# SETTLEMENT STUDY

## FINAL REPORT

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ABSTRACT

This report covers field observations of several medium and high embankments' settlement along Interstate Highways 12 and 20. The predictive settlements from laboratory tests (consolidation tests) are given in an interim report published in July, 1980 (FHWA/La-80/119, "Settlement Study: Interim Report"). The procedures for computing the amount of settlement were standard ones, only the number of samples per boring varied from the normal number that is usually run. The "time of settlement" computations included both a procedure developed by Ray, Covington and Arman reported in Louisiana State University (LSU) Engineering Bulletin 82 as well as the regular method used by Louisiana Department of Transportation and Development (La. DOTD) at the time. Essentially, this research project is intended to determine whether the LSU method is a better procedure than the one the La. DOTD uses, i.e., whether the former comes closer to predicting the actual time of settlement than the latter.

The results, for the most part, are rather disappointing in that the actual settlement curves did not follow very closely the predictive curves using both the LSU and the La. DOTD methods. The closest that the actual settlement curve followed the predictive curves were for those embankments that were subject to very little settlement. For instance, the average $c_v$ for one location was 0.011 $cm^2/sec$ (0.1055 $in^2/min$) and the length of drainage is less than 1.5 m (5 ft) so that most of the settlement took less than two months.

In the opinion of the writer, the discrepancy can be ascribed to one or any combination of three usual factors, (1) the lack of sample saturation, (2) sample handling, and (3) disturbance through the sample procedure (core diameter was too small).

## METRIC CONVERSION FACTORS*

| To Convert from | To | Multiply by |
|---|---|---|
| | **Length** | |
| foot | meter (m) | 0.3048 |
| inch | millimeter (mm) | 25.4 |
| yard | meter (m) | 0.9144 |
| mile (statute) | kilometer (km) | 1.609 |
| | **Area** | |
| square foot | square meter ($m^2$) | 0.0929 |
| square inch | square centimeter ($cm^2$) | 6.451 |
| square yard | square meter ($m^2$) | 0.8361 |
| | **Volume (Capacity)** | |
| cubic foot | cubic meter ($m^3$) | 0.02832 |
| gallon (U.S. liquid)** | cubic meter ($m^3$) | 0.003785 |
| gallon (Can. liquid)** | cubic meter ($m^3$) | 0.004546 |
| ounce (U.S. liquid) | cubic centimeter ($cm^3$) | 29.57 |
| | **Mass** | |
| ounce-mass (avdp) | gram (g) | 28.35 |
| pound-mass (avdp) | kilogram (kg) | 0.4536 |
| ton (metric) | kilogram (kg) | 1000 |
| ton (short, 2000 lbs) | kilogram (kg) | 907.2 |
| | **Mass per Volume** | |
| pound-mass/cubic foot | kilogram/cubic meter ($kg/m^3$) | 16.02 |
| pound-mass/cubic yard | kilogram/cubic meter ($kg/m^3$) | 0.5933 |
| pound-mass/gallon (U.S.)** | kilogram/cubic meter ($kg/m^3$) | 119.8 |
| pound-mass/gallon (Can.)** | kilogram/cubic meter ($kg/m^3$) | 99.78 |
| | **Temperature** | |
| deg Celsius (C) | kelvin (K) | $t_K=(t_C+273.15)$ |
| deg Fahrenheit (F) | kelvin (K) | $t_K=(t_F+459.67)/1.8$ |
| deg Fahrenheit (F) | deg Celsius (C) | $t_C=(t_F-32)/1.8$ |

*The reference source for information on SI units and more exact conversion factors is "Metric Practice Guide" ASTM E 380.

**One U.S. gallon equals 0.8327 Canadian gallon.

## TABLE OF CONTENTS

LIST OF TABLES

## LIST OF FIGURES

## IMPLEMENTATION

This research showed that the LSU system of predicting the rate of settlement of large embankments came closer to the actual settlement rates than the system used by La. DOTD personnel at the time. However, errors in the techniques of testing and sampling, pointed out by subsequent research, was the probable cause of errors prevalent in even the closer method. (However, this research shows that the amount of settlement predicted by the Department personnel is fairly close to the actual amount.) Therefore, any implementation of this research will have to wait until the procedure can be repeated with better sampling and testing techniques.

# INTRODUCTION AND METHODOLOGY

In 1964 a report by Ray, et al. (1)* was published in which it was suggested the Louisiana Department of Transportation and Development could better predict the time of settlement of the embankments which Louisiana is required to construct at its bridge and overpass ends. The method described by Ray, et al., herein called the LSU method, is the square root of time fitting with some of the secondary consolidation considered as part of the settlement. This project was developed in order to determine whether, in fact, the LSU method is better than the standard La. DOTD method for predicting settlement of embankments. As a part of this study, a method which is a slight modification of the standard La. DOTD procedure was also checked. A short description of the three is warranted here. A part of the Interim Report, which presented the laboratory phase of this project (2), is quoted below.

> Comments on the Methods of Computation
>
> This project intends to check several methods of predicting amount and rates of settlements against one another and against field settlement records. Theoretically, if one was to measure the consolidation properties of all samples taken from a continuously cored hole, he should get the best possible prediction for that area. Unfortunately, this procedure is not often used because of cost. However, this study does just that for a comparison with the normal test program. Also, as mentioned before, a new procedure for predicting rate of settlement was to be compared to field data. All methods are listed as follows:

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*Underlined numbers in parentheses refer to the list of references in the back of the text.

Method A1 - Normal DOTD procedure for computing amount of settlement.

Method A2 - Modified normal DOTD procedure for predicting rate of settlement.

Method B1 - Computation of amount of settlement using all samples taken and DOTD procedure as above.

Method B2 - Rate prediction using DOTD system and all samples taken.

Method C2 - Rate computation using the method suggested by the research done by Ray, et al (1) and Method A1 for the amount.

A discussion of each method follows:

Method A1

Normal DOTD procedure requires that one representative sample be tested for each layer encountered. For this procedure continuous cores are taken and brought into the laboratory where they are opened and inspected. Cores which are adjacent to one another vertically and are similar in texture and stiffness are grouped into one layer, and a representative sample is selected, tested and used for computing the settlement characteristics of all samples within that group. Even though all samples were tested for this study, the process described above was adhered to so that the representative sample for the layer could be used for computation.

Method A2

The normal DOTD procedure for predicting rate of settlement is modified somewhat to fit into this project. Normally the rate of settlement computations are made so as to determine whether 12 inches (30.48 cm) of consolidation will occur between one and thirty years. (If the total amount of consolidation is less than 12 inches (30.48 cm) using Method A1, no rate is computed at all.) Terzaghi's time factor is utilized in the "one- to thirty-year" approach, determining the amount that takes place in one year and the amount that takes place in 30 years. The two are subtracted for the amount to take place after one year and before 30.

This procedure has been modified so that settlement curves can be drawn and compared to the curves required by Method C2--LSU's. In other words, the normal DOTD method does not require settlement curves. Here the same computations are altered so as to obtain the curve.

Method B1

Instead of using just one test specimen per layer, all samples taken are used to determine the amount of settlement. Computation procedures are exactly the same as Method A1.

