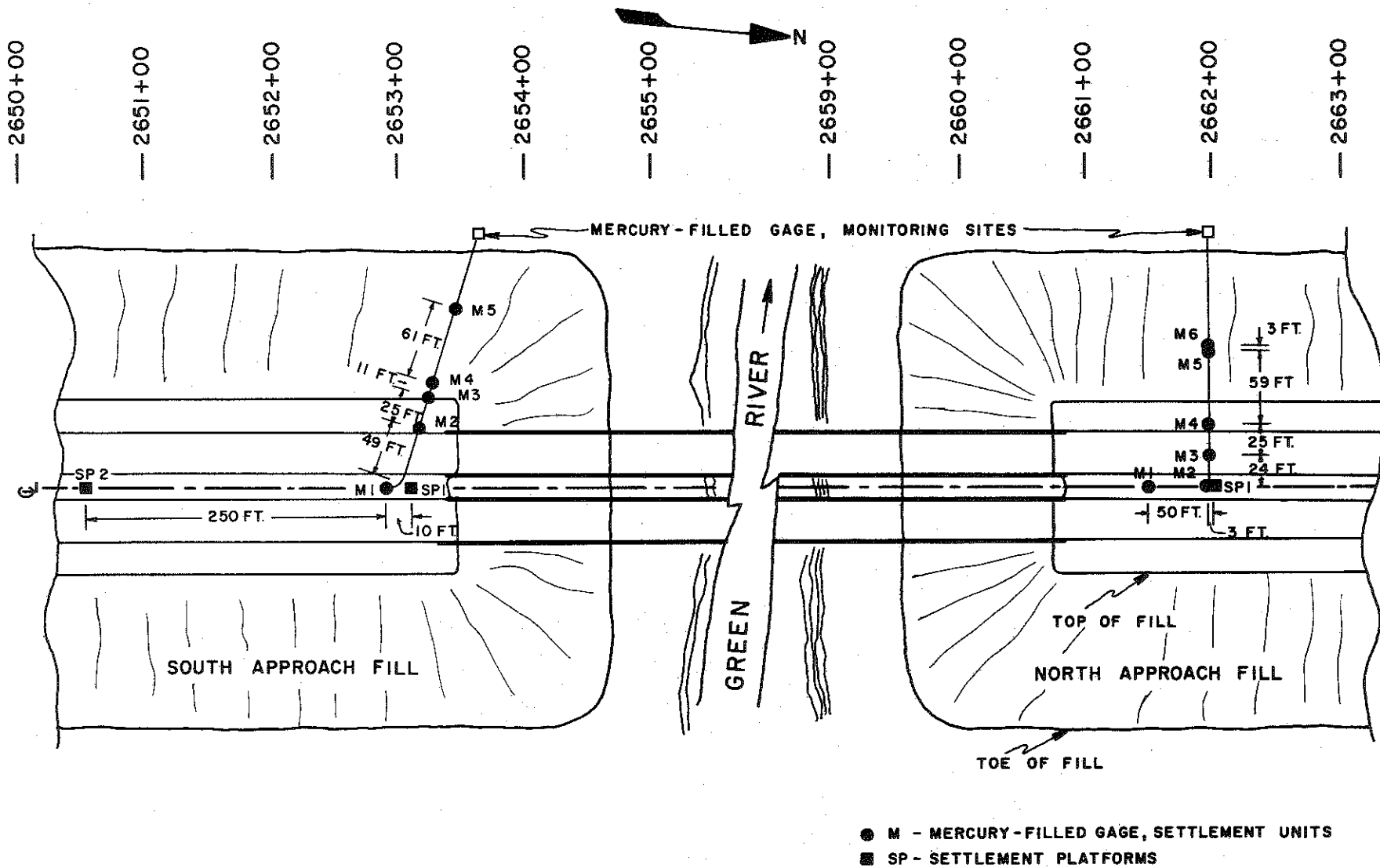


Figure 3. Plan View of Green River Site Showing Locations of Mercury Gages and Settlement Platforms.

