STUDIES OF FILL CONSTRUCTION OVER MUD FLATS INCLUDING A DESCRIPTION OF EXPERIMENTAL CONSTRUCTION USING VERTICAL SAND DRAINS TO HASTEN STABILIZATION*

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Final completion of an adequate and permanent road bed across marsh lands in California has often been delayed many years because of the inherent instability and slow settlement of the underlying foundation. The poor condition of the roadway surface during this period of settlement constitutes a hazard to traffic as well as a difficult and expensive maintenance problem.

Although theoretical knowledge of these foundation problems has increased rapidly in the last few years through the studies of Terzaghi, Cummings, Casagrande, Moran, and many other engineers,[1] much remains to be done in correlating theory with practice; and to this end, intelligently designed experimental field projects offer the best means of developing a more accurate and complete understanding of the subject.

Before proceeding with a discussion of an experimental section constructed in 1934 to determine the effectiveness of vertical sand drains in hastening stabilization, a brief outline will be given of the foundation studies made for the easterly fill approach to the San Francisco-Oakland Bay Bridge and of a standpipe water level test made on this project to determine the hydrodynamic pressure resulting from the fill load. Hydrodynamic pressure as used herein may be defined as the pressure taken by the water when the load is in excess of the carrying capacity of a saturated foundation.

EASTERLY FILL APPROACH—SAN FRANCISCO-OAKLAND BAY BRIDGE

A very thorough investigation of the foundation conditions underlying the proposed roadway fill approach to the easterly end of the San Francisco-Oakland Bay Bridge was made during 1933. The construction extends three miles westerly from the main line tracks of the Southern Pacific Company in Oakland over tide flats and shallow water. The Key System Railroad fill parallels the project on one side and the main outfall sewer of the City of Oakland for a portion of the distance on the other side.

Borings disclosed deep mud layers to depths of 90 ft. below water. The mud was very soft, containing a water content varying between 50 and 90 per cent by weight of the dry soil samples. Figure 1 shows the project before and after dredger fill construction.

The studies were conducted to determine:

1. Method of constructing the fill with minimum slippage and without damaging the sewer line or endangering the safety of the Key System Railroad fill.

2. Required yardage of fill material, including yardage necessary to compensate for unavoidable lateral displace-

* *Western Construction News*, Vol. 12, No. 2, Feb. 1937; also in abstract in *Proceedings*, International Conference on Soil Mechanics and Foundation Engineering, Harvard University, Vol. I, p. 229, 1936.

[1] "The Science of Foundations—Its Present and Future," by Chas. Terzaghi, *Transactions*, American Society of Civil Engineers, Vol. 93, 1929. "Distribution of Stresses under a Foundation," by A. E. Cummings, *Proceedings*, American Society of Civil Engineers, August, 1935. "Earths and Foundations," with discussions, Progress Report of Special Committee on Earths and Foundations of the American Society of Civil Engineers, *Proceedings*, May and September 1933.

ment and loss between dredger cut and fill.

3. Probable rate of subsidence and total settlement subsequent to initial construction due to slow dehydration and consolidation of the mud strata.

To properly design a fill over marsh land, it is essential that reliable information be available regarding probable ultimate settlement so that the grade may be constructed high enough to compensate, insofar as practicable, for such future settlement. In this way it is

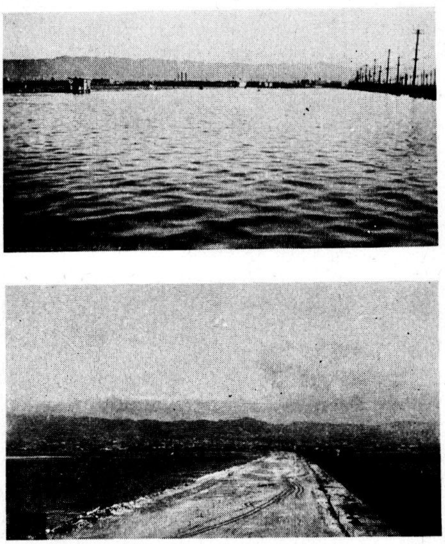

Figure 1. Showing East Approach to San Francisco-Oakland Bay Bridge Before and After Fill Construction.

possible to avoid major refilling and reconstruction operations.

The data from deep borings, studies of the foundation pressure, and laboratory analyses of foundation material, including the determination of unit weight, density, moisture content, grain size, consolidation, cohesive strength, and angle of internal friction, were used in the fill design and construction to determine the probable settlement and embankment quantities. The 4,000,000 yards of sand required for the construction of this dredger-built fill, which has been completed approximately two years, and the amount and rate of settlement to date are in very close agreement with estimates based on the foundation studies made prior to commencement of the work.

The action of this fill clearly confirms the dependability of the method of foundation analysis used. Much care and judgment were necessary in selecting suitable samples for testing and in correctly estimating the loads and the mass action of materials. Even so, due to the lack of adequate practical tests, some doubt remained regarding the true distribution of pressure through various types of strata and the "fatigue" or increased load affecting the foundation structure as a whole.

STANDPIPE TEST

The standpipe test, subsequently installed on this approach fill, was devised by the writer; first, to check the assumptions and theoretical analyses of foundation pressures previously made; and second, to furnish a practical field demonstration of the nature and intensity of pressure developed by the application of a load to a saturated material, and the principle phenomenon causing consolidation and instability.

