Performance of a Harbor Embankment

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SYNOPSIS

An instrumentation program to monitor deformations and pore pressures in foundation soils during construction of a container wharf and backlands fill at the Port of Los Angeles is described in this paper. Inclinometers, vertical settlement systems, and pneumatic pore-pressure transducers were used to monitor the performance of a silty clay during various phases of container wharf and backlands construction. Results of the monitoring program and their impacts on wharf construction are presented and discussed. Instrumentation program refinements that were required during data gathering and interpretation are also noted.

INTRODUCTION

A geotechnical instrumentation program was carried out in 1986 and 1987 for the Port of Los Angeles (POLA) as part of a container wharf and backlands improvement project. The program involved placing instrumentation in and beneath a quarry-run dike that had been constructed across a berth in Los Angeles Harbor. This instrumentation was used to monitor soil settlement, lateral soil displacement, and excess pore water pressures as a function of time after dike and backlands construction.

Information collected during this program was used to decide whether or not sufficient settlement and lateral movement had taken place in fine-grained soil to allow installation of production piles through the quarry-run dike. Information from the instrumentation program also was used to evaluate whether or not vertical and lateral movement of the pile-dike system was within anticipated and tolerable magnitudes following the installation of production piles.

This paper describes procedures used to instrument the dike and soil and presents instrumentation data collected through October 1987. Effects of dike and backlands construction, production pile installation, and the 1987 Whittier Narrows earthquake on soil response are discussed.

BACKGROUND

The POLA project involved expansion of an existing marine terminal located along the main channel of Los Angeles Harbor. Improvements to the terminal included constructing a 600-foot-long quarry-run (rockfill) dike across the front of a 40-feet-deep berth and filling the berth behind the dike with approximately 450,000 cubic yards of sand fill. Over 500 twenty-four-inch octagonal, prestressed concrete piles were installed through the quarry-run dike to support a new concrete deck.

Field explorations and laboratory testing of soil during the design phase of the project revealed that foundation soil beneath the quarry-run dike is composed of nearly 60 feet of low plasticity silty clay and clayey silt over a very dense sand (Erickson, et al., 1986). The fine-grained soil is moderately over-consolidated with undrained shearing strengths typically greater than 1000 psf. The underlying sand is very dense, with blow counts from the Standard Penetration Test (SPT) typically greater than 100 blows per foot (bpf) and friction angles in excess of 35 degrees.

In the berth area, construction of the dike and filling of the backlands resulted in the addition of nearly 60 feet of soil and rock. The change in stress from the backlands fill material and the quarry-run dike was predicted to cause up to 27 inches of vertical movement and 13 inches of horizontal movement in the fine-grained soil over the 50-year design life of the structure. Approximately 70 percent of this movement was estimated to occur during primary consolidation. Ninety percent of the primary consolidation was expected to occur within 60 days of placing the quarry-run dike and backlands fill.

The magnitude of predicted horizontal movement created a significant design issue. If piles were driven before this horizontal movement occurred, they would be subjected to lateral loads from the displacing soil. Lateral pile load analyses using COM624 (Reese and Sullivan, 1980) revealed that allowable bending stresses in the piles might be exceeded because of the soil loading.

In view of the potential effects of lateral soil movement, it was decided that the quarry-run dike should be built and the backlands filled before the piles for the wharf were installed. Furthermore, it was decided that the amount and rate of vertical soil movement, lateral soil movement, and pore water pressure dissipation should be monitored to assure that at least 70 percent of the primary consolidation and associated lateral movement had occurred before production piles were driven. Lateral soil movement occurring after 70 percent primary consolidation would result in stresses within the piles, but those stresses were predicted to be within allowable levels.

INSTRUMENTATION

Four clusters of instruments were installed in the quarry-run dike (Figure 1). Each cluster included one inclinometer casing, one Sondex system, one surface settlement plate, and two pneumatic piezometers. Instrumentation was manufactured by the Slope Indicator Company (SINCO).

The casing used in the inclinometer installation extended from the top of the dike (elevation +6 mllw) through the fine-grained soil into the dense sand, ending at approximately elevation -125 feet. Figure 2 shows a cross section of the soil profile and inclinometer locations.

The Sondex system extended from the top of the dike to elevation -105 feet. The Sondex system consists of a corrugated plastic tube fitted with stainless steel sensing rings. Sensing rings were attached to the tubing at approximately 2.5- and 5-foot intervals through the fine-grained material zone. As the soil settles, the corrugated tubing collapses in proportion to the soil settlement, causing the sensing rings to move together. The change in position of the sensing rings is measured by lowering a sensing probe down the tubing. Settlement is determined by measuring the relative distance between rings located in the fine-grained soil and a bottom "anchor" ring which is located (fixed) in the lower dense sand.

Settlement monuments were used to record settlement caused by densification of the dike material and settlement caused by consolidation of the underlying fine-grained soil. During the field monitoring phase of the program, survey elevations were also taken on top of 6-inch-diameter steel casings that were installed to protect the instrumentation systems within the quarry-run dike.

Pore water pressure was monitored using pneumatic push-in pore pressure transducers. These were conventional SINCO pneumatic transducers that were fitted with a pushing mandrel and a stainless steel push tip.

