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Accelerated Consolidation of Soft Clays Using Wick Drains

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SYNOPSIS: Construction of the New Istana for the Sultan of Brunei required that fill slopes up to 85 feet high be placed on very soft compressible floodplain soils. Wick drains installed in the soft sediments accelerated their consolidation and reduced long-term settlements. The consolidation also produced a strength increase in the soft soils that allowed the fill to be constructed without danger of a major base slip failure. Instrumentation installed in the floodplain soils provided data on excess porepressures built up during the fill placement, and on the resulting settlements. The measured porepressures and settlements were in good agreement with the predicted values.

INTRODUCTION

The New Istana (Royal Palace) of the Sultan of Brunei is located on high ground above the tidal floodplain of the Brunei River (Figure 1). As part of construction, it was necessary to place fill slopes, some as high as 85 feet, on the floodplain to accommodate the main access road and essential utilities, and to achieve desired architectural effects. Computations made before the fill placement in late 1981 predicted several feet of fill settlement would occur over a period of years from the consolidation of recently deposited sediments beneath the floodplain area. The computations also showed that placement of the fill at the projected construction rate of about 1 foot every 2 days would cause a slip failure through these soft sediments. The tight construction schedule (the New Istana had to be completed before Brunei became independent in July 1983) did not allow for any slowdown in the rate of fill placement, nor could continuing large settlements be tolerated years after project completion. The solution lay in accelerating the consolidation of the floodplain sediments, both to speed up the settlement and to strengthen the soft soils. This paper describes the method employed to accelerate consolidation, the instrumentation installed, and the results of measurements taken before and after fill construction.

SUBSURFACE CONDITIONS

Soils beneath the floodplain (at about El. +5 feet) consisted of muck, peat, silt, and very soft clay and silty clay. These deposits extended as deep as 60 feet under the toe of the new fill, decreasing to about 10 feet beneath the maximum 85-foot height of the 1-V to 3-H slope, as shown in Figure 2. Information on subsurface conditions was obtained from an extensive series of soil borings; the locations of some of the borings are shown in Figure 3.

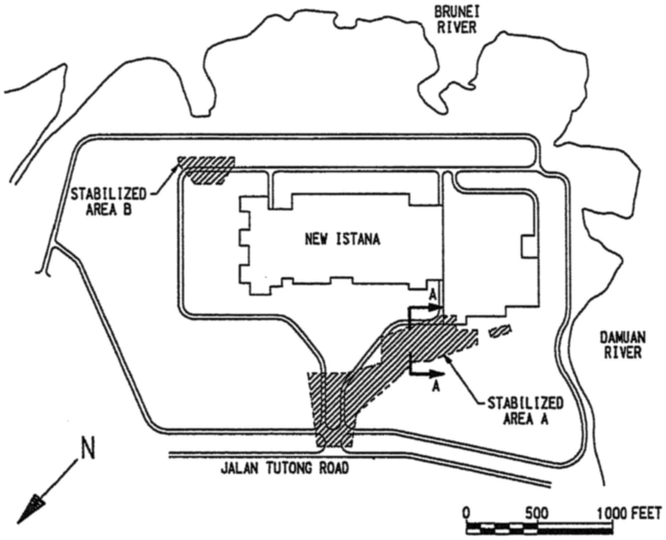

Fig. 1 Plan of New Istana

The very soft clays and silty clays, which made up the majority of the soft floodplain sediments, were generally highly plastic with natural water contents close to the liquid limit. The selected values of the design parameters for this stratum were based on the results of field and laboratory testing. These values are shown on Table 1, along with the values for the other strata described below.

Hard clayey silt extended below the soft floodplain sediments, down to the limit of the borings, i.e., to at least El. -70 feet. The material appeared to be grading into a siltstone with increasing depth, although no structure could be detected from the samples recovered. As shown in Figure 2, a thin layer of stiff residual clay was found above the hard clayey silt in some areas.