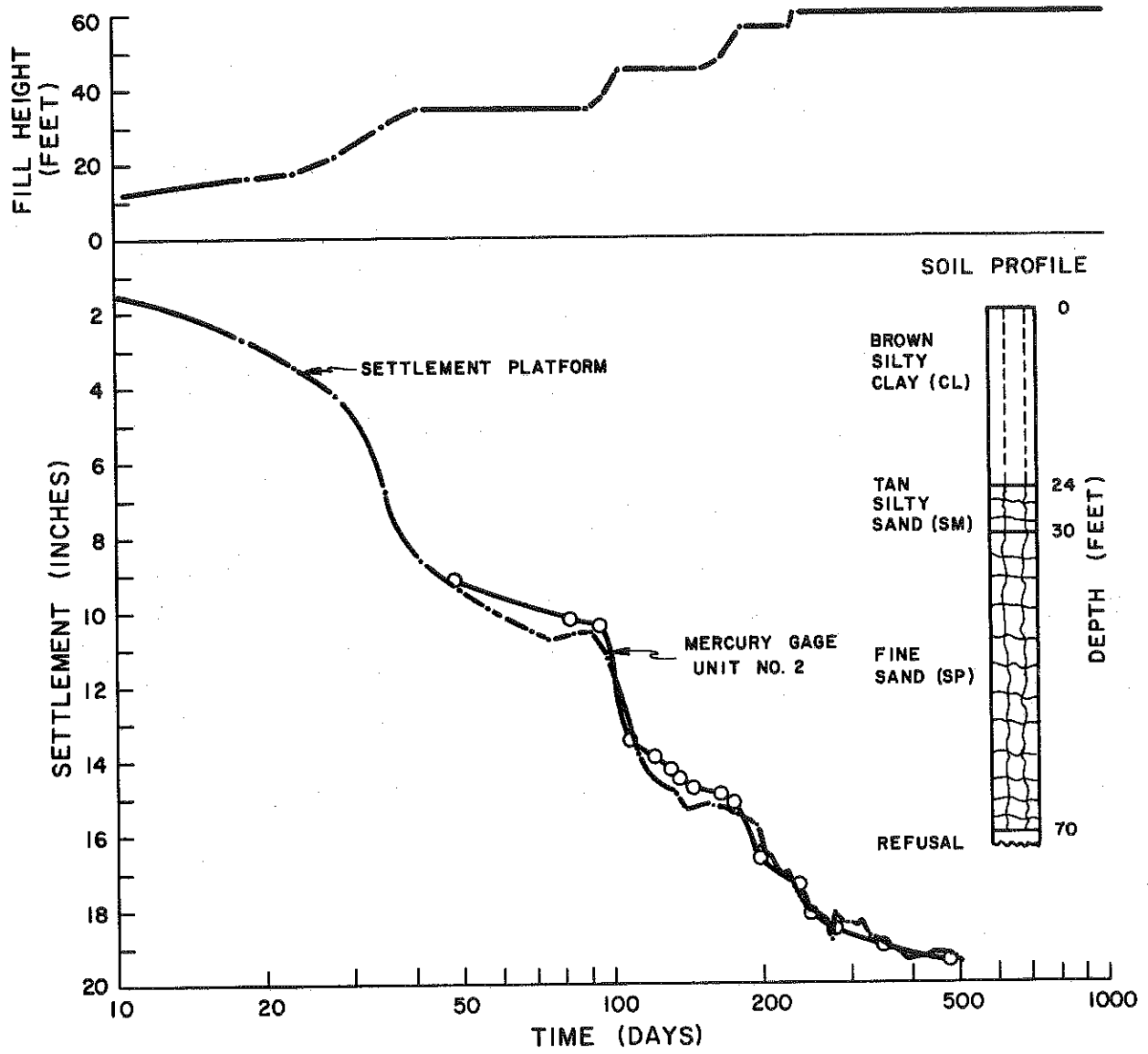


Figure 4. Settlement Curves for North Approach Foundation, Green River Site.

