REGRESSION. The proposed model was found to be statistically valid and accurate. Equation 1 allows one to predict or control the given response in terms of important compaction variables—namely, water content and compaction pressure.

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Stabilization of a Sanitary Landfill to Support a Highway

RONALD E. SHEURS AND RAJ P. KHERA

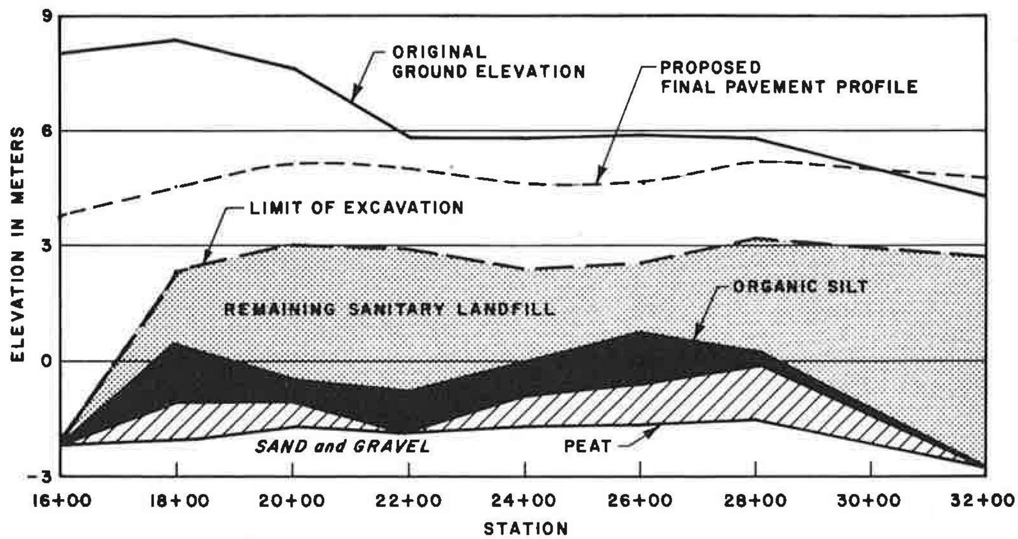
The results of the stabilization of a sanitary landfill by use of surcharges are reported. The New Jersey Department of Transportation has undertaken the construction of two experimental roadways—I-85 eastbound and I-85 westbound—directly over landfills that contain partially decomposed garbage. Field measurements of settlement and pore-water pressure are presented. The data indicate that the settlement response of a landfill area is similar to that of fine-grained soils. Stress history plays an important role in this response. When the ratio between the stress increase caused by surcharge load and the existing stress was <1, the measured strain was only 5-7 percent. When this ratio was 1.4 or greater, the strain varied between 11 and 17 percent. The compression ratio for the sanitary landfill was found to range between 0.16 and 0.20. Piezometric heads were found to be erratic and frequently much higher than the projected values. This was attributed to the expulsion of methane gas from the inner piezometric tube.

Relatively little is known about the behavior of a sanitary landfill subjected to loadings such as buildings or embankments. Extensive foundation problems can result unless the landfill has been stabilized before structures are placed on it. Studies have been reported on a range of stabilization techniques, from chemical injections of grout and fly ash to applications of surcharges (1). Most of the work done to date has been done only under laboratory conditions or small, controlled field conditions.

The New Jersey Department of Transportation (DOT) has undertaken the construction of two roadways directly over landfills that consist of partially decomposed garbage. The project is located on the north side of an active sanitary landfill. The experimental roadways are I-85 eastbound and I-85 westbound. These roadways have a total length of 975 m (3200 ft) and are part of the I-280 construction project in Kearny, New Jersey. Stabilization is being attained by the use of 1.8-m (6-ft) surcharges over a minimum period of 24 months. Settlement plates and piezometers are being used extensively to monitor the progress of the work.

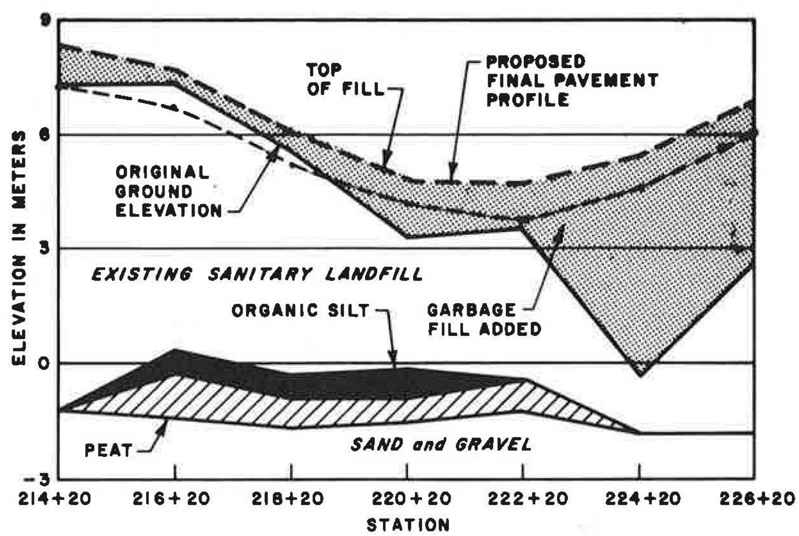
This is an experimental approach to highway construction that the New Jersey DOT has not previously attempted. In the past, it has used overloads with and without the aid of vertical sand drains to accelerate the stabilization of natural deposits of clays and marshlands but not of landfill areas. If adequate stabilization of the