Method B2

Again all samples are used to determine the rate of settlement and a curve drawn using the same computation as Method A1.

Method C2

This is the method suggested by Ray, et al in the "Consolidation Study." It deals strictly with rate of settlement and considers secondary consolidation as well as primary. Assuming that the amount of consolidation is being computed correctly, the proposed method is quoted below (1).

Proposed Method for Estimating Settlement

1. Run laboratory consolidation tests.

2. Plot dial reading versus time curves for each load increment using both square root of time and logarithm of time to find 100% primary consolidation.

3. If the values obtained for 100% primary vary appreciably, fit theoretical curves to the laboratory curves and determine which method (square root of time or logarithm of time) fits the data best. Use the method which best fits the data for finding the coefficient of consolidation.

4. Using the void ratio for 100% primary consolidation under each loading increment, plot a void ratio versus logarithm of pressure curve.

5. Find the maximum past pressure and determine the change in void ratio under the new load.

6. Using the relationships:

$$t_F = \frac{T(H_F)^2}{c_v} \quad \text{and}$$

$$\Delta H = \frac{H_F \Delta e}{1 + e_o}$$

Find the total settlement due to primary consolidation and draw the field settlement curve.

7. From the laboratory curve nearest the new overburden pressure, find $C_s$, the change in height per log cycle of the initial secondary slope.

$$\Delta H_L = C_s \log \frac{t_2}{t_1}$$

8. For secondary compression, estimate the time in the field and the change in height in the field on the basis of a linear relationship for change in height and the square of the ratio of the height for time.

$$\Delta H_F = \frac{\Delta H_L}{H_L} \quad (H_F)$$

$$t_F = \left(\frac{H_F}{H_L}\right)^2 \quad (t_L)$$

9. Draw a secondary settlement curve. This means add more points to settlement curve using eq above instead of

$$t_F = \frac{T(H_F)^2}{C_V}$$

10. Beginning at 90% primary consolidation, add the ordinate of the secondary curve to the primary curve.

IDENTIFICATION OF VARIABLES

$t_F$ = Time in the field
$T$ = Terzaghi's time factor
$H_F$ = Height in the field
$H_L$ = Height in the lab
$C_V$ = Coefficient of consolidation
$\Delta e$ = Change in void ratio
$e_o$ = Original void ratio
$t_1$ = Time in the lab at the beginning of the secondary compression cycle
$t_2$ = Time in the lab at the end of the secondary compression cycle
$\Delta H$ = Change in height
$t_L$ = Time in the lab

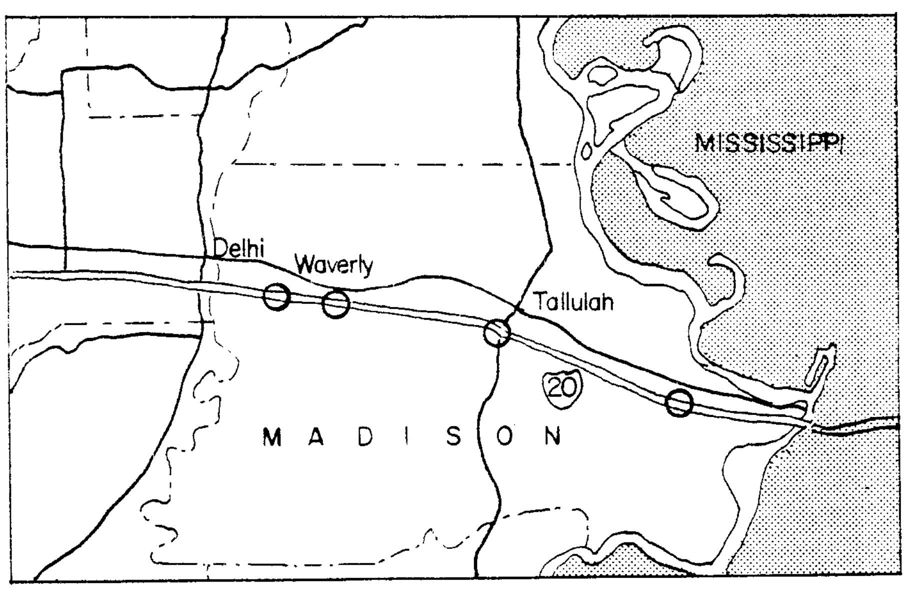
# RESULTS

## Interim Report

Before the results of the field settlements can be reported, a short discussion of the Interim Report should be presented. Six locations were chosen along two of the interstates in Louisiana. Four were along I-20 in the northern part of the state, and two were along I-12 located in the toe of the boot-like boundary of Louisiana. Those located in the north are situated on normally loaded soils while those in the southeast are on overconsolidated foundation material. The third condition, underconsolidation of the underlying materials, was considered for study by this project. But, as it was learned, the Department has made a practice of not building large embankments in areas that embody underconsolidated soils (soft soils) since the late '40s or early '50s.

The four (4) locations are shown in Figure 1 and described as follows (Table 1)--from west to east.

NORMALLY LOADED CONDITION




*Vicinity Map of I-20 Locations*

*FIGURE 1*

TABLE 1

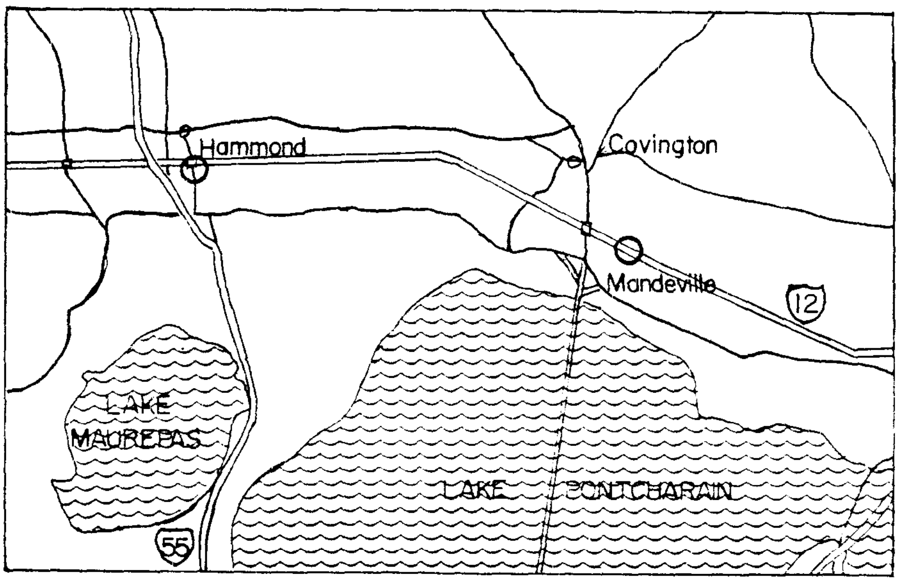
DESCRIPTIONS OF I-20 LOCATIONS

| FAP No. | Sta. Loc. | Structure Description | Fill Height | Crown Width |
|---|---|---|---|---|
| I-20-4(4)154 | 238+32 | Parish Road Overpass over I-20 | 23' | 34' |
| I-20-4(4)154 | 906+00 | I-20 over M.P.R.R. and Walnut Bayou | 32' | 132' |
| I-20-3(25)118 | 596+50 | Parish Road Overpass over I-20 | 22' | 34' |
| I-20-3(25)118 | 232+40 | La. 577 over I-20 | 25' | 34' |

All embankments were constructed with 4:1 side slopes.