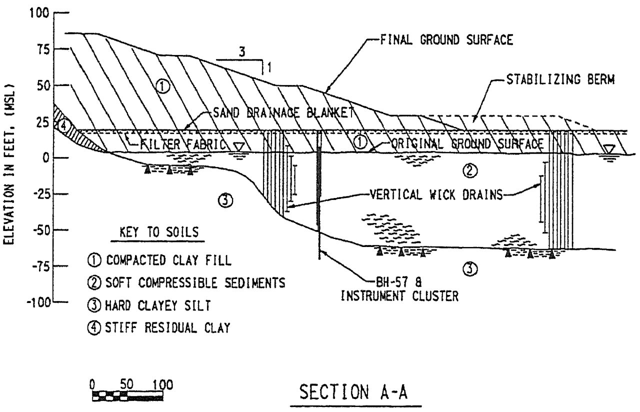

Fig. 2 Subsurface Conditions

The fill soil that made up the new embankment was very silty clay that had been excavated during extensive grading operations for the palace on the hill above the floodplain. This clay was placed in maximum 1-foot-thick lifts, and compacted to at least 90 percent of the modified Proctor maximum dry density, at a moisture content ± 2 percent of optimum.

The measured ground water table was, on average, slightly above the water level in the adjacent Brunei River, and essentially at ground surface at about El. +5 feet.

PLAN OF ACTION

As shown in Figure 2, the maximum height of the new fill lay above the thinnest zone of the compressible sediments, while the toe of the fill was above the greatest thickness. This resulted in the predicted primary consolidation settlement of these sediments over the majority of the area being within a fairly narrow range, i.e., 6 to 7 feet. The maximum computed settlement (due to 100 percent primary consolidation) was 8.3 feet, from 45 feet of soft sediments consolidated by 40 feet of fill, while the minimum value was 3.7 feet, from 17 feet of soft sediments being consolidated by 65 feet of fill.

TABLE I. Soil Design Parameters

	Compacted Clay Fill	Soft Floodplain Sediments	Hard Clayey Silt
USCS Symbol	CL/ML	CH to OH	CL/ML to SM/SC
Total Unit Weight, pcf	125	110	130
Natural Moisture Content, %	22	50	11
Liquid Limit	40	53	38
Plasticity Index	16	27	17
Undrained Shear Strength, psf	1600	300	4000
Compression Index	-	0.55	0.12
Coeff. of Consolidation, ft^2/year	-	60(1)	400
State of Consolidation	-	NC	Highly OC

Notes: (1) This value was assumed to represent both vertical and horizontal coefficients.

(2) The thin layer of stiff residual clay found in some areas above the clayey silt had a unit weight of 120 pcf and an undrained shear strength of 1000 psf.

For the maximum 60-foot thickness of the compressible soil, 50 percent of the settlement was estimated to take 3 years to complete, while 90 percent would take almost 13 years. Slope stability analyses showed factors of safety as low as 0.7 against a slip failure through the soft soils, even with a 15-foot-thick stabilizing berm added at the toe of the slope. Obviously some action was required to accelerate the consolidation rate, and increase the strength of the soft sediments.

The only viable course of action was to install wick drains in the soft floodplain sediments, and to place the fill embankment at a rate that allowed these sediments to consolidate and strengthen sufficiently to avoid a slip failure. Instrumentation was essential to monitor buildup of porewater pressure in the soft soils during the embankment construction, and to determine the settlement of these soils.

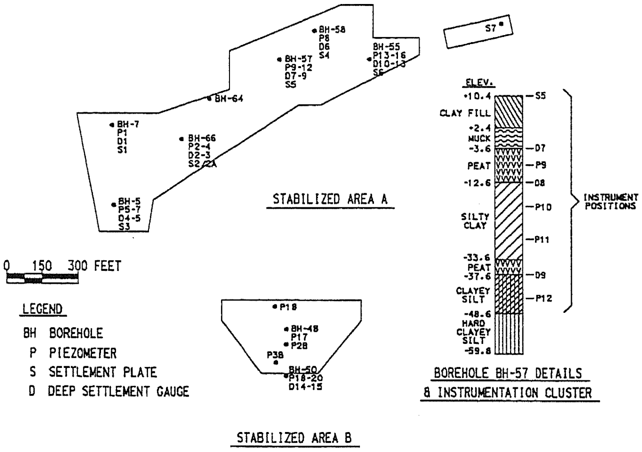

Fig. 3 Boring and Instrumentation Locations

WICK DRAIN DESIGN AND SHEAR STRENGTH INCREASE

Using the soil parameters shown in Table 1, a center-to-center spacing for the wick drains of 5 feet was computed by the method outlined in Hansbo (1979), based on a requirement that 90 percent consolidation of the soft floodplain sediments occur within 6 months. This rate of consolidation was needed to increase the strength of the soft sediments sufficiently to avoid a slope failure. The predicted increase in shear strength of the underlying soft soils during the fill placement was computed using a simplified approach, with the following assumptions.