In preparing for the test, a heavy 6-in. diameter casing was driven through the fill into an impermeable clay mud stratum, thus preventing water from flowing readily up along the outside of the pipe. Each joint of the casing was heavily leaded and thoroughly tightened in order to insure permanent water tight connections. The casing was then cleaned to the bottom (elevation −34), and continuous undisturbed core samples obtained from the botton of the casing to elevation −52, in order to check the results of previous borings and to furnish a complete record of the material in the portion under test. Immediately following this operation, a 2-in. diameter per-

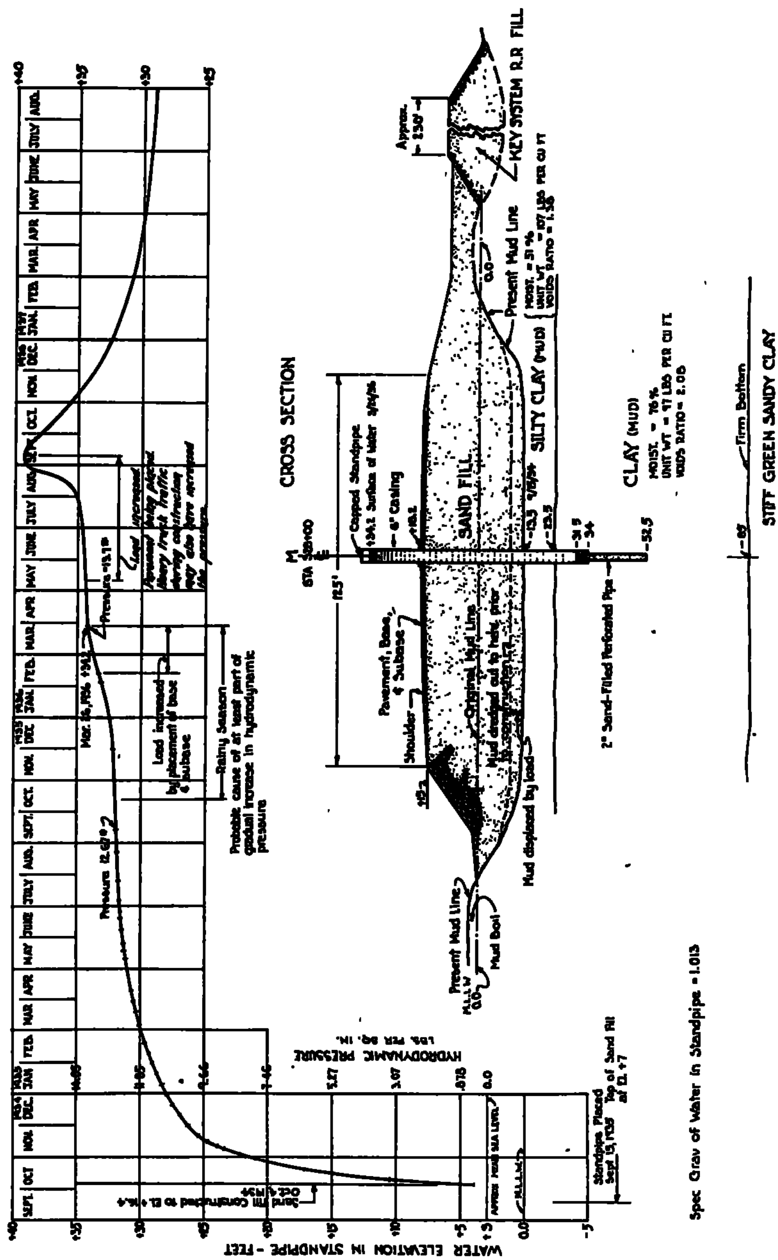

Figure 2. Diagram Showing Rise of Water in Standpipe and Hydrodynamic Pressure Resulting from Fill Load. East Approach San Francisco—Oakland Bay Bridge

forated sand filled pipe was placed between elevations −32 and −52.2 to serve as a filter, thus allowing the water below elevation −34 to pass upwards through the standpipe. The bottom 2 ft. of the 6-in. casing was also filled with sand to prevent mud from entering.

The installation was made on September 15, 1934, after the fill had been built to an elevation of approximately +7. The water level at this time was below the top of the sand in the standpipe (elevation −31.5). The next stage of filling was started on September 16, but no further water level readings were taken until after the embankment was up to grade (elevation +16.4) on October 4, 1934.

Figure 3. Showing Relative Height of Fill above Marsh Land at Low Tide Stage, East Approach to the San Francisco-Oakland Bay Bridge.

The general assembly and the data gathered from this test to date (Dec. 1936) are shown in Figure 2. The relative height of the fill and the head of water developed in the standpipe are shown in Figures 3 and 4. The slope of the curve, Figure 2, indicates that the head in the standpipe, during the early fall of 1935, practically equaled the hydrodynamic pressure in the foundation. It is interesting to note that the test is sufficiently sensitive to reflect the increased weight of the fill during the 1935–1936 wet season and the load resulting from placement of subgrade material, base, and pavement during this year.