The other location in which two (2) sites were built is shown by Figure 2 and described below (Table 2)--from east to west.

OVERCONSOLIDATED CONDITION




*Vicinity Map of I-12 Locations*

*FIGURE 2*

TABLE 2

DESCRIPTIONS OF I-12 LOCATIONS

| FAP No. | Sta. Loc. | Structure Description | Fill Height | Crown Width |
|---|---|---|---|---|
| I-12-1(9)39 | 248+40 | I-12 over U.S. 51 and I.C.R.R. | 30' | 120' |
| I-12-1(9)39 | 1580+00 | I-12 over La. 59 and G.M.O.R.R. | 35' | 120' |

Both of these were built with 3:1 slopes.

Three (3) bore holes were made at the La. 59/G.M.O.R.R. (I-12) location--one at either end of the two (2) structures that were constructed over the two features and one at the approximate center of the embankment between them. This center hole, as were the two end holes, was located in the median between the two (2) roadways. The other location on I-12 (U.S. 51/I.C.R.R.) had only one (1) boring centered between the two structures because there were houses located at the future ends of the structures at the time of drilling. Along I-20, the site at Walnut Bayou/M.P.R.R. had two (2) holes, one drilled in the western end adjacent to the west end of the bridge over the railroad and one between the two structures. Both were drilled on the median centerline. The other had two (2) holes at either end of the single structure.

The reader is referred to the Interim Report (2) for the details of the calculations; however, Table 3, which appeared therein as Table 1, is reproduced here. This table presents in summary what was found in the first phase of this study, namely, the amount and time/rate of settlement. As can be seen, the amounts of consolidation predicted for the normally loaded soils vary between 0.38 and 1.10 feet under fill heights that vary between 22 and 32 feet, whereas those fills along I-12 (preconsolidated soils) were predicted to settle as much as 1.73. Although the fills on the preconsolidated

TABLE 3
SUMMARY OF PREDICTED SETTLEMENTS

| Structure Type | Parish Road Over I-20 | | I-20 Over Walnut B., U.S. 65 & M.P.R.R. | | Parish Road Over I-20 | | La. 577 Over I-20 | | I-12 Over U.S. 51 & M.P.R.R. | I-12 Over G.M. & O.R.R. And La. 59 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boring Number | 1(20) ** | 2(20) ** | 3(20) | 4(20) ** | 5(20) | 6(20) | 7(20) | 8(20) | 1(12) ** | 2(12) ** | 3(12) | 4(12) ** |
| Station Location | 238+15 | Not Shown | 904+00 | 908+00 | 596+50 @ 51+25 | 596+50 @ 55+85 | 235+40 @ 17+50 | 232+40 @ 22+15 | 244+00 | 1572+50 | 1579+46 | 1597+00 |
| Fill Height | 23' | Not Shown | 32' | 32' | 22' | 22' | 25' | 25' | 30' | 21' | 39' | 48' |
| Amount Compressible Material | | Not Shown | 36' | 35' | | | | | | 74' | 64' | 52' |
| Method A-1 | 0.48' | Not Shown | 0.79' | 1.10' | 0.54' | 0.38' | 0.56' | 0.59' | 0.68' | 1.30' | 1.55' | 0.56' |
| Method B-1 | 0.38' | Not Shown | 0.81' | 0.87' | 0.55' | 0.49' | 0.66 | 0.59' | 0.84' | 1.38' | 1.73' | 0.61' |
| Method A-2* | 3 mos. | Not Shown | 80 mos. | 20 mos. | 58 mos. | 5 mos. | 29 mos. | 45 mos. | 36 mos. | <40 mos. | 10 mos. | 5½ mos. |
| Method B-2* | 3½ mos. | Not Shown | 45 mos. | 36 mos. | 73 mos. | 19 mos. | 45 mos. | 33 mos. | 20 mos. | 38 mos. | 12 mos. | 8 mos. |
| Method C-2* | 3/4 mos. | Not Shown | 18 mos. | 8 mos. | 9½ mos. | 8 mos. | 10 mos. | 7 mos. | 18 mos. | <40 mos. | 10 mos. | 6½ mos. |

*Time to reach 75% consolidation.

**Plates damaged during construction.

foundations were predicted to settle more than those on normally loaded soils, the preconsolidated fills are generally higher and there is more compressible material underlying them.

The predicted rates of consolidation are summarized by showing how long it was predicted to reach 75% of total consolidation discussed in the above paragraph. As can be seen, the times vary from 0.4 to 6.6 years. Only in one case does the C-2 time (LSU) exceed the standard methods of computation. This cannot be explained by the author.

Present Report

Figures 3 through 6 in the Appendix are photographs of the structures at which the settlement plates were placed. The reader will find little sign of distress from consolidation in these photographs. The exception is I-12 over U.S. 51 and M.P.R.R., but, unfortunately, no pictures of it are shown. An asphalt "leveling course" was placed subsequent to construction in order to smooth the bump that developed between the bridge and the fill.

Time of settlement curves are presented in the Appendix. Several of the plates were damaged during construction to such an extent as to render them unusable. These locations are indicated by a double asterisk on Table 3.

Seventy-five percent consolidation ($U_{75}$) as determined by the three predictive methods--standard La. DOTD method (A-2), modified La. DOTD method (B-2), and the LSU method (C-2)--is shown on the curves as well as the total amount predicted by A-1 and B-1 methods (standard and modified La. DOTD methods). The $U_{75}$ of the curves falls closest to the LSU method. Table 4 presents a summary of those values shown on the curves.

Some discussion of Table 4 is in order even though the results speak for themselves. There is no doubt that the closest agreement

TABLE 4

SUMMARY OF FIELD RESULTS

| Structure | I-20 Over Walnut B., U.S. 65 & M.P.R.R. | Parish Road Over I-20 | | La. 577 Over I-20 | | I-12 G.M. & O.R.R. And La. 59 |
|---|---|---|---|---|---|---|
| Station Location | 904+00 | 596+50 @ 51+25 | 596+50 @ 55+85 | 235+40 @ 17+50 | 232+40 @ 22+15 | 1572+46 |
| Fill Height | 32' | 22' | 22' | 25' | 25' | 39' |
| Total Consolidation | | | | | | |
| Method A-1 | 0.79' | 0.54' | 0.38' | 0.56' | 0.59' | 1.55' |
| Method B-2 | 0.81' | 0.55' | 0.49' | 0.66' | 0.59' | 1.73' |
| Field | 0.94' | 0.60' | 0.58' | 0.60'(?) | 0.46' | 1.20' |
| Time to Reach 75% of Total Consolidation $U_{75}$ | | | | | | |
| Method A-2 | 85 mos. | 58 mos. | 5 mos. | 29 mos. | 45 mos. | 10 mos. |
| Method B-2 | 45 mos. | 73 mos. | 19 mos. | 45 mos. | 33 mos. | 12 mos. |
| Method C-2 | 18 mos. | 9½ mos. | 8 mos. | 10 mos. | 7 mos. | 10 mos. |
| Field | 25 mos. | 12 mos. | 28 mos. | 15 mos. | 16 mos. | 4 mos. |