Figure 1. Soil profile for I-85 eastbound.



Note: 1 m = 3.3 ft.

Figure 2. Soil profile for I-85 westbound.



Note: 1 m = 3.3 ft.

sanitary landfill can be achieved in the present project, then a similar or a modified approach can be used on future highway projects.

In April 1977, actual construction and excavation work began at the easterly end of I-85 eastbound, and a general leveling process to a maximum cut of about 9 m (30 ft) began at its westerly end (see Figures 1 and 2). Because of original ground conditions, I-85 westbound required the addition of sanitary landfill. The material used for this fill was obtained from the excavation of I-85 eastbound. All material placed along the westbound roadway was compacted by using from three to five passes of a 312-kN (35-ton) sheepsfoot compactor.

Work progressed at an average excavation of 1913 m^3/day (2500 yd^3/day). This rate decreased considerably following days of rain because of slippery ground conditions and large differential settlements.

A total of 119 360 m^3 (156 000 yd^3) of sanitary landfill was excavated along the experimental roadway. To add to the overall difficulty in excavation operations, approximately 38 260 m^3 (50 000 yd^3) of oil-saturated material was encountered and had to be hauled to specially prepared and lined disposal sites.

SOIL CONDITIONS

Soil borings and laboratory testing of soils were done between 1966 and 1971. The ground elevations and the elevations of the groundwater table recorded on the boring logs and those determined at the time of construction were not in agreement. Most of the landfill material encountered was between 5 and 15 years old. The age of the material was determined from conversations with local authorities responsible for the landfill and the personnel working at the site. This was confirmed from visual examination of the state of the landfill during the excavation of such materials: Newspapers were still readable, cans were not completely rusted, and various types of household refuse were still distinguishable.

The materials in the landfill included normal household refuse, truck bodies, paints, plastics, and chemicals in various states of decomposition, with thin layers of cover material. The underlying material consisted of an average of 1.25 m (4 ft) of gray-black clayey organic silt. Below the organic silt was about 0.9 m (3 ft) of brown peat and fibrous vegetation, followed by 6-7.5 m (20-25 ft) of dense, coarse to fine sand and gravel with traces of silt. The soil profile and the amount of garbage removed and/or replaced along the experimental roadway are shown in Figures 1 and 2.

The soil profile within the experimental sections is basically consistent throughout the project areas, the major difference being that the landfill operations had extended only about one-third the length of the entire project.

Laboratory consolidation tests were performed on undisturbed samples of various underlying natural deposits. Since the number of consolidation tests was limited, based on the nature of the materials present below each of the settlement plates, appropriate test results were selected to best represent the properties of the undisturbed underlying materials, such as organic silt and peat strata. No laboratory consolidation tests were done on landfill materials.

PROPERTIES OF LANDFILL MATERIALS

The density of a typical landfill can vary greatly. The density of the material, as delivered to a sanitary landfill, ranges from 120 to 419 kg/m³ (7.5-26 lb/ft³), and the water content ranges from 10 to 35 percent (2). After the garbage is deposited, it is spread by means of a bulldozer in layers as thick as 3 m (10 ft), which are compacted to different degrees and covered with soil, as required by various local authorities and ordinances. In the past, virtually no control has been exercised in landfill operations, but such operations are being managed better on more recent and better-designed landfills.

The total unit weight of the present landfill materials, which have been in place for several years, was taken as 1129 kg/m³ (70 lb/ft³). Under buoyant conditions, the unit weight was assumed to be 484 kg/m³ (30 lb/ft³). Where the existing landfill was excavated and then compacted (after a certain amount of sorting, which consisted of removal of large articles such as refrigerators, truck bodies, and washing machines), its unit weight was taken as 1450 kg/m³ (90 lb/ft³).

POTENTIAL PROBLEMS IN LANDFILL AREAS

The major areas of concern from a geotechnical viewpoint were the large total and differential settlements, both short- and long-term. The short-term settlements occur during construction as a result of the operation of the construction equipment. Such settlements make the work with construction equipment very difficult, time-consuming, and expensive. The long-term settlements are the result of the weight of the material itself and of applied loads as well as the decomposition of the landfill materials (chemical and biological).