While observations over many years will be necessary to complete the test, and determine the rate of reduction in the hydrodynamic pressure and the time required for dehydration and consolidation at the depth tested, the following conclusions are tentatively drawn from present data:

1. The hydrodynamic excess pressure agrees closely with the theoretical analysis made prior to construction. The test, then, may assist in establishing the correctness of the method used which, in general, followed that previously outlined by the Committee on Earths and Foundations of the A.S.C.E.[2]

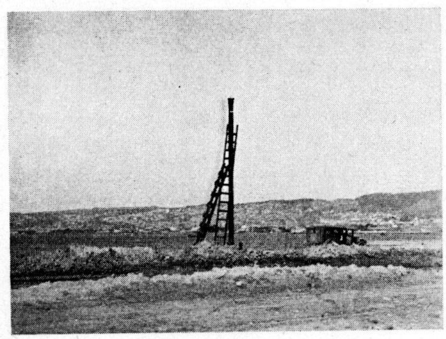

Figure 4. Showing Standpipe Installed in Mud Foundation, East Approach San Francisco-Oakland Bay Bridge. The mark on pipe indicates the water level on January 2, 1936.

2. Little or no consolidation has taken place to date at the depth tested, 20 to 40 ft. below the bottom of the sand fill. Laboratory consolidation tests indicate that 3 to 6 years will be required to obtain an appreciable consolidation at this depth. The settlement now occurring at the rate of about 1 in. per month is probably due to dehydration of the first 15 or 20 ft. of mud below the sand fill.

3. The hydrodynamic pressure, at the point tested, reached 2300 lb. per sq. ft. during September 1936. The pressure recorded during the latter half of 1935 and the first nine months of 1936 was approximately equal to the vertical load applied.

4. The standpipe test furnished reliable

[2] *Proceedings*, A. S. C. E., May 1933.

information regarding the active pressure producing consolidation and instability of the saturated soil. As this hydrodynamic pressure operates laterally, as well as vertically, it is deemed proper to assume that such pressure is a vital factor in connection with fill slipouts.

The test promises to be useful for measuring the rate of core solidification and the horizontal component in hydraulic-fill dams, and the distribution of foundation loads on saturated compressible soils to the end that definite information may become available to assist in clarifying the foundation problem as a whole. A somewhat modified assembly, using a small riser pipe and a gauge, operates with a small flow of water from the soil, thus increasing the sensitivity of the test, quickly recording any change in the active load.

FILL SLIPOUTS

Slipouts may result from one or more of four distinct causes:

1. Slippage along a definite, lubricated, or slippery stratum. This movement frequently occurs along a bedding plane between two layers of firm material. Correction of this type may be accomplished by breaking up and draining the sliding plane.

2. Water pressure entrapped above a saturated impervious fill. In this case, adequate drainage with cut off trench above the fill may result in stabilization.

3. Insufficient shearing resistance in a fill to withstand the horizontal stresses produced by its own weight. This condition occurs when the slopes are too steep for the type of material and height of the fill or when the state of compaction of the material is too low. Proper fill compaction and correct slope design are both essential for permanent fill stability.

4. Lateral movement of a saturated foundation soil when the fill load produces a horizontal component greater than the shearing strength. Displacement of marsh mud during fill construction is an example of this type. A large number of fill slipouts under other conditions on California highways can, however, be classed in this group.

The horizontal component causing this fourth type of failure may be entirely due to hydrodynamic pressure. Movement occurs whenever this pressure is greater than the shearing strength of the supporting ground. Failure may, however, be delayed until all of the supporting strata below the fill reaches a low shearing strength from saturation. Shearing resistance of homogeneous foundation material can be analyzed from the cohesive strength and the angle of internal friction in accordance with the method suggested by Krey of Germany and Terzaghi.[3]

The water pressure, demonstrated by the standpipe test, was first observed by the writer during investigations of large fill slipouts on saturated clay soils. Water squeezed up along the shearing plane after failure and, in some cases, caused an appreciable flow over the embankment. Test holes made through these embankments to determine the cause of slippage encountered pressure which raised the water through the boring and to the top of the fill, even though the water level in the adjacent ground remained many feet below.

These water level observations conclusively demonstrated that stabilization of foundations could not be quickly accomplished, if ever, without special drainage treatment of the saturated substrata. Foundations for heavy fills have been drained and stabilized by constructing rock-filled drainage ditches at proper

[3] Terzaghi—*Public Roads* Vol. 10, No. 3 and No. 10, May and Dec. 1929.

Krey—"Erdruck, Erdwiderstand, und Tragfahigkait des Bougrundes, 4th Edition, 1932.

Fellenius "Erdstabische Aufzaben," Berlin.