between the field time and the three predictive methods is the C-2 (LSU's) versus field comparison. True, the differences varied for field times from -82% to +240% in the A-2 method, and -32% to +508% in the B-2 method, but the C-2 variance was from -20.8% to +150%. Statistically speaking, standard error of the estimate of a first degree regression analysis (straight line) of C-2 (X) versus field (Y) is 7.66 months (see Figure 13 in the Appendix). The equation is $Y = 10.06 + 0.65X$. Therefore, one would expect a C-2 method of prediction of say 15 months for 75% of total consolidation ($U_{75}$) to yield a field $U_{75}$ of 19.5 months (a pretty accurate estimate to say the least) (see Figure 13). The difficulty comes in with the 7.66 (months) standard error of estimate. Standard errors are analogous to standard deviations in that 68% of all data points fall within ± 1 standard error band about the regression line, 95% of all the points are within ± 2 standard errors, and ± 3 standard errors contain virtually all points (99.7%). Therefore, to be 95% accurate one has to consider two standard errors of the estimate in one's prediction. Hence a prediction of 15 months for $U_{75}$ could yield anywhere from 42 months to 34.8 months time in the field for 75% of consolidation (15 ± 2 X 7.66).

## DISCUSSION OF RESULTS

The following should not be considered an excuse as to why there was such a wide variation in the predictive and field times, but rather as a defense of the methods of prediction. Errors of commission and omission were committed by technicians doing the sampling and testing through no fault of their own. The "state of the art" within the Department at the time dictated which techniques the technicians used. The writer believes that the majority of the variations were of this type.

### Sampling

Since the completion of the laboratory phase of this project, the Department undertook another project entitled "The Effects of Conventional Soil Sampling Methods on the Engineering Properties of Cohesive Soils in Louisiana" (3). This study, also done at Louisiana State University, demonstrated that several techniques used by the Department were in error. Radiography showed that the Department's method of preparing the sample for transportation to the laboratory was hazardous to the sample. Further, the research indicated that the method of extruding the soil from the core barrel and the handling of the core after extrusion were not "state of the art." These erroneous techniques were in use at the time of this study.

### Testing

Additionally, core diameter was discussed in the Arman and McManis (3) report. Three-inch-diameter (3"-ø) cores, 5"-ø cores, and one-cubic-foot block samples (undisturbed) were examined. A significant difference was found between the $C_v$'s in a 2"-ø test sample carved from a 3"-ø "undisturbed" core and the $C_v$'s of the same size test sample carved from both the 5"-ø core and the block sample. The implication here was that a certain amount of disturbance takes place in a 2"-ø test sample taken from the center of a 3"-ø core that is not present in the same size test sample carved from either the 5" core or the block. That is to say, pushing a 3"-ϕ core drives the particles closer together, which decreases the permeability, which increases the $C_v$, which increases the time of settlement. Similar differences were exhibited in the shape of the e-log P curve which affects the amount of consolidation and differences in compression testing.

Other examples of testing errors were:

1. Pushing a sample cutter into the core instead of trimming with a wire saw.
2. Smearing the sample at the top and bottom by planing the soil even with the consolidometer ring.
3. Storage of the sample for two or three weeks before testing.

And sampling errors were:

1. Ejecting the core from the barrel with hydraulic pressure.
2. Extrusion of the sample through the tapered cutting edge rather than the way it entered the barrel.

One other shortcoming of this procedure is the fact that the theory of consolidation is one-dimensional, i.e., the interstitial water is forced from a foundation soil in a vertical direction only. Common sense would dictate that some of the moisture would drain in the horizontal direction, especially at the interface of two layers the upper of which has a lesser permeability than the lower. In a literature review by Olsen and Daniel cited in Reference 4, it is indicated that in fine-grained soils the permeability obtained from field tests is observed to be 0.4 to 64 times the laboratory values. Al-Dhahir, et al. (5) observed that the in-situ constant head test rendered 20 to 50 times the values obtained from the oedometer.

## CONCLUSIONS

1. The amount of settlement is closely predicted by both methods of interpretation shown in this report. The highest variation between the laboratory and the field was six inches.

2. The results of the testing indicate that the Department need not run every core taken from a boring to obtain the needed accuracy. Only those who have to maintain close tolerances need the extra tests.

3. The foundation group could eliminate the expense of transporting all cores to the laboratory by allowing the squad leader to choose representative cores of similar and adjacent samples.

4. The rate of consolidation prediction methods were not as accurate as the "amount" predictions. Rate predictions were as much as five times field rates. A statistical analysis showed the standard error of the estimate to be in excess of ± 1 year on method C-2, the method which exhibited the least variation in prediction with the field settlement.

5. The sampling and testing techniques that the Department was using at the time of this project have been improved. The extent to which these improvements have affected predictions has not been investigated.

## REFERENCES

1. Ray, J. R., Convington, B. J., Arman, A., "Consolidation Study," Louisiana State University, Baton Rouge, La., 1964.

2. Walters, W. C., "Settlement Study - Interim Report No. 1," Louisiana Department of Transportation and Development, Research and Development Section, Baton Rouge, La., July 1980.

3. Arman, A. and McManis, K. L., "The Effects of Conventional Soil Sampling Methods on the Engineering Properties of Cohesive Soil in Louisiana," Louisiana State University, Engineering Bulletin 117, July 1977.

4. Tumay, M. T., et al., "Analysis of Dissipation of Pore Pressures After Cone Penetration," Louisiana State University, College of Engineering, Baton Rouge, La. (unpublished preliminary report).

5. Al-Dhahir, A. A., et al., "Observations of Pore Pressures Beneath the Ash Lagoon Embankments at Fiddler's Ferry Power Station," Conference on In-Situ Behavior of Soil and Rock, Institute of Civil Engineers, pages 175-186, 1975.

# APPENDIX

*Parish Road Overpass - I-20, Station 238+00*
*No sign of embankment distress. However,*
*a pavement failure is to the left.*

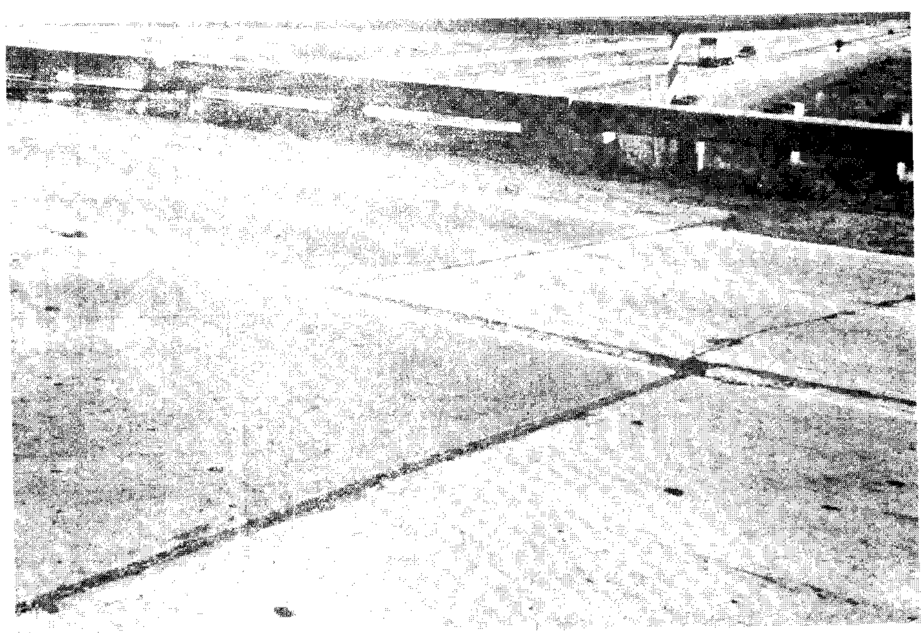
*FIGURE 3*

*I-20 Overpass - M.P.R.R. and Walnut Bayou*
*Station 904+00 Looking west on the eastbound*
*roadway. Structure is over M.P.R.R.*