1) One foot of fill is placed about every 2 days, i.e., 85 1-foot increments in 6 months.

2) At the end of the 6-month placement period, the compressible soils will have consolidated 90 percent due to the first foot of fill placed, and essentially zero due to the 85th foot.

3) For each 1 foot of fill placed between the first and 85th foot, the resulting degree of consolidation U of the soft

soils follows the relationship between U and the radial time factor T for sand drains, as outlined in Leonards (1962). In this relationship, the ratio of wick drain spacing to the wick drain's equivalent radius was calculated as 50.

4) The relationship between consolidation time elapsed and T is based on 90 percent consolidation in 6 months.

5) After 100 percent consolidation under a load equivalent to 1 foot of fill surcharge (about 125 psf), the soft sediments increase in shear strength by 30 psf (i.e., $c/p \simeq 0.25$, based on CIU laboratory tests).

6) Shear strength gain is linearly proportional to the degree of consolidation.

As an example, we can predict the increase in shear strength of the soft soil 6 months (180 days) after the start of fill operations due to the 50th foot of fill being placed, as follows.

- The 50th foot of fill is placed 100 days after the start of fill operations (i.e., 1 foot every 2 days).
- The underlying soft soils consolidate for 180 days - 100 days, i.e., 80 days under this 1 foot increment of surcharge.
- At U = 90% consolidation, time factor T = 0.712 from Leonards (1962), for the ratio of well spacing to wick drain equivalent radius of 50.
- Since time of consolidation
  t = constant x T,
  and t = 180 days at 90% consolidation
  and T = 0.712 at 90% consolidation
  then t = 253 T.
- For t = 80 days, T = 0.316
- From Leonards (1962), for T = 0.316, U = 64%
- Increase in shear strength = 0.64 x 30 = 19 psf, since shear strength gain is assumed to be linearly proportional to the degree of consolidation.

Using the above approach, the shear strength of the soft floodplain sediments 6 months after the beginning of fill operations was computed by summing the strength increases due to each fill increment. For the maximum 85-foot-high embankment, the 6-month undrained shear strength was about 1,700 psf, compared with the initial 300 psf value. At the end of one year after start of fill placement, about 99 percent consolidation would have occurred due to the first foot of fill placed, with about 90 percent consolidation due to the 85th foot. In the long term, assuming 100 percent consolidation, the computed undrained shear strength of the compressible sediments was around 2,600 psf.

The stability analysis of the section shown in Figure 2 indicated a factor of safety against slip failure through the floodplain soils of about 1.2 for the end of construction condition and 1.4 for the long-term condition, using the computed increased strengths due to the wick drain consolidation. This compared with a factor of safety of 0.7 computed for the pre-wick drain condition. It may be noted that the factors of safety increased proportionally far less than the shear strength of the soft sediments. This is because the effects of the shear strength of the clay fill (85 feet thick) and the influence of the stabilizing berm (see Figure 2) were the same in both the before and after analyses.

Although the use of wick drains indicated that primary consolidation settlement would be accelerated by a factor of about 25, the rate of secondary compression was not affected. In fact, the computed amount of secondary compression actually increased slightly because a longer period of secondary compression occurred due to the decreased period of primary consolidation. However, the total predicted secondary compression settlement over 50 years amounted to only about 10 percent of the primary consolidation, and was thus not considered as an important factor in the design. Similarly, settlement of the compacted clay fill above the soft sediments, and the hard clayey silt below these sediments, was considered insignificant in comparison with the settlement of the soft sediments themselves.

WICK DRAIN INSTALLATION AND FILL CONSTRUCTION

The type of wick drain selected was the Alidrain, manufactured by Burcan Industries, Canada. The Alidrain consists of a thin plastic core, approximately 100 mm by 7 mm wrapped in a special filter of cellulosic material. Small closely-spaced plastic studs embossed on the inner surface of the core form channels that allow flow when the sleeve is pressed together.