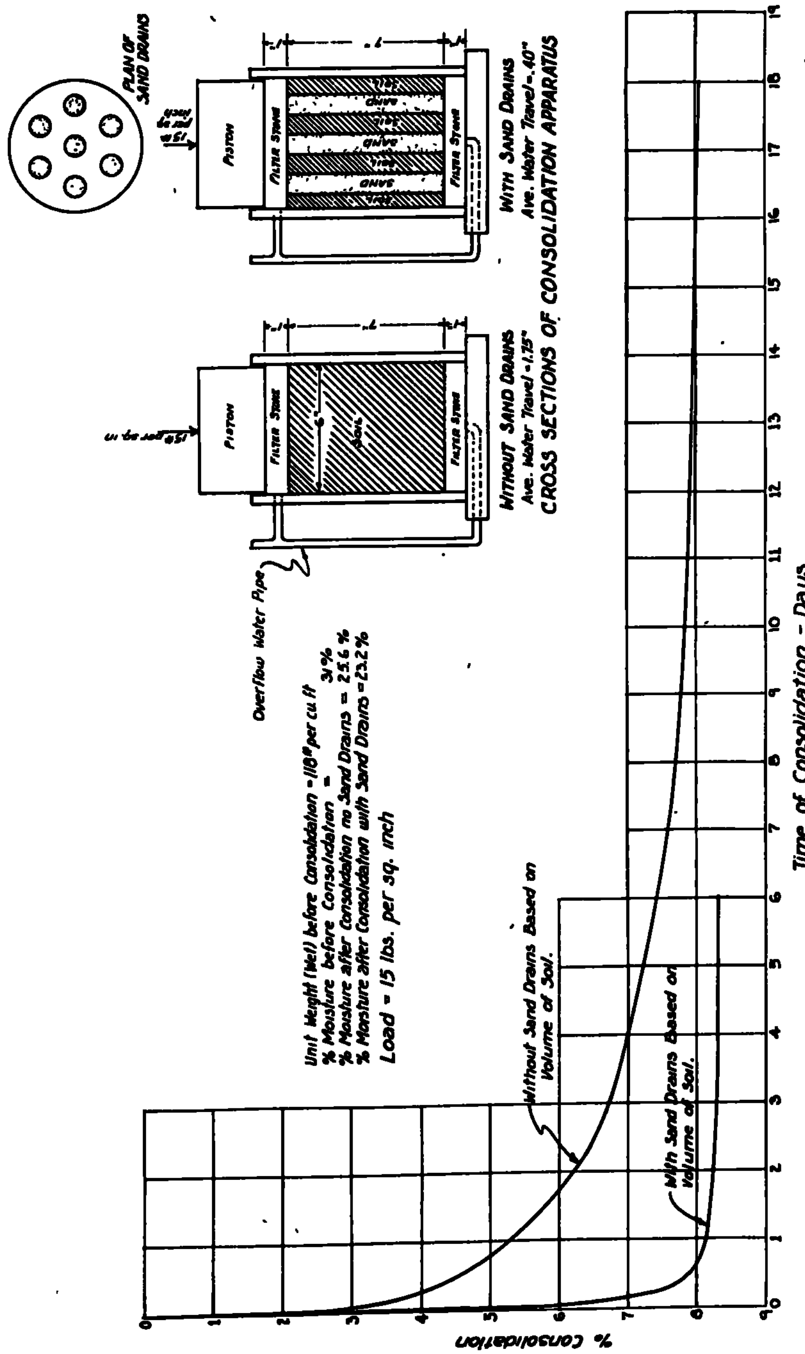

Figure 5. Time Consolidation Curves Showing Effect of Vertical Sand Drains on Rate of Consolidation

locations to the bottom of a relatively shallow saturated material.

The substrata drainage problem is much more difficult, however, where the bottom of the unstable material is below an economical trenching depth and particularly on marsh land construction where part, at least, of the surrounding ground may be under water. Appropriate construction over this type of soft, saturated ground has been given special study. Small-scale tests with vertical drains were first made in the laboratory and then experimental sections of the same type constructed in the field, to determine the feasibility and advantage of deep subsurface drainage. Before describing these experiments in detail, we should note the settlement characteristics of construction on marsh ground and briefly consider the factors influencing the subsidence rate.

RATE OF SETTLEMENT

Observations of elevations indicate that the settlement period on marsh ground may vary from a few months to many years. Some embankments constructed 20 years ago are still settling at a rate of a few inches or more per year. A study of these projects has clearly indicated that the permeability and depth of the mud are definitely related to the length of settlement period. Information regarding the permeability of the materials can be obtained from consolidation tests. Theory, substantiated by experience on construction work, indicates that the time required for consolidation is proportional to the square of the depth of the layer. This suggested the possibility of greatly reducing the length of the normal settlement period for deep mud deposits by construction of vertical drains, thus permitting horizontal flow to the drains and reducing the distance the water would otherwise travel through impervious material before elimination.

VERTICAL DRAINS TESTED IN LABORATORY

A small-scale experiment was made in the laboratory in 1935 to check calculations of the theoretical advantage of properly spaced sand drainage columns.

A disturbed sample of very impervious adobe soil was obtained for this test. After wetting the sample to a very plastic state, the material was uniformly molded in two special 6-in. dia. consolidation molds to a height of 7 in.

Seven vertical 1-in dia. drainage channels were then constructed in one of the soil specimens by cutting out the material and backfilling the space with sand. The specimens were placed under a load of

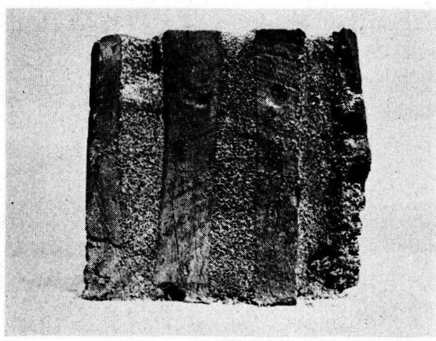

Figure 6. Showing Vertical Section through Consolidated Specimen Containing Vertical Sand Drains. This specimen consolidated more than 20 times as fast as a similar sample without the drains.

15 lb. per sq. in. and readings taken until an approximate state of equilibrium was reached.

The general assembly of the apparatus, together with the time consolidation results for both the treated and untreated specimens are shown in Figure 5. A vertical section through the consolidated specimen containing the sand drains is shown in Figure 6.