Other problems arise from the potential of spontaneous combustion and possible ill effects on workers attributable to chemical actions and the generation of gases.

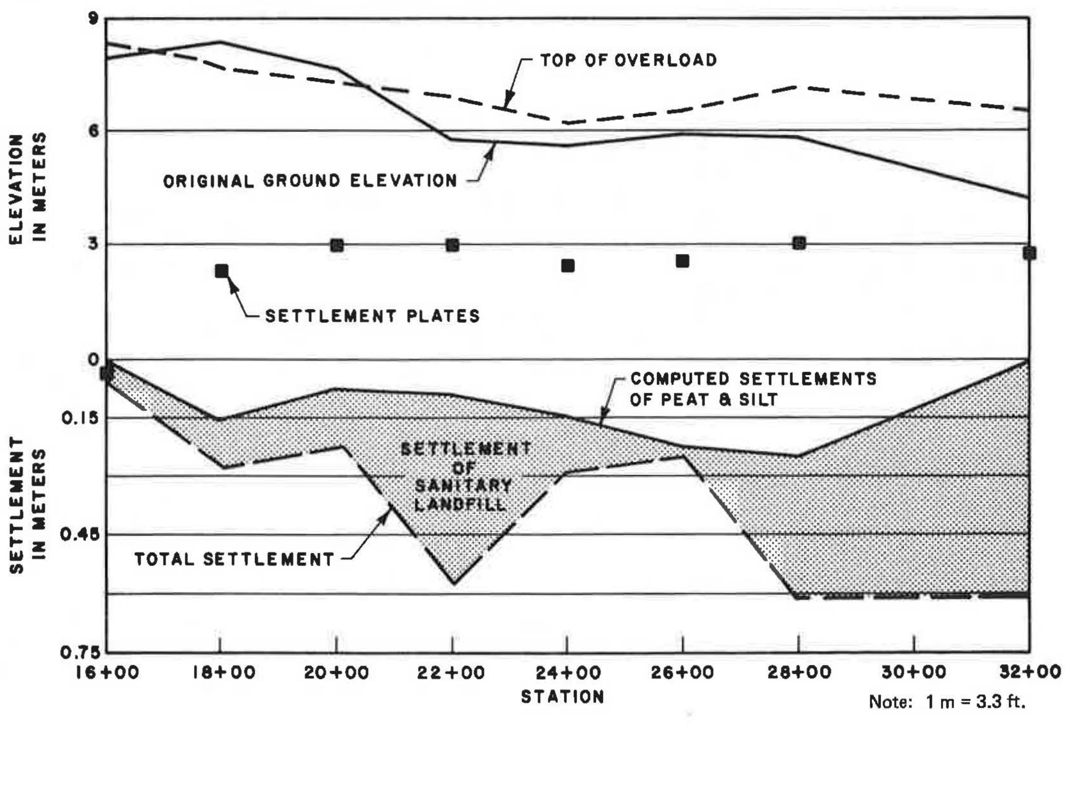
SETTLEMENT PLATFORMS AND PIEZOMETERS

All settlement platforms were placed three in a group, and each group was located 61 m (200 ft) on center. At each location, all platforms were placed at the same elevation, one unit at each shoulder and one along the centerline of the proposed finished pavement. The results reported were for those settlement platforms along the centerline of the roadways.

Before the placement of the settlement platforms along I-85 eastbound, a 15- to 30-cm (6- to 12-in) layer of cohesionless material was placed to provide a suitable level base for the settlement platform. The settlement platforms consisted of a 0.9-m by 0.9-m by 12.7-mm (3-ft by 3-ft by 0.5-in) steel plate attached to a 1.22-m by 12.7-mm (4-ft by 0.5-in) standpipe. All plates were set level, and standpipes were set plumb. Base elevations of settlement plates are shown in Figures 3 and 4.

After the settlement platforms had been placed, heavy liquid piezometers were installed so that the piezometer tips were in the underlying natural soil deposits. The piezometers were intended to serve as a control on the rate of placement of surcharge, which was designed to be placed at a weekly rate of 1.22 m (4 ft). The monitoring of the piezometers indicated that the piezometric heads did not conform to the expected values but were highly erratic, as Figure 5 shows. This response was attributed to the expulsion of methane gas from the inner piezometer tube. Thus, the effectiveness of the piezometers became highly questionable and their readings unreliable. So far, however,

Figure 3. Settlements for eastbound roadway.



Note: 1 m = 3.3 ft.

Figure 4. Settlements for westbound roadway.