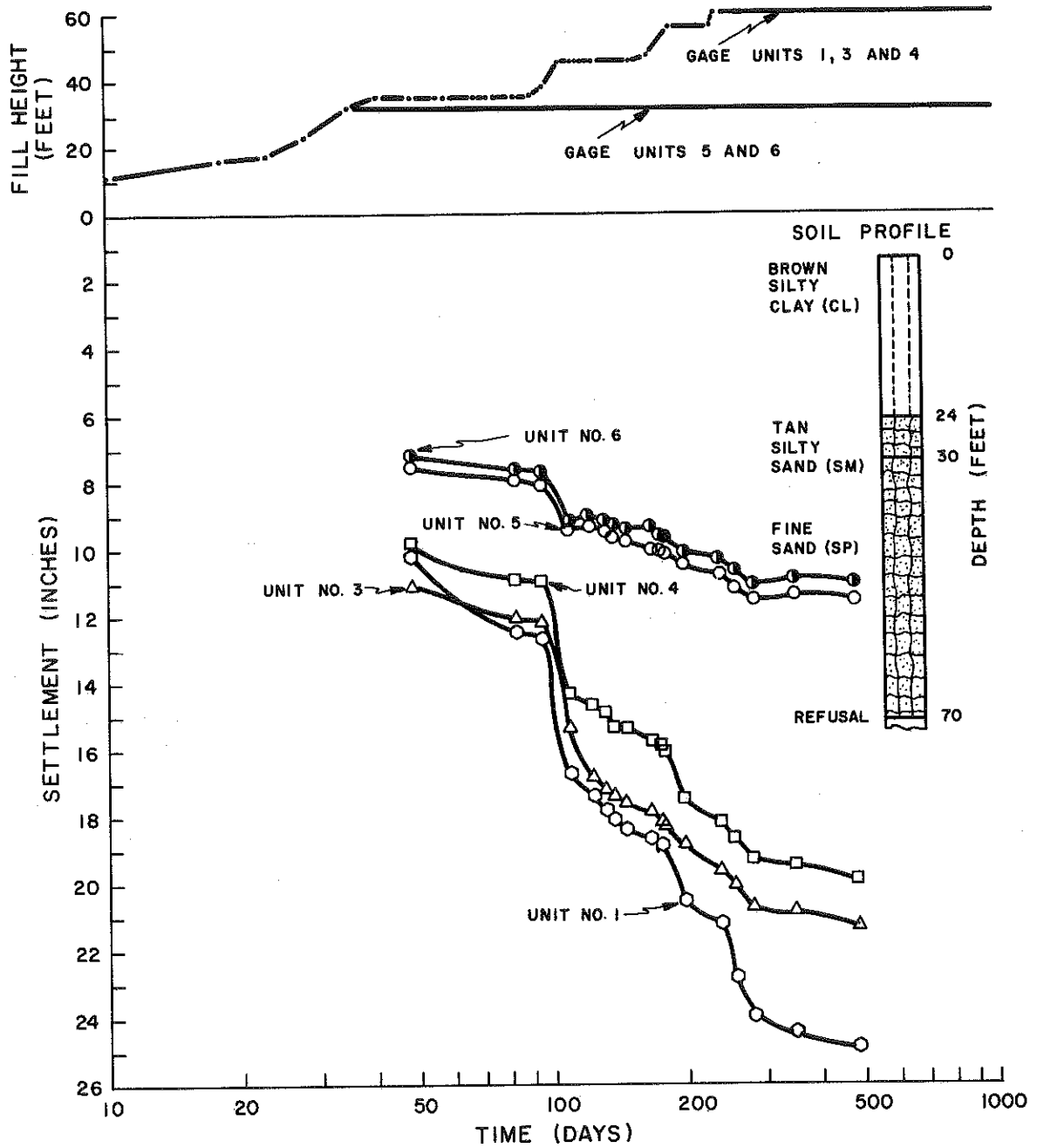


Figure 5. Settlement Curves for North Approach Foundation, Green River Site.