Comparison of the curves indicates that the specimen with sand drains consolidated 20 to 25 times faster than the untreated specimen. Theoretically, the ratio should have been about 19 to 1.

VERTICAL SAND DRAINS INSTALLED IN BEATRICE MARSH

Opportunity developed in 1934 for testing the drains under field conditions in connection with a foundation investigation for proposed reconstruction of the road across Beatrice Marsh, a portion of the Redwood Highway near Eureka, Calif.

This section of highway constructed in 1930 and 1931 had subsequently settled unevenly into the soft underlying marsh land, producing miniature hills and valleys in the surface as shown in Figure 7. The grade line thus lowered subjected the roadway to flooding and saturation

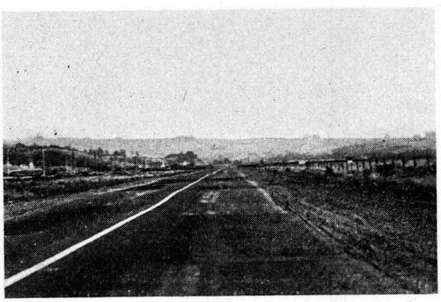

Figure 7. Roughness and Surface Failures Resulting from Unequal Settlement. Road across Beatrice Marsh near Test Section 3.

whenever a high tide occurred concurrently with heavy run off from the adjacent hills. This, together with the roughness and deterioration of the temporary surface, resulted in high maintenance costs, indicating reconstruction would be required in the near future.

Borings made through the fill at frequent intervals indicated that the upper 10 to 20 ft. of marsh land consisted of very soft and very peaty blue clay (mud) containing about 90 per cent of moisture by weight of the dry material. Immediately underlying this was 20 to 35 ft. of soft blue clay (mud) intermixed with some pockets of peat and containing 40 to 50 per cent of moisture. Soil profiles and theoretical pressure contours, together with complete test data, were prepared and analyzed to determine:

1. Future settlement with present fill load.

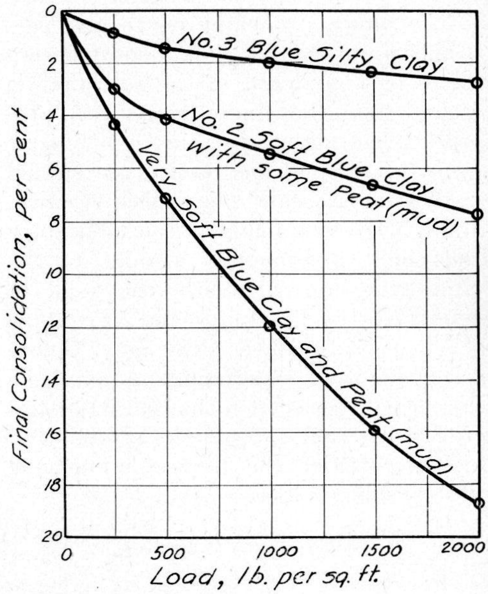

Figure 8. Average Load Consolidation Curves, Beatrice Marsh Test Section

Curve No.	Sample No.	Station	Elev.	Unit Wt.	% Water
1	9-2-I	430 + 30	−8.4	88	92
	9-2-II	430 + 30	−8.2	84	107
	9-3-XI	430 + 30	−11.4	84	121
2	9-6-VI	430 + 30	−44	107	45
	10-5-III	468 + 90	−40	113	42
	10-7-VIII	468 + 90	−65	107	48
3	8-5-V	372 + 00	−11	126	23
	8-6-I	372 + 00	−17	116	36

Test made on undisturbed cylindrical sample 1.93″ x 1″ ht.

2. Additional material required for reconstruction to compensate for the total ultimate settlement.

3. Probable rate of subsidence following reconstruction, with and without the theoretical accelerating effect of sand drains.

4. The supporting value (cohesion and internal friction) of the mud foundation. This indicated the maximum amount of additional material that could be applied without causing lateral displacement.

The data required for this study are too

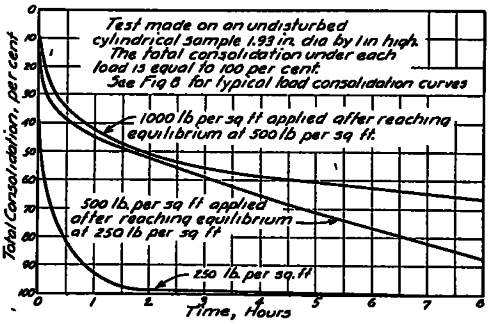

Figure 9. Typical Time-Consolidation Curves. Beatrice Marsh Test Section. Unit weight of sample 84 lb. per cu. ft. Water 121.0 per cent.

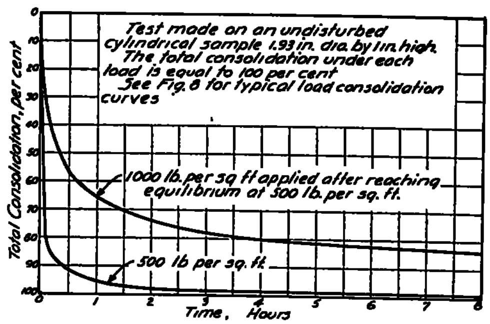

Figure 10. Typical Time-Consolidation Curves. Beatrice Marsh Test Section. Unit weight of sample 113 lb. per cu. ft. Water 42 per cent.