Because settlements of as much as 8 feet were predicted due to consolidation of the soft floodplain sediments during and after fill placement, 12 feet of fill was placed and compacted on top of the original ground before installation of the wick drains and the instrumentation. A 1-1/2-foot-thick sand drainage blanket was then constructed above the 12 feet of fill. This ensured that the drainage blanket and the top of the wick drains and instrumentation would be above the ground water level throughout the fill construction operations. It also served as a working mat for the heavy equipment needed to install the wick drains.

The Alidrains were installed in the areas shown in Figure 3, by Techniques Louis Menard, S.A. of Singapore. Installation began in mid-July and was completed by mid-October, 1981. In all, 20,075 Alidrains totaling 967,000 linear feet were placed in about 75 working days using three rigs operating on average about 9 hours per day. Drain lengths ranged from 15 to 65 feet, with an average of about 48 feet.

Three cranes specially modified by Menard were used for the drain installation. Two of these were smaller rigs (a Hitachi and a Koehring crawler crane) that installed drains less than about 40 feet deep. A larger Manitowoc 3900 crawler crane was used for the deeper drains. The drains were installed within a 6-inch-diameter mandrel that was pushed into the ground by a vibrator, the whole system being supported by fixed leads attached to the crane. A special shoe on the bottom of the drain anchored it into the ground as the mandrel was withdrawn. After mandrel withdrawal, the drain was cut off leaving about a 3-foot-long pigtail at the top of the sand blanket.

In numerous cases, excess porewater pressures existed in the soil, either due to the fill already placed and/or the installation of the Alidrains themselves, and the outflow of porewater began within minutes of the mandrel withdrawal. The instrumentation to measure porewater pressure and settlement, described in the following section, was installed after the Alidrains but before fill placement started.

Fill placement and compaction above the sand blanket started in mid-September 1981 and was completed by the end of March 1982. In most areas, the rate of filling averaged about 1 foot every 3 days, compared with the 1 foot every 2 days assumed in the wick drain design. However, the rate of fill placement was somewhat uneven, with as much as 8 feet being placed in 5 days at one location.

No stability problems were encountered in the underlying soft floodplain sediments during or after the fill installation. The apparent reasons for this success, namely the rapid drainage, consolidation and consequent increase in strength of the soft sediments, are discussed in a later section. It may be noted, however, that the physical presence of 1 million linear feet of wick drain material within the soft materials probably also helped reinforce and stabilize these soils.

INSTRUMENTATION

Piezometers, surface settlement markers and deep settlement gauges were installed throughout the stabilized area to provide porewater pressure and settlement data before, during and after the fill embankment construction, enabling ongoing evaluation of the wick drain performance. The instruments were installed and monitored by Techniques Louis Menard, S.A. of Singapore. Instrument locations are shown in Figure 3.

Twenty-three Slope Indicator Company porepressure transducers were installed during July through September of 1981. These 1-1/2-inch-diameter instruments had standard Cassagrande-type 6-inch-long porous stone filters, and were installed at depths ranging from 16 to 76 feet below the top of the sand blanket. The instruments were operated by a hydropneumatic balance of forces across a flexible diaphragm, and were read from a remote sensing station, well outside the area of the fill operations, using a portable pneumatic indicator. Readings were taken twice weekly during the fill operations,, and once a week before and after the filling. Only two of the transducers (P-14 and P-16) failed during the 10 to 12-month monitoring period.

Settlement was monitored using 7 surface settlement markers to record total settlement and 15 deep settlement gauges to measure settlement at different depths in the compressible material. The settlement markers, installed during September 1981, consisted simply of a square metal plate (about 2 feet by 2 feet by 1 inch thick) placed on the surface of the sand blanket, with a vertical steel rod attached to the plate. The rod was inside a PVC tube to isolate it from the soil. The rods and PVC tubes were extended vertically in sections as the filling operations proceeded.