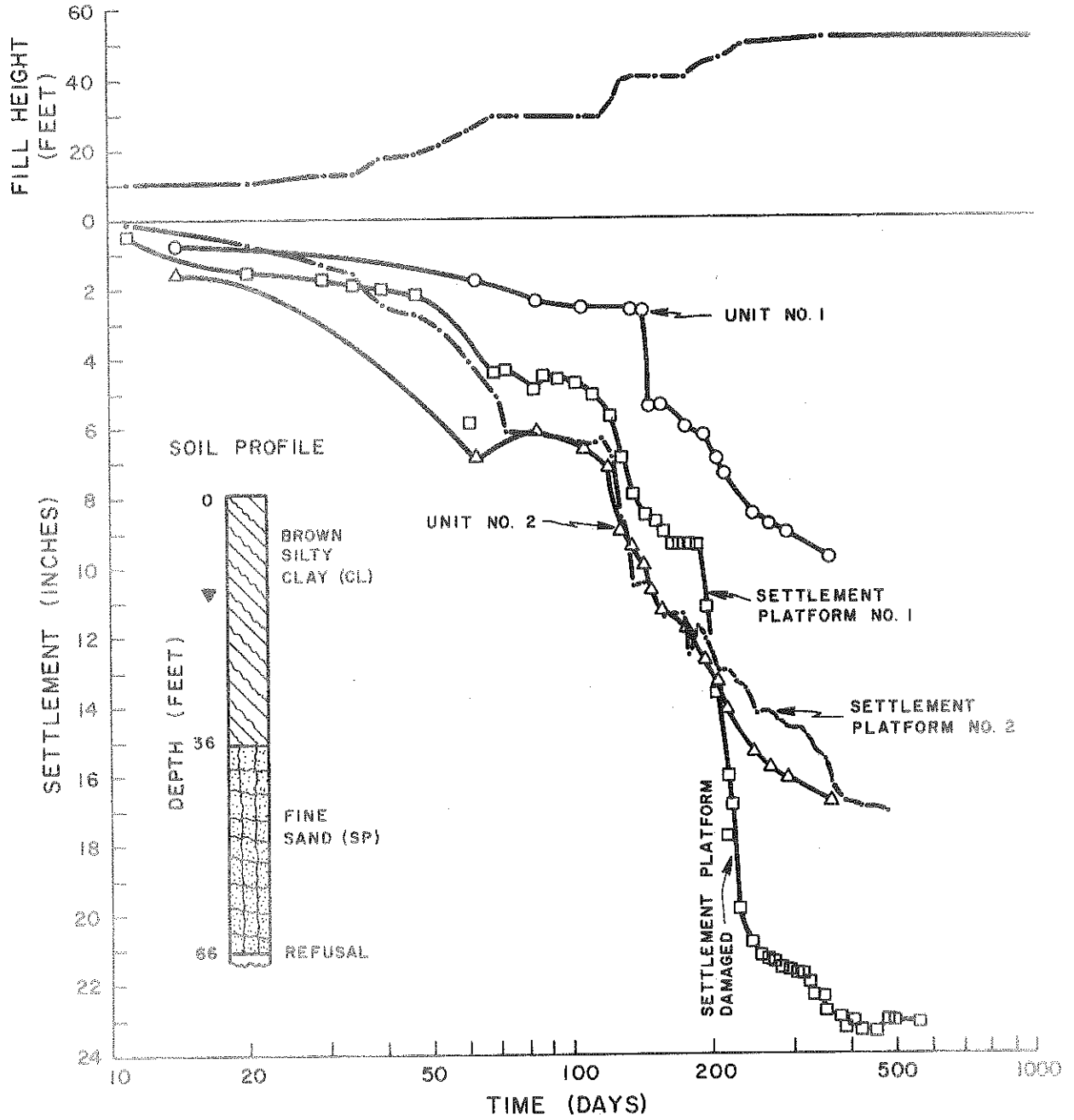


Figure 6. Settlement Curves for South Approach Foundation, Green River Site.