TABLE 1

TYPICAL TEST DATA—BEATRICE MARSH BORINGS

Sample No.	Elev.	Water[1]	Unit wt.—wet	Grain size analysis[2]			
				Gravel	Sand	Silt	Clay
		%		%	%	%	%
12-1-X	−1.3	100	90	0	6	37	57
12-1-IV	−2.5	92	92	0	9	32	59
12-4-VI	−10.0	82	97	0	5	40	55
12-4-I	−11.3	43	120	0	5	49	46
12-3-XVI	−20.5	43	115	0	33	41	26
12-3-VIII	−22.0	42	112	0	55	22	23
9-1-VI	−2.0	94	90	0	4	31	65
9-2-III	−8.0	100	88	0	19	32	49
9-3-V	−12.5	90	98	0	1	45	54
9-4-I	−19.0	43	112	0	8	50	42
9-5-VIII	−27.3	69	91	0	4	42	54
9-5-VII	−27.5	55	103	0	3	44	55
9-6-VIII	−37.4	42	107	0	3	40	57
9-6-IV	−38.2	64	102	0	5	34	61
9-7-XIX	−45.3	43	106	0	20	40	40
9-7-IX	−47.3	48	102	0	11	39	50
9-7-III	−48.3	56	100	0	1	38	61
9-8-IV	−58.6	26	120	0	20	51	29
7-1-III	−0.7	102	83	0	5	29	66
7-2-I	−6.7	104	86	0	4	23	73
7-5-III	−11.2	79	86	0	4	36	60
7-8-III	−36.0	33	114	0	19	49	32

[1] Percentage of moisture by weight of dry soil sample.

[2] Gravel—particles larger than 2000 microns.
Sand—particles 50 to 2000 microns.
Silt—particles 5 to 50 microns.
Clay—particles smaller than 5 microns.

extensive to be included in this report; however, typical test data are shown in Table 1 and Figures 8, 9, 10, and 13.

Three test sections totaling 431 lineal feet of roadway were constructed during November and December of 1934. A total of 84 holes, 28 in. in diameter, averaging 42 ft. in depth and aggregating 3530 lineal feet, were bored at a cost of 22 cents per foot ($9.24 per hole). Clean, river-run sand, similar to a very coarse concrete sand, was used to backfill the holes and provide drainage.

Test Section 1 was constructed in the stiffest muds encountered in the marsh. Test Sections 2 and 3 were placed in softer material, and in the case of No. 2 at the point where the mud depth was maximum.

The spacing of the drains and general data for Test Section 3 are shown in Figures 13 and 14. The construction on the other sections was similar, except that all longitudinal spacing between drains was either 10 or 12 ft.

The settlement of the roadway for both treated and untreated portions of each test section is shown in Figure 15. These curves, together with the complete profiles of progressive settlement, show that the vertical drains have functioned satisfactorily, and have materially accelerated the settlement.

RECENT CONSTRUCTION EXPERIENCE

Since most of the data for this paper were prepared, stabilization treatment with vertical sand drains has been successfully applied on two construction projects, in Alameda and San Luis Obispo Counties. The East Bayshore Highway Approach to the San Francisco-Oakland Bay Bridge in Alameda County, constructed in 1936, crossed marsh land for a distance of 600 ft., in the vicinity of El Cerrito. The mud consisted of very soft clay and peaty-clay and extended to a depth of approximately 30 ft. below the surface. A fill, 16 ft. in height, was successfully constructed after stabilizing the mud by installing a total of 260 vertical sand drains on 10-ft. centers. As the fill load was built up the mud consolidated 3 to 4 ft. and the water flowed out through the top of the drains. Most of the drains were installed by drilling a 30-in. diameter hole to firm bottom and backfilling same with a mixture of pea gravel and coarse concrete sand. A few of the vertical drains, however, were constructed by jetting a large casing down to firm bottom, filling the casing with sand and then withdrawing the casing.

While the cost of stabilizing the 600 ft. length of 4-lane divided highway was about $6,000.00, it is estimated that a saving of approximately $20,000.00 was obtained over the conventional method of overloading and displacing the soft foundation material.

Vertical sand drains were also utilized in 1937, to stabilize a foundation for a large fill on the Cuesta Grade Project in San Luis Obispo County. Where this 4-lane divided roadway crosses School House Canyon on a fill 60 ft. high, test borings showed the presence of plastic slide material to a depth of 75 ft. below the surface of the ground. This deep deposit of unstable overburden consisted of blue and brown clay containing between 30 and 50 per cent of water. Due to the depth and the wet condition of the material, it is considered impracticable and uneconomical to stabilize the foundation by stripping or trenching.

The area was treated by constructing 300 vertical sand drains which extended below the surface to firm material, generally encountered at a depth ranging between 50 and 70 ft. The drains were spaced on 10-ft. centers where the unstable overburden was very soft and on 15-ft. centers over a portion of the area where the unstable overburden carried a

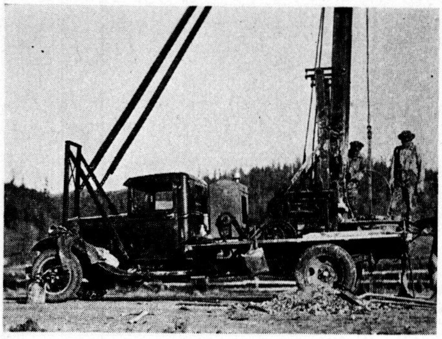

Figure 11. Showing the Rotary Type Drill Outfit Used in Connection with the Installation of Vertical Sand Drains. Holes, 28 in. in diameter, were bored to a depth of about 50 ft.