The settlement gauges were installed during September 1981 in holes predrilled to a depth 1-1/2 feet short of the desired gauge elevation. Each gauge consisted of a 5-inch diameter screw-type auger, about 1-1/2 feet long, screwed into the undisturbed soil at the bottom of the borehole. The depths of the gauges ranged from 15 to 65 feet. The vertical steel rod attached to the auger extended to the surface through a PVC tube installed to isolate it from the surrounding soil. As with the settlement markers, the rods and the PVC tubes were extended vertically in sections as the filling operation proceeded. Like the porepressure transducers, the settlement instruments were measured weekly except during filling operations when measurements were taken twice weekly. During the fill construction, one settlement marker (S-2A) and one settlement gauge (D-2) were damaged to the extent that they could no longer be read.

As shown in Figures 2 and 3, the instruments were usually installed in clusters at the borehole locations to enable development of a settlement and porewater pressure profile with depth through the soft floodplain sediments. For example, the instrument cluster at borehole BH-57 had porepressure transducers at depths of 24,36,45 and 60 feet below the top of the sand blanket. For settlement measurement, a marker was installed on top of the sand blanket, and gauges were placed at 19,28 and 53-foot depths. These instrument locations are shown in profile in Figure 3. The results from this cluster of instruments are discussed in the following section.

RESULTS OF MEASUREMENTS

Typical results from the porewater pressure and settlement measurements are shown on Figures 4 and 5, respectively, for the instrument cluster at BH-57, near the center of Area A (Figure 3).

Figure 4 shows that excess porepressures built up in the clay sediments (P-10 and P-11) directly reflected the weight of the surcharge fill added. This is well illustrated by the porepressure response from 20 feet of fill placed between mid-December and

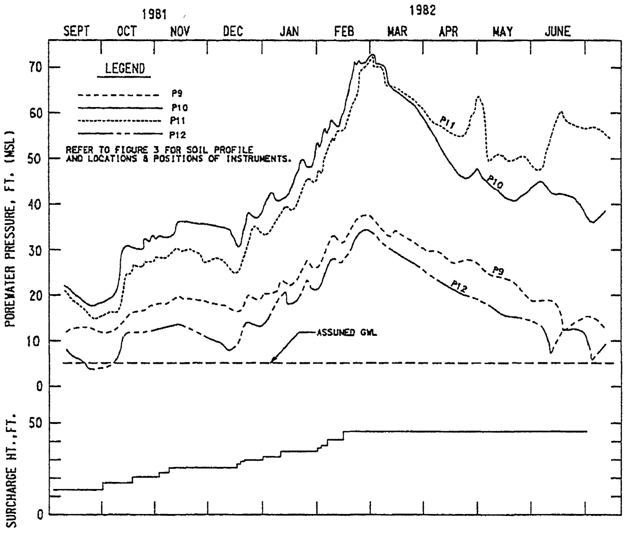

Fig. 4 Piezometer Measurements

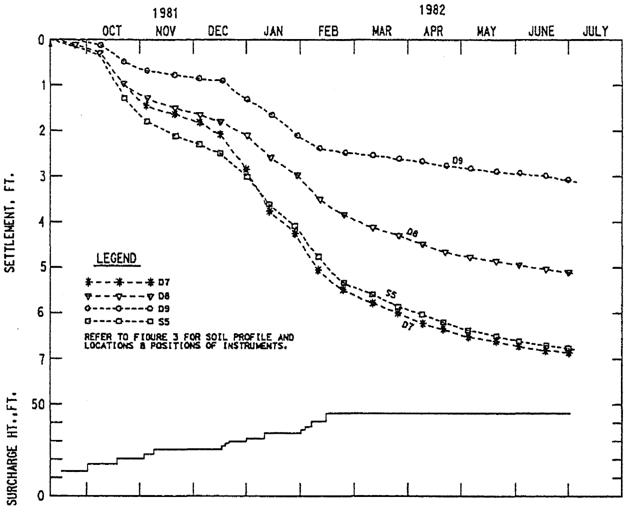

Fig. 5 Settlement Measurements

early February. (There had been no fill placement from early November to mid-December, and porepressure readings had stabilized). The maximum porepressure rise resulting from the 20 feet of fill (at 125 pcf) was equivalent to 40 feet of water (at 62.5 pcf). Porepressures built up in the more permeable peat and silt (P-9 and P-12) dissipated more rapidly with the maximum excess porepressure generated by the 20-foot fill placement being equivalent to only about 15 to 20 feet of water.