*FIGURE 4*

*Parish Road Overpass - I-20, Station 596+50*
*Smooth transition from roadway to bridge.*

FIGURE 5



*La. 577 Overpass - I-20, Station 232+40*
*Failure (crack) shown here is due to the offset relief joints designed to accommodate the skewed bridge. Not a settlement crack.*

FIGURE 6

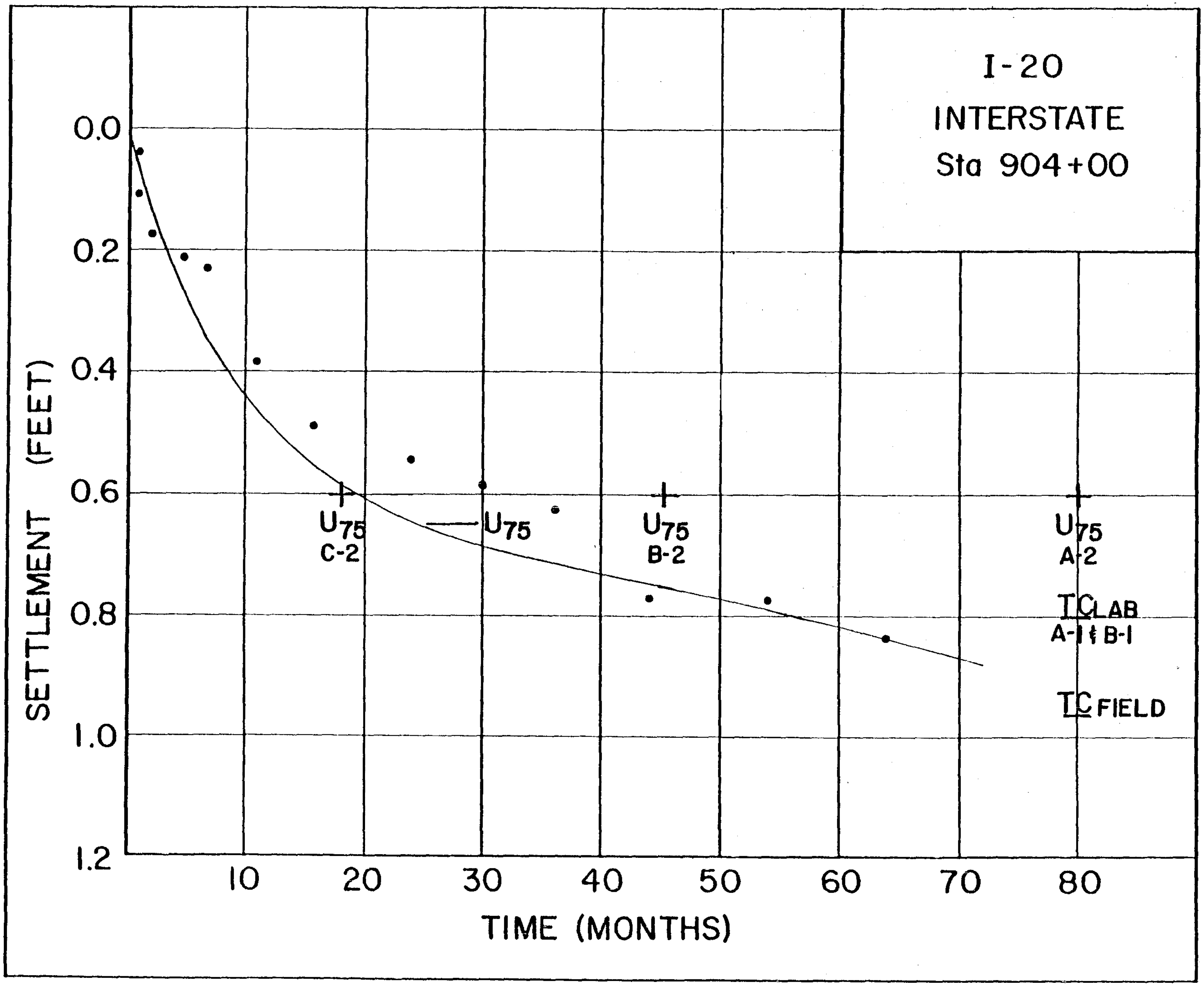



*Figure 7: Settlement Rate - I-20, Station 904+00*

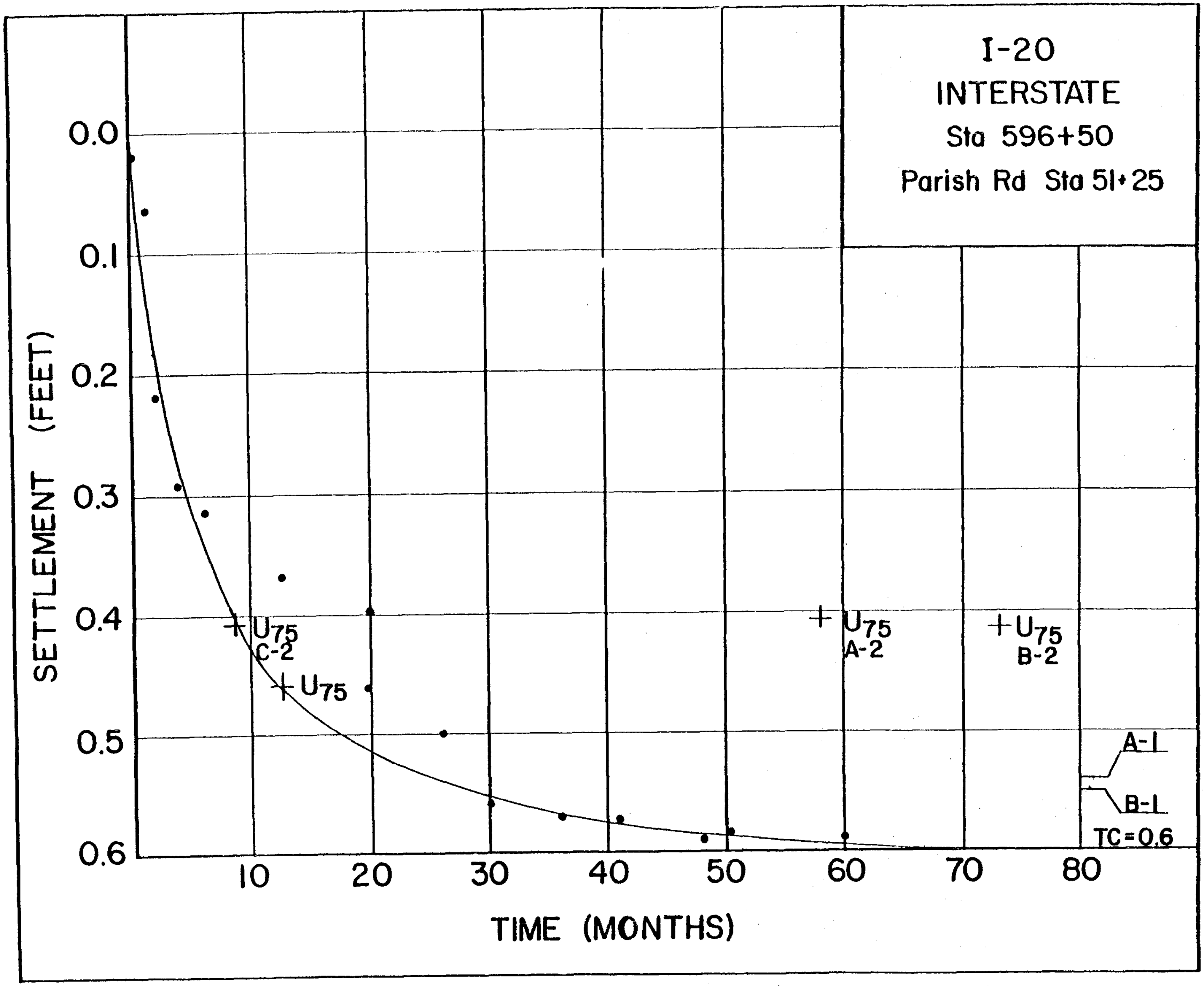



*Figure 8: Settlement Rate - I-20, Station 596+50*