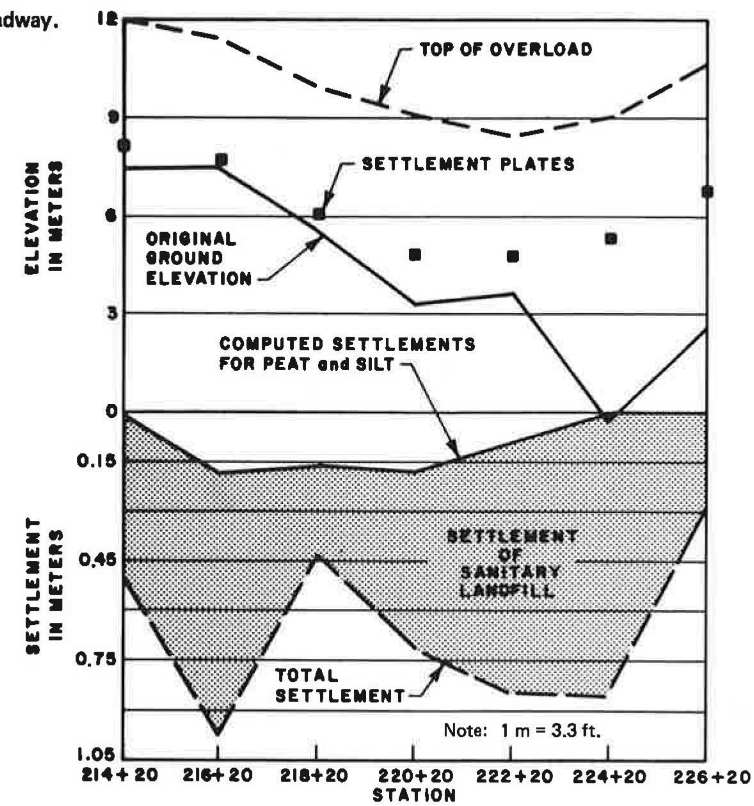
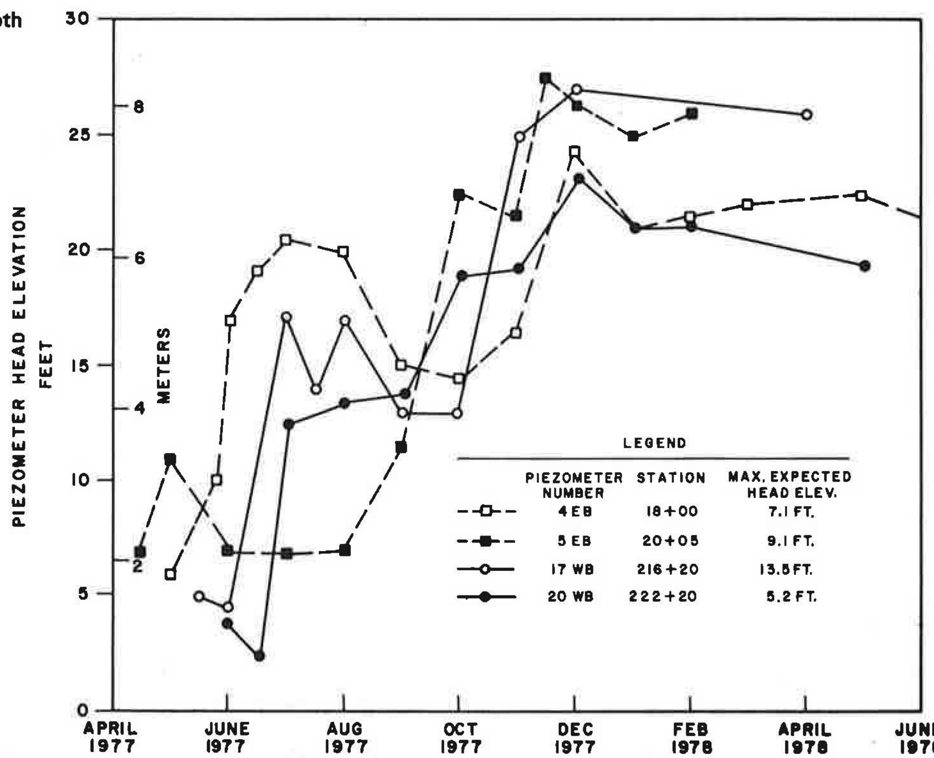


Figure 5. Piezometric heads for both roadways.



failure has not occurred at this rate of application of surcharge.

SETTLEMENT DATA AND ANALYSIS

Settlement-plate readings were taken for all settlement platforms from time to time. Figure 6 shows plots of settlement values for two of the settlement platforms for the eastbound section. Plots for the westbound section are shown in Figure 7. Settlement plots for stations under which only landfill existed but no peat or organic material was encountered are shown in Figure 8.

In general, all of these settlement-time curves are alike and not much different in shape from those observed for fine-grained soils. In the early periods of time, the settlement increases rapidly and then continues to increase

Figure 6. Settlement time for eastbound roadway.