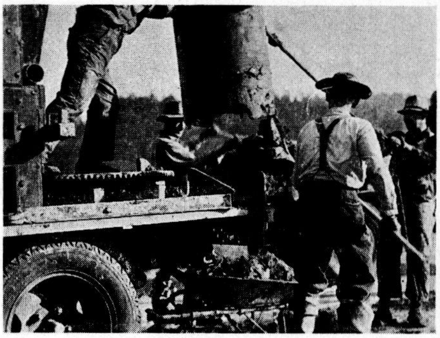

Figure 12. Removing Mud from Rotary Bucket. Bottom of bucket and cutting blades are hinged to permit quick removal of the mud.

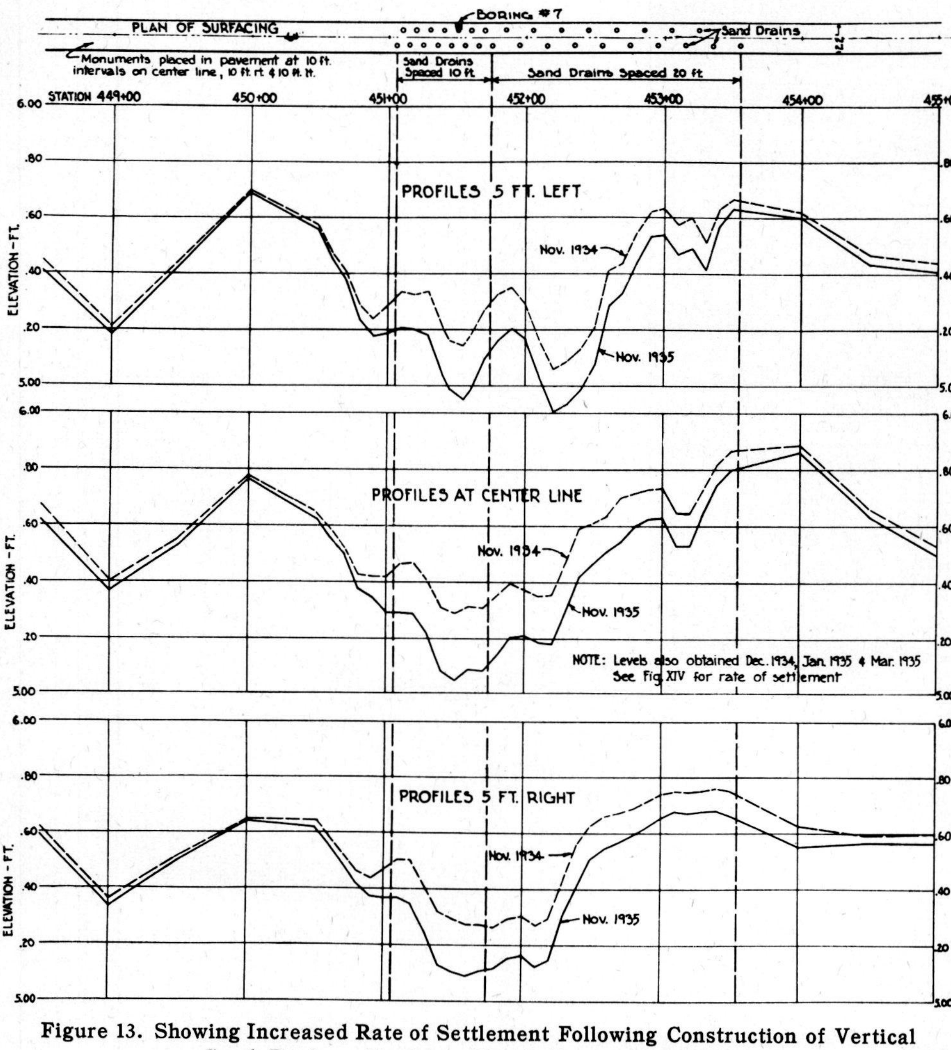

Figure 13. Showing Increased Rate of Settlement Following Construction of Vertical Sand Drains. Beatrice Marsh Test Section No. 3