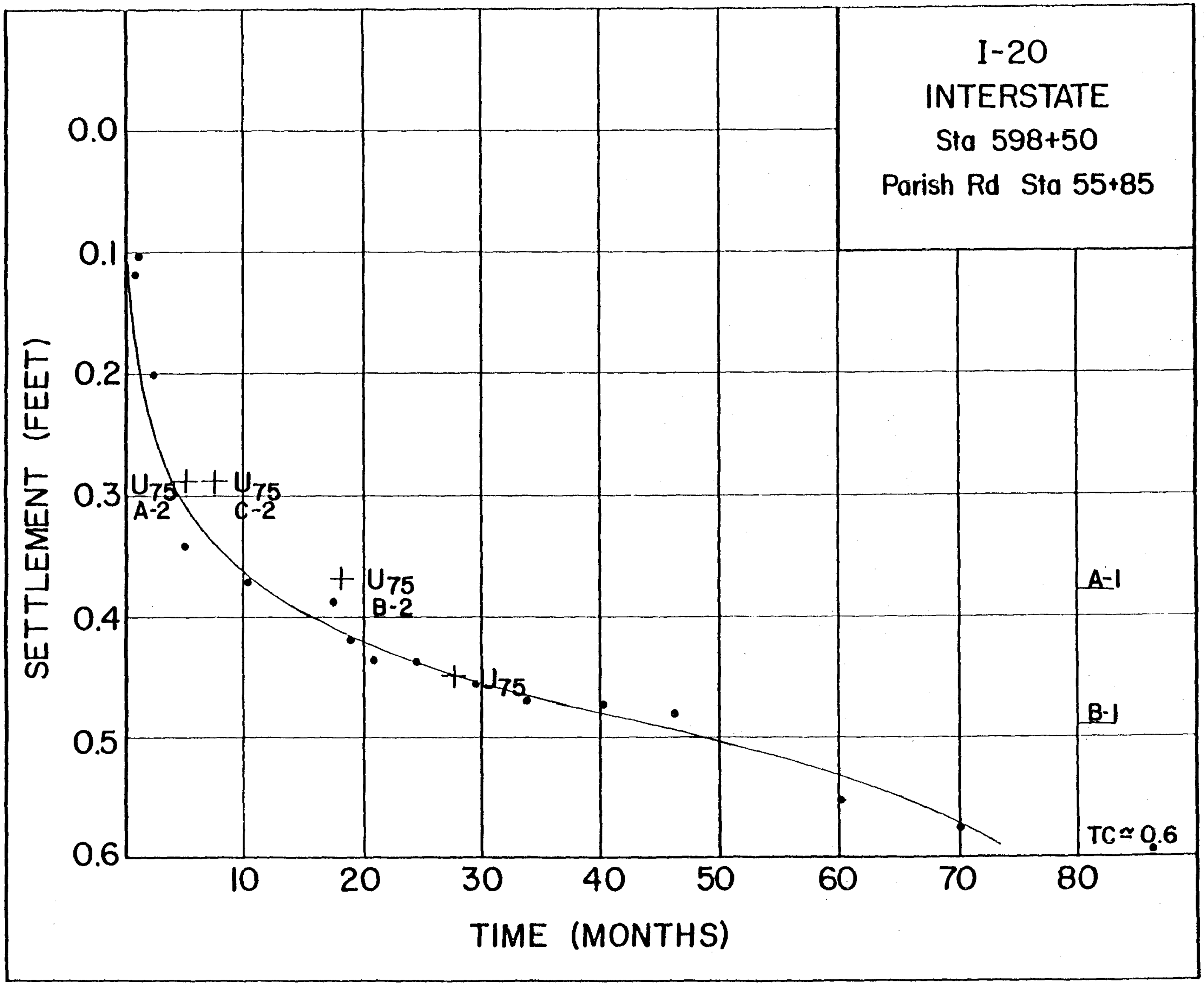



*Figure 9: Settlement Rate - I-20, Station 598+50*

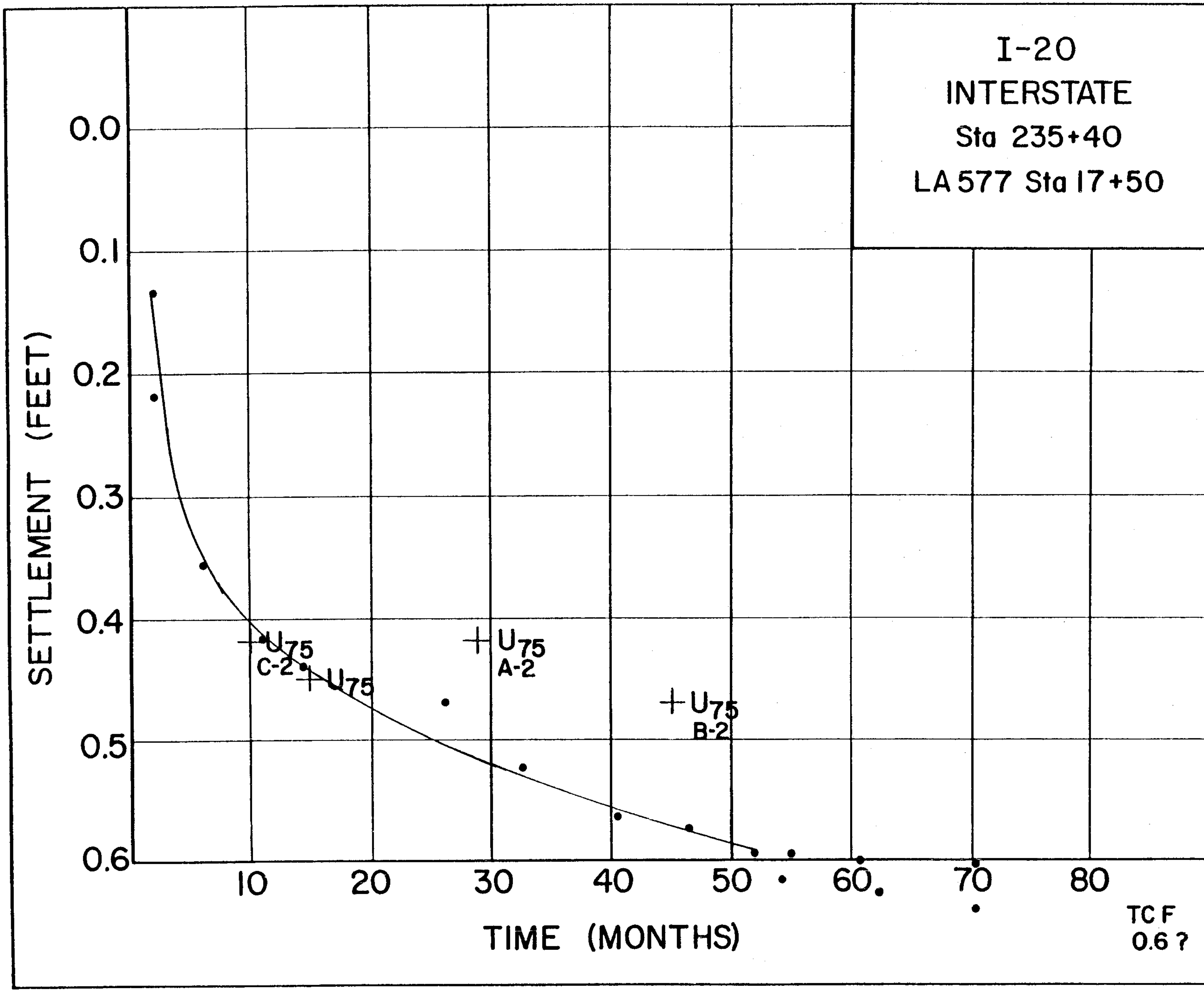



Figure 10: Settlement Rate - I-20, Station 235+40

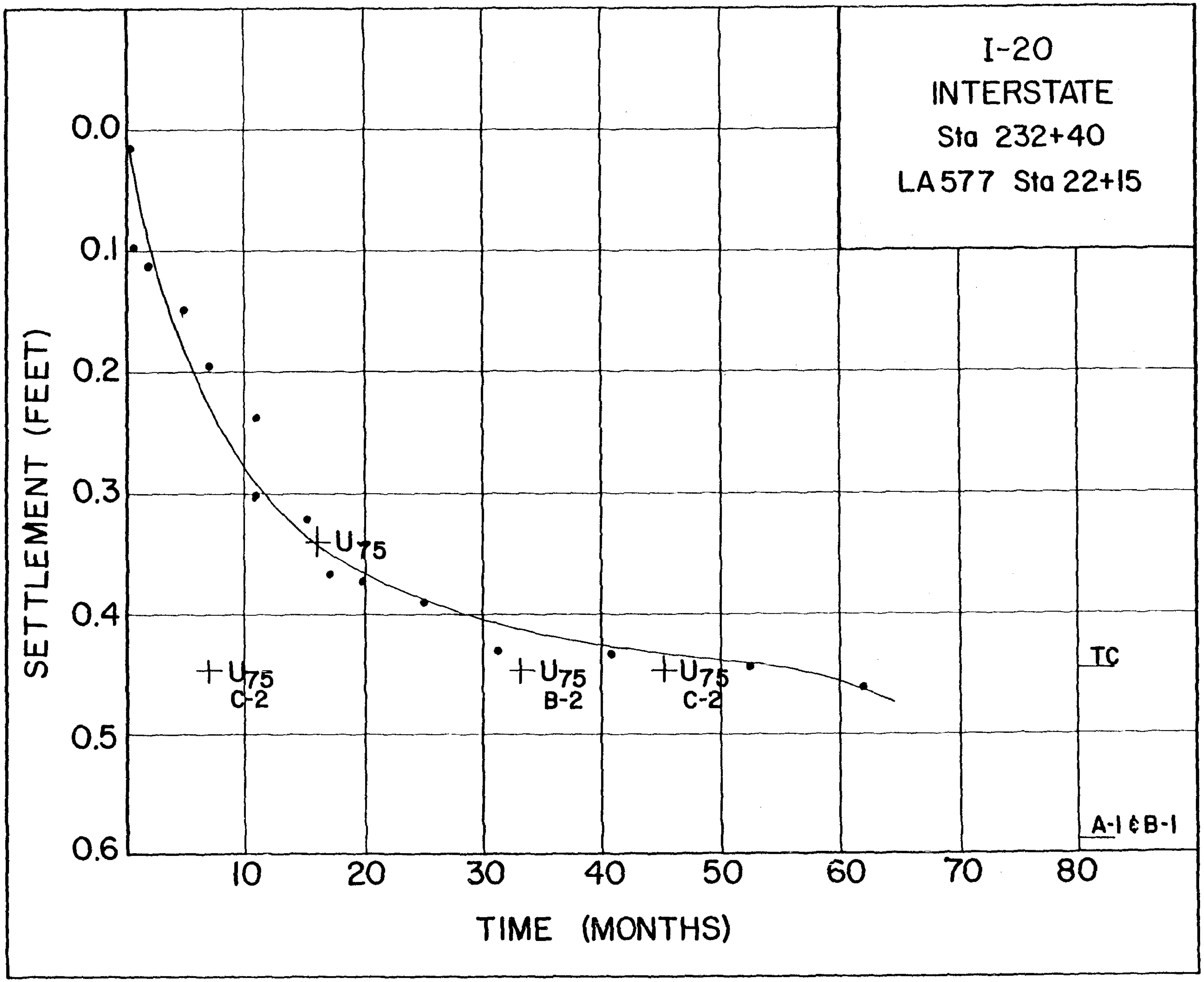