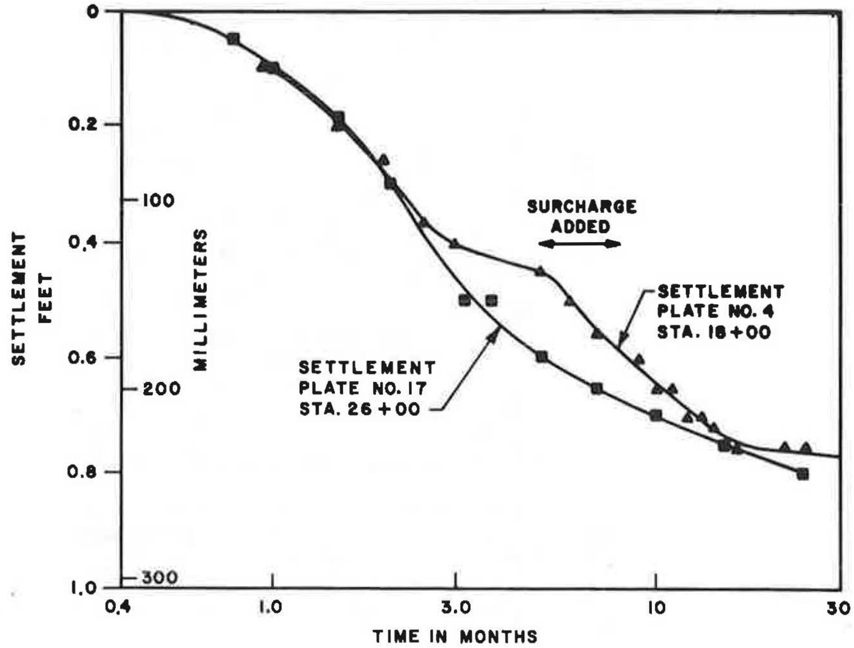
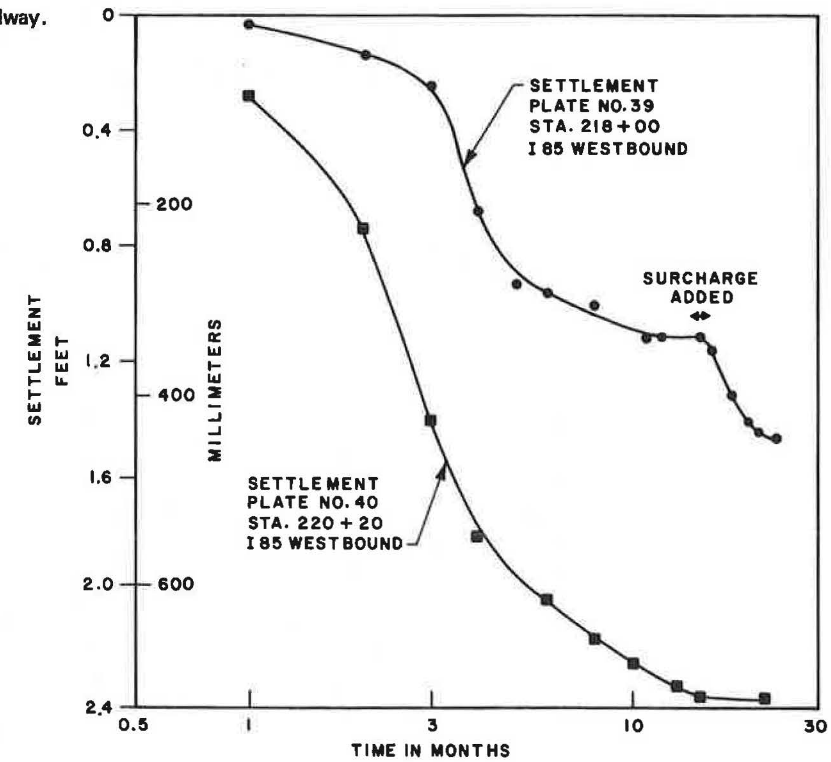


Figure 7. Settlement time for westbound roadway.



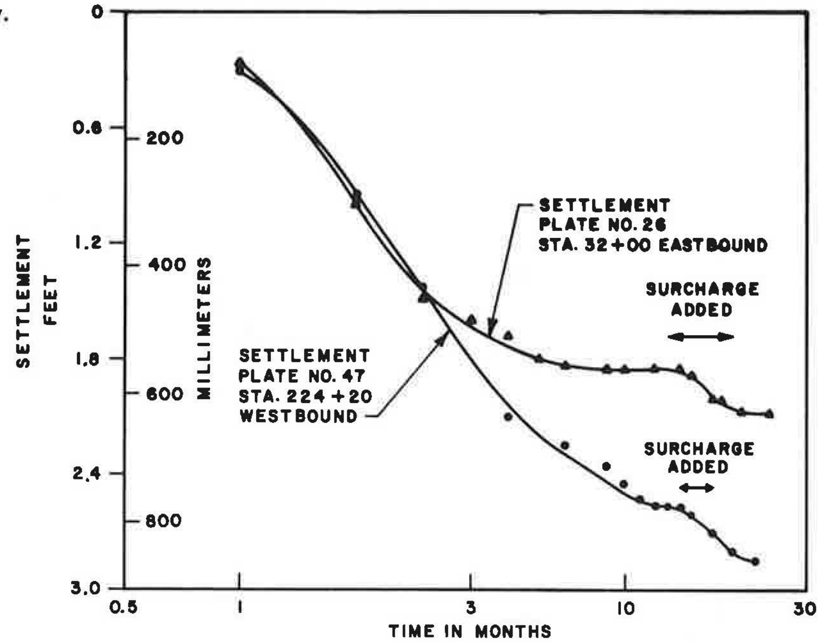
at a decreasing rate. At some stations where additional surcharge was applied at a later date—e.g., SP-26, SP-47, SP-8, and SP-39—as one would expect, the rate of settlement increased.