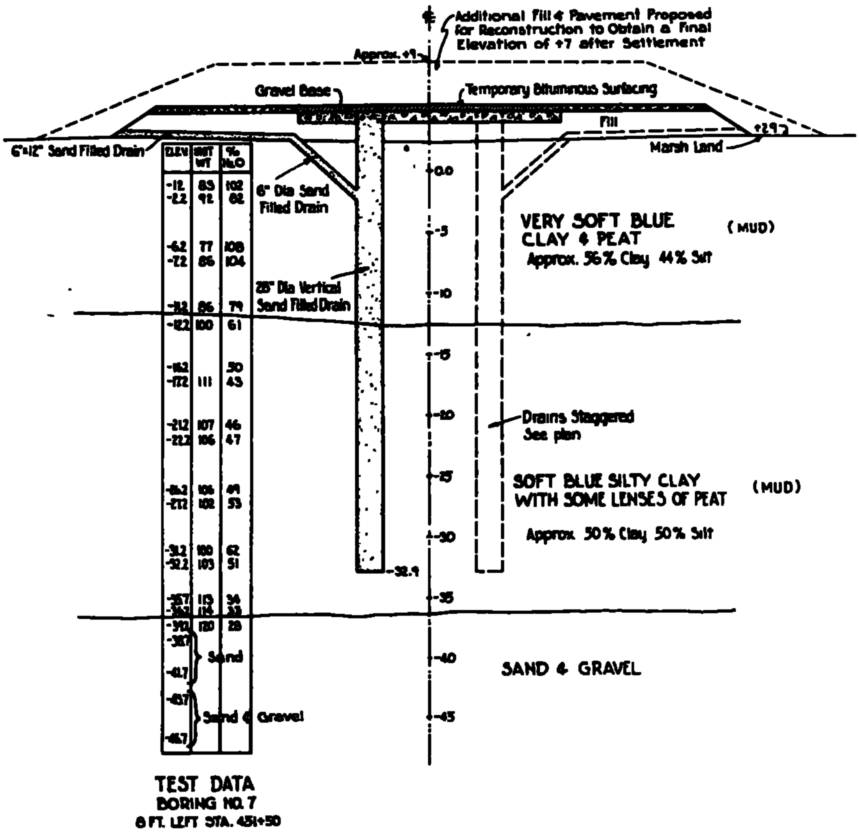

Figure 14. Typical Cross Section through Sand Drains. Beatrice Marsh Test Section No. 3

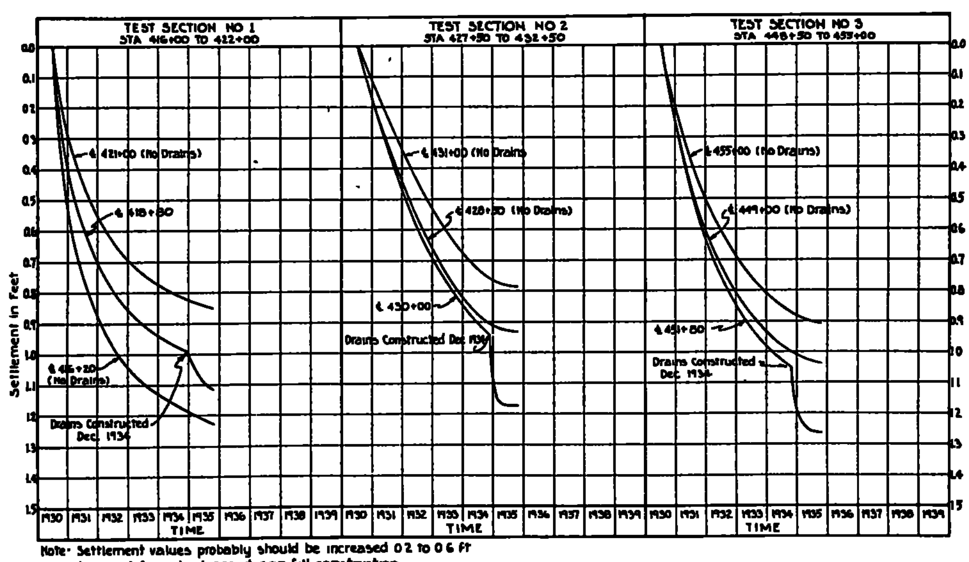

Figure 15. Time Settlement Curves Showing the Rate of Settlement of Fill without Drains and the Acceleration of Settlement Resulting from the Construction of Vertical Sand Drains. Beatrice Marsh Test Section.

lower percentage of water and was only semi-plastic. The drains were installed to depths of 70 ft. by driving a seamless steel tube mandrel, with a pile driver, and filling the hole with sand as the mandrel was withdrawn. A system of horizontal drains was connected with these vertical drains at the surface of the ground to release the water from the top of the vertical drains.

Monuments and an inspection tunnel were installed on top of the foundation to facilitate measurement of the settlement and to determine the amount of consolidation of the foundation. Between 2 and 3 ft. of settlement occurred during the time the fill was being built. The water that flowed out of the top of the vertical drains was measured at the end of horizontal drains. A maximum flow of about 20,000 gallons per day was measured at the outlet, immediately following completion of the fill. No horizontal displacements or slipouts occurred during, or since, construction of this embankment. Only a very small amount of settlement has occurred during the last year and it appears that the stabilization treatment is effective.

All of the foundation studies described were carried on by the Materials and Research Department of the California Division of Highways, under the general direction of Thomas E. Stanton, Jr., Materials and Research Engineer.

CONCLUSIONS

1. Substrata drainage is necessary to relieve hydrodynamic pressure and stabilize impermeable saturated ground.

2. Theoretical advantages of vertical drains in connection with fill construction over deep marsh land have been confirmed by the experimental construction described herein. Further construction now under way should determine the practicability of a broader application of this type of treatment and the economic limitations.

3. It is possible, with proper spacing of the drains, to obtain practically all of the settlement during six months to one year's time following construction.

4. Water usually travels through soil deposits more readily horizontally (with the bedding than vertically. In addition to the increased rate of movement resulting from a decrease in the distance the water must travel through impervious material to be eliminated, the drains may accelerate the rate of settlement by providing an outlet for horizontal movement of excess moisture.

5. Drains, with a spacing consistent with the type of material and the desired rate of loading, readily release the excess water, relieve the hydrodynamic pressure, and thus prevent lateral displacement during fill construction. In some cases, therefore, the saving in fill yardage alone may economically justify the added expense of this type of construction.