Figure 11: Settlement Rate - I-20, Station 232+40

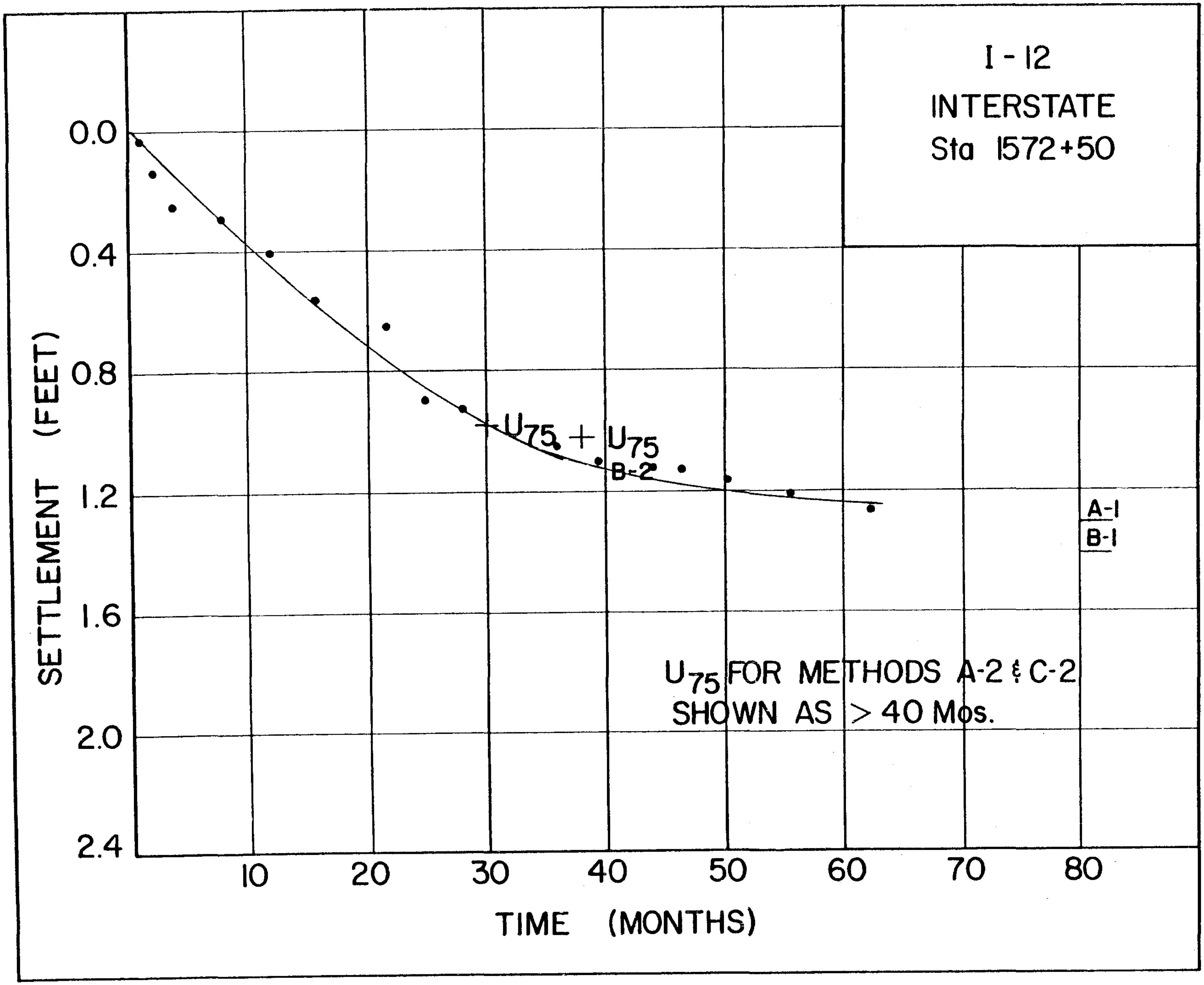



Figure 12: Settlement Rate - I-20, Station 1572+50

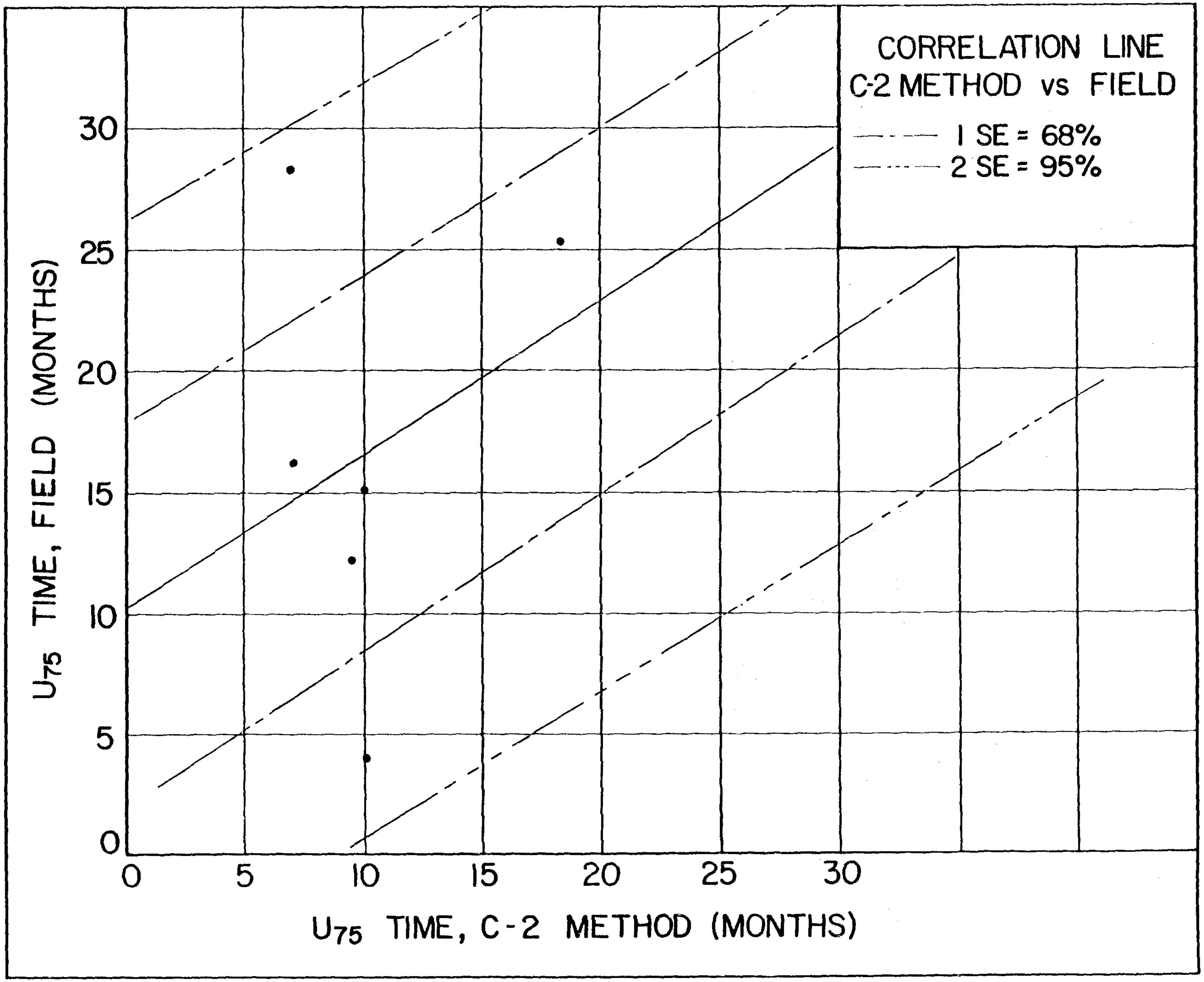



*Figure 13: Correlation Line - C-2 Method vs Field*