The thickness of the garbage fill along the westbound roadway varies from 5 to 9.5 m (16.5-31 ft), and the thickness of the underlying peat and organic silt ranges from only 0.75 to 1.7 m (2.5-5.5 ft). Therefore, a large proportion of the total settlement is contributed by the garbage fill. In general, the total strain varies between 11 and 14 percent, with the exception of three stations. The strain values are lower at the two end stations (214+20 and 226+20) because the overload extended only about 15 m (50 ft) beyond the location of the settlement platforms. The low strain value at station 218+00 cannot be explained.

Below the settlement plates where there was only landfill and no peat or organic silt was found, as was the case for station 32+00 eastbound and station 224+20 westbound, the measured strain ranged between 11.4 and 11.8 percent. This is in close agreement with the values recorded for the westbound roadway.

For both the roadways, the total settlement attributable to surcharge varied, depending on the nature of the underlying materials. At the time surcharging was completed, an average of about 66 percent of the total settlement had occurred, whereas the settlements one month and three months after the completion of surcharging were, respectively, 77 and 83 percent of the total

Figure 8. Settlement time for landfill area only.



settlement. Chang and Hannon (4) reported that 80 percent of the settlement was attained within 30 days after the completion of overload on CA-52.

In order to interpret the settlement response of the eastbound roadway, an analysis was carried out on the basis of the amount of landfill material removed or excavated and the amount of surcharge added. In other words, the stress-history effects were considered:

1. Station 16+00 has the lowest values of settlement because there is neither landfill material nor organic silt and peat below it. The measured deflection of 60 mm (0.2 ft) is attributable to the settlement of newly placed sandy backfill material that the contractor had end-dumped into water after having excavated all organic materials down to the sand and gravel stratum.
2. Four of the stations (18+00, 20+00, 24+00, and 26+00) show strains between 5 and 7 percent. For each of these stations, the ratio between the increase in stress attributable to the surcharge load and the stress from the excavated landfill materials was ≤1.
3. The remaining three stations for which the strains vary between 11.4 and 16.8 percent had corresponding stress ratios of 1.4 and greater.

SETTLEMENT OF NATURAL ORGANIC MATERIALS

An attempt was made to separate the settlement contribution of the landfill materials from those of the underlying natural deposits of peat and organic silts. Laboratory test results were used to compute the settlement in the natural deposits. The difference between the settlement-platform readings and those computed for peat and organic silt was considered to reflect the settlement of the sanitary landfill. Since consolidation tests were available for a few typical samples, based on the classification of underlying soils, the most appropriate soil parameters were selected for computation of settlement in the underlying natural deposits. One must keep this fact in mind in viewing these results.

Initial calculations were made by using ground elevations and water levels as indicated by the boring logs. The results of this analysis yielded computed settlements somewhat larger than the measured settlements. Upon reexamination, it was determined that groundwater and ground elevation, as shown on the boring logs, were different from those observed at the time of construction. Comparative values are given below, measured in feet in relation to New Jersey data at mean sea level. Water-table values indicate actual groundwater observed in the field at elevation plus 4.0 (1 ft = 0.3 m):

Station	Original Borings (%) Water Table	Original Borings (%) Ground Elevation	Actual Ground Elevation (ft)
Eastbound			
16+00	27.4	29.6	26.3
18+00	19.3	27.8	27.4
20+00	14.8	25.3	24.8
22+00	13.9	16.9	19.2
24+00	7.3	17.8	18.7
26+00	12.8	17.3	19.2
28+00	11.3	14.3	18.9
32+00	7.7	10.7	14.0
Westbound			
214+20	–	–	24.4
216+20	22.0	23.0	24.8
218+20	11.8	16.3	18.2
220+20	6.5	16.3	11.0
222+20	2.3	11.3	12.2
224+20	5.8	5.8	-1.0
226+20	5.8	5.8	+8.6

The error in the boring logs was believed to be caused by incorrect inferences by the boring crew, either because of perched water conditions or the water used during boring operations. After adjustments were made to ground and groundwater elevations, settlement computations were revised. Both computed and measured settlement values are given in Table 1.