Figure 4 shows the excess porepressures dissipating fairly steadily in the peat, silt and clay after completion of the fill placement in early February. Excess porepressures in the peat (P-9) and the silt (P-12) had almost completely dissipated by the last reading in early July; readings in the clay were still moderately high at that time. This porepressure dissipation is reflected also by the changes in settlement shown in the time versus settlement curves for each layer in Figure 6. For example, the settlement of the peat (derived by substracting the D-8 from the D-7 readings) responded rapidly to the change in load, with little settlement being observed much beyond the end of the surcharge addition in mid-February. Recordings in the silt (D-9) showed a distinct reduction in the rate of settlement at the end of the surcharge addition. Settlement of the clay (D-8 minus D-9), on the other hand, indicated little or no rate reduction at that time. Early readings in the muck (D-7 minus S-5) demonstrated a rapid response to loading; the anomalous readings shown between early December and mid-February must be attributed to a temporary malfunction or misreading of deep gauge D-7 or settlement plate D-5 during that period.

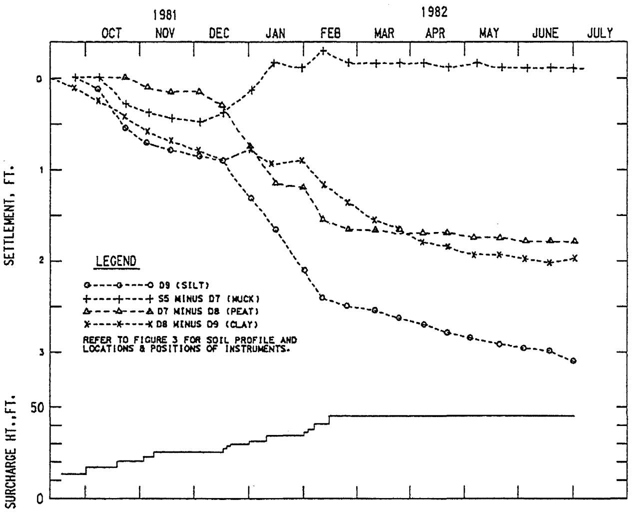

Fig. 6 Settlement Measurements for Each Soil Layer

Figure 5 shows maximum settlement at the BH-57 location to be around 7 feet at the last reading in July. Assuming this represents approximately 90 percent of the primary consolidation (see next paragraph), total primary consolidation settlement will be around 7.8 feet. This compares well with the predicted maximum primary consolidation settlement of 8.3 feet. At the other instrument cluster locations, 100 percent primary consolidation settlement values extrapolated from the July measurements ranged from 3.3 to 7 feet, and were in good agreement with the predicted values.

It is not possible to verify precisely from the porewater pressure and settlement results whether 90 percent of overall primary consolidation settlement was completed in 6 months, since: a) the incremental nature of the fill placement (over a period of 5 months) obscured the rate of porepressure dissipation and settlement, and b) the various sediments behaved differently, in accordance with their different permeabilities. Regardless, from the end of loading increase in mid-February to the last reading taken in early July, (a period of about 5 months), Figures 4 through 6 show that the majority of excess porepressures built up were dissipated (except possibly in the clay), and most of the settlement was completed.

CONCLUSIONS

The installation of almost one million linear feet of wick drains in the soft floodplain sediments enabled construction of the fill embankment on top of these sediments to proceed on schedule. The projected rate of consolidation and the long-term undrained shear strength of the soft sediments were increased by factors of about 25 and 10, respectively. The measured settlements agreed well with the predicted values. The filling operation was completed without any slip failures occurring in the soft sediments, supporting the conclusion that the soft sediments had gained the predicted increase in strength due to consolidation. In short, the wick drains brought about the desired results. The instrumentation installed to measure porepressure changes and settlement during and after fill placement proved to be reliable and robust, as demonstrated by the generally reasonable readings, and very few instrument failures.

REFERENCES

Hansbo, S. (1979), "Consolidation of Clay by Band-Shaped Prefabricated Drains", Ground Engineering, pp 16-25.

Leonards, G.A. (1962), "Engineering Properties of Soils", Chapter 2 in Foundation Engineering, edited by G.A. Leonards, McGraw Hill.