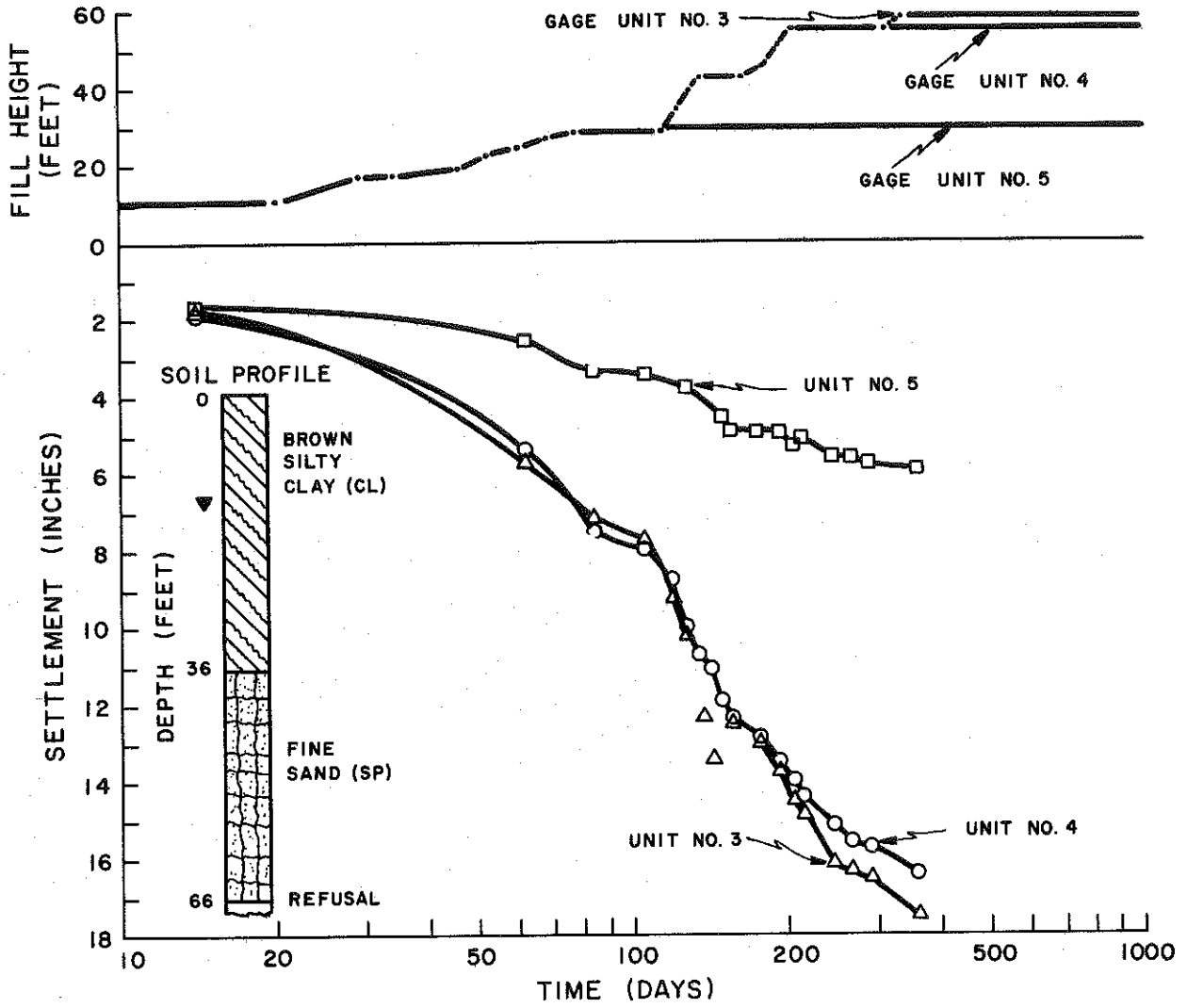


Figure 7. Settlement Curves for South Approach Foundation, Green River Site.