For the westbound roadway, the strain in the garbage fill and the underlying peat and organic silt is about the same. For the eastbound roadway, similar agreement is found for all but two stations.

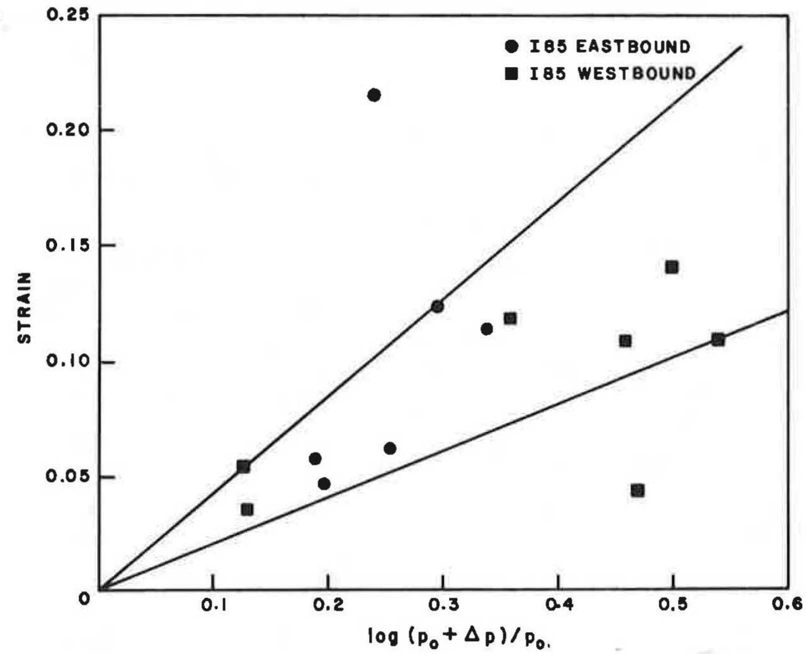
In the case of station 26+00, the computed settlements for the underlying natural deposits were equal to the total measured settlements, which indicates that the landfill stratum that was 1.8 m (6 ft) thick had no settlement. Before the installation of the settlement platform, this area was used as a haul road. This construction activity resulted in a high degree of compaction of the underlying garbage fill prior to the application of the surcharge load.

Table 1. Computed and measured settlement values.

		Thickness (ft)		Settlement (ft)			Strain (%)	
Station	Settlement Platform	Landfill	Peat and Silt	Total (measured)	Peat and Silt (computed)	Landfill	Total	Landfill
Eastbound								
16+00	2	-	-	0.20	-	-	-	-
18+00	4	6.5	8.0	0.90	0.53	0.37	6.2	5.7
20+00	8	11.5	4.0	0.75	0.22	0.53	4.8	4.6
22+00	11	7.3	3.5	1.85	0.27	1.58	16.8	21.6
24+00	14	8.0	5.5	0.95	0.46	0.49	7.0	6.1
26+00	17	6.0	8.0	0.80	0.80	0.00	5.2	-
28+00	20	9.5	6.0	2.00	0.82	1.18	12.9	12.4
32+00	26	17.5	-	2.00	-	2.00	11.4	11.4
Westbound								
214+20	32	31.0	-	1.65	-	1.65	5.3	5.3
216+20	35	24.0	5.5	3.25	0.63	2.62	11.0	10.9
218+00	39	21.0	4.0	1.45	0.56	0.89	5.8	4.2
220+20	40	16.5	4.5	2.35	0.58	1.77	11.2	10.7
222+20	44	17.5	2.5	2.80	0.34	2.46	14.0	14.1
224+20	47	24.2	-	2.85	-	2.85	11.8	11.8
226+20	50	28.7	-	0.95	-	0.95	3.3	3.3

Note: 1 ft = 0.3 m.

Figure 9. Strain versus stress for both roadways.



At station 22+00, after the adjustment was made to the total settlement, a much greater strain was indicated to have occurred in the landfill. Since most of the rest of the data indicate that the sanitary landfill had a strain of about 11 percent, incorrect choice of the soil parameters for the peat and organic silt may have been one of the reasons for this discrepancy.

SETTLEMENT OF LANDFILL MATERIALS

Along the eastbound roadway, before the placement of settlement platforms, it was necessary to remove about 1.5-6.1 m (5-20 ft) of the landfill material while leaving several feet of the underlying landfill in place. In the removal process, such articles as the bodies of trucks and washers and dryers were uncovered. Along the westbound roadway, the top of the existing garbage fill was below the points where settlement plates were to be installed. The landfill material that was excavated from the eastbound section was cleared of larger articles and recompacted along the westbound section. The compacted landfill material was as deep as 5.5 m (18 ft) in some sections. Because of the sorting and controlled compaction conditions, the added garbage fill was considered to have a higher density [1450 kg/m^3 (90 lb/ft^3)] than the existing fill [1129 kg/m^3 (70 lb/ft^3)], which was neither sorted nor compacted in any controlled manner.

The relation between strain and stress for both roadways is shown in Figure 9. All but two points lie between two lines that have a slope-compression ratio of 0.16 and 0.20. As discussed before, the computed strain value for the point that lies above the upper line that represents SP-11 is most likely incorrect. Another point previously discussed is the fact that the low strain value for SP-39, which lies below the lower line, could not be explained. Thus, disregarding these two points, the average compression ratio of the landfill is 0.18.

CONCLUSIONS

Based on readings taken from several settlement platforms and piezometers along I-85, which is to be constructed on a stabilized sanitary landfill material, the following conclusions can be made:

1. Piezometer readings were marred by the methane

gas that was still being generated in the landfill.

2. Settlement-time curves were found to have shapes similar to those of fine-grained soils.

3. Strain in the sanitary landfill was between 11 and 14 percent for the applied stress range.

4. The underlying deposits of peat and organic silt exhibited strains similar to those of the overlying landfill materials.

5. The compression ratio for the sanitary and fill material, some of which was undisturbed and some of which was excavated and recompacted, was between 0.16 and 0.20 and averaged 0.18.

6. The observed rates of settlement correlate well with those reported for a highway constructed on sanitary landfill in California (4).

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Prediction of Density and Strength for a Laboratory-Compacted Clay

D. W. WEITZEL AND C. W. LOVELL

Predictions of compacted soil strength for a highly plastic clay are developed by statistically correlating the results of unconsolidated-undrained triaxial tests with the compaction variables of water content, dry density, and compactive work. Work was calculated from measurements of the force and displacement of a kneading-compactor foot as it loaded the soil. The statistical models for prediction of density and strength gave results consistent with well-documented experimental evidence. The model for density prediction dry of optimum included variables of water content and a compactive work ratio; for compaction wet of optimum, dry density was a function of water content only. The model for strength prediction dry of optimum included variables of water content, dry density, degree of saturation, and confining pressure. Wet of optimum, the logarithm of strength decreased linearly with initial void ratio. All of these models had good statistical validity. By using such models, the designer can predict soil strength at particular compaction levelsor, if a minimum strength value is required, the necessary levels of compaction values can be estimated. These relations were developed from laboratory compaction. Similar relations for field compaction are being developed with the intention of correlating the two.

Compaction is commonly used to improve the strength of embankments, although the placement specification usually controls only certain compaction variables. This study developed predictions of strength from compaction variables that are more commonly and simply measured than strength. The as-compacted strengths of a laboratory-compacted, highly plastic clay were measured in unconsolidated-undrained triaxial tests. Samples were prepared by kneading compaction to densities that fit on three impact-energy curves, on each of which were four water contents. Samples were then sheared at four levels of confining pressure to simulate a variety of compaction conditions and embankment depths. In addition, the work expended to compact the soil was estimated from measurements of force and displacement for the compactor foot.

The results of these tests were used in statistical regression analysis to develop prediction equations for density and as-compacted strength in terms of the compaction variables. Correlation of these results with similar ones currently being developed for field compaction will allow better control of short-term shear behavior in embankments. Such predictions are of particular interest as (a) strength becomes more extensively used as a compaction specification element and (b) greater attention is paid to the potential overloading of the compacted soil by construction equipment.

LITERATURE REVIEW

The clay fabric established by compaction has an important effect on soil behavior. Modern fabric explanations were first introduced by Barden and Sides (1) and then by Hodek (2) and his "deformable aggregate" theory (deformable aggregate is an agglomeration of clay particles, or macropeds).

The size and distribution of the pore space of compacted-clay fabric have also been studied considerably in recent times. Bhasin (3) defined pore-size distributions for several different clays at various energy levels. The distributions of the pore sizes for soil at equal porosities wet and dry of optimum were very different: The dry sample had larger pores than the wet one. In addition, as compactive effort increased at a constant water content dry of optimum, the quantity of larger pores was vastly reduced until a point was reached at which further changes in the pore-size distribution would not occur. These results agreed with those of Sridharan and others (4) and Ahmed and others (5). Garcia-Bengochea (6) also reached similar conclusions for a 50-50 silt-kaolin mixture.

Such studies deemphasize the role of individual clay particles in the compaction process and focus on the nature and action of collections of particles into groups called domains, packets, macropeds, or aggregates. The arrangements of these aggregates vary significantly wet and dry of optimum. Dry of optimum, the aggregates are distinct. The void space is principally between aggregates, and a considerable quantity of it is in larger pores. As optimum water content is approached, the soil gets closer to its plastic limit and the aggregates become more deformable. Hence, in compaction the aggregates distort and squeeze together, and this reduces the number of large