INSTALLATION

The instruments were installed through 6-inch-diameter steel casings that were driven through

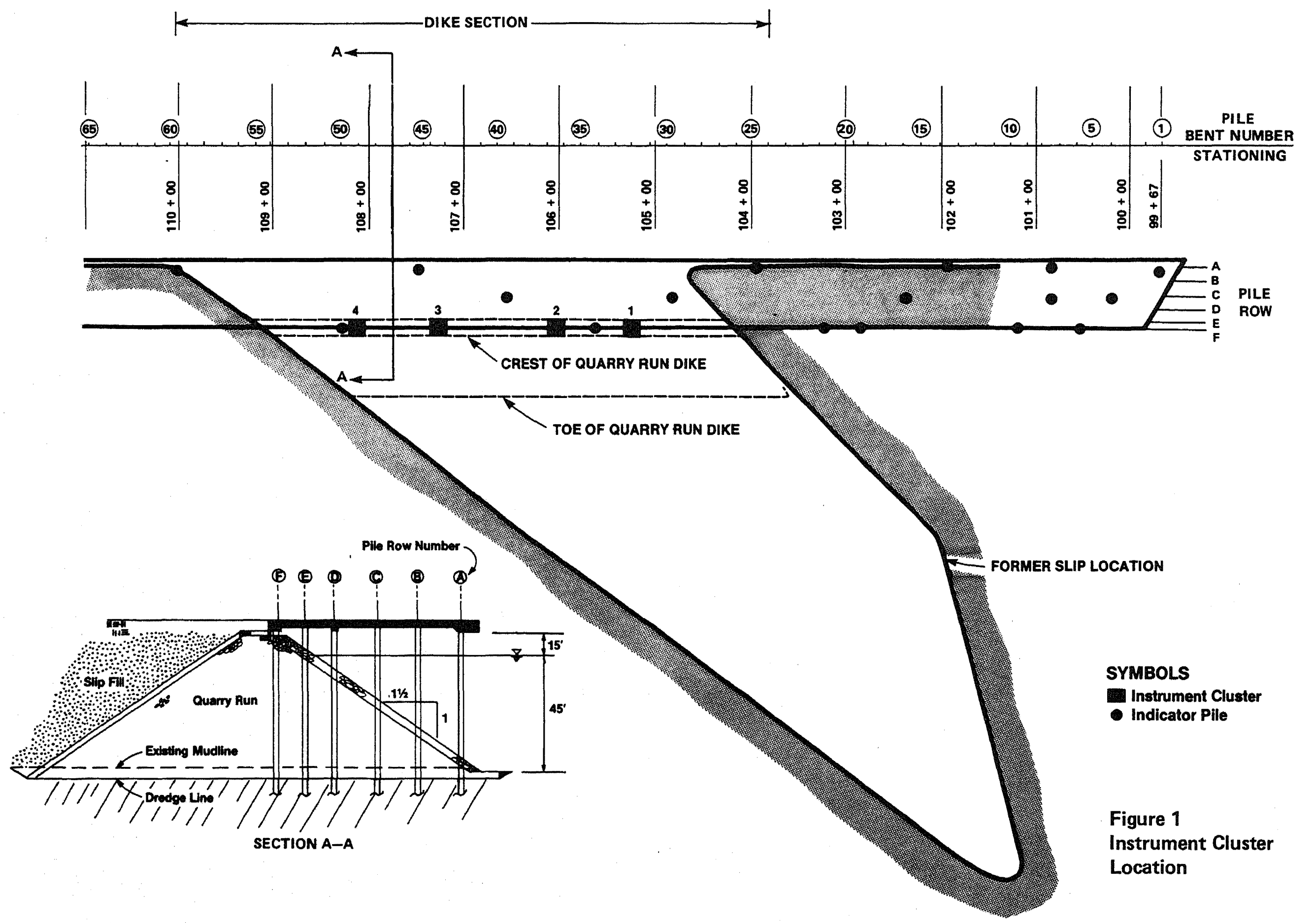

Figure 1
Instrument Cluster Location

the quarry-run material. The purpose of the casing was to protect the instrumentation through the quarry-run dike and provide a cased hole through which a rotary mud drill rig could be used to drill in the soil beneath the quarry-run material.

For each cluster of instrumentation, the borehole for the inclinometer/Sondex system was drilled and sampled first since this was the deepest borehole of a cluster, extending through the fine-grained soil into the lower dense sand. The inclinometer casing was placed inside the Sondex tubing and the two were installed as a single unit. This combined installation isolated the inclinometer casing from downdrag caused by soil settlement, eliminated the need for telescoping couplings in the inclinometer system, and reduced the number of boreholes, thus allowing data to be gathered at an earlier date. The accuracy of the Sondex sensing probe was not affected by the inclinometer casing.

The anchor point for the inclinometer casing was approximately 20 feet into the lower dense sand layer. A Sondex ring was mounted on the inclinometer casing below the bottom of the Sondex tubing and just above the bottom of the hole. Since the inclinometer casing is relatively rigid from top to bottom, any changes measured in this distance represented Sondex cable stretch. The outside of the Sondex tubing was grouted-in using a low strength grout mix.

The pore pressure transducers were installed in boreholes that were drilled to approximately 24 inches above the desired depth of the transducer. The soil profile revealed during drilling for the inclinometer/Sondex system was used as a basis for selecting the installation depth. Once the borehole was drilled to the appropriate depth, the transducer was tied to a push mandrel that was mounted on a section of drill rod, lowered to the bottom of the borehole, and pushed into the soil. Prior to installation, the porous stone for the transducer was saturated for 24 hours. The transducer assembly was sealed in a thin, water-filled plastic bag to protect it from drilling mud and to maintain tip saturation. After installation the borehole was filled to the surface with a bentonite-cement grout.

DATA MONITORING AND INTERPRETATION

Data from each instrumentation system were recorded immediately after installation and at regular intervals thereafter. Initially, the recording intervals were relatively close, i.e., weekly to biweekly. The interval was increased to monthly and later every 3 months when the change in data indicated that settlement, pore pressure change, and lateral movement were relatively slow.

The inclinometer data were interpreted using the computer program PC-SLIN. The PC-SLIN program is a proprietary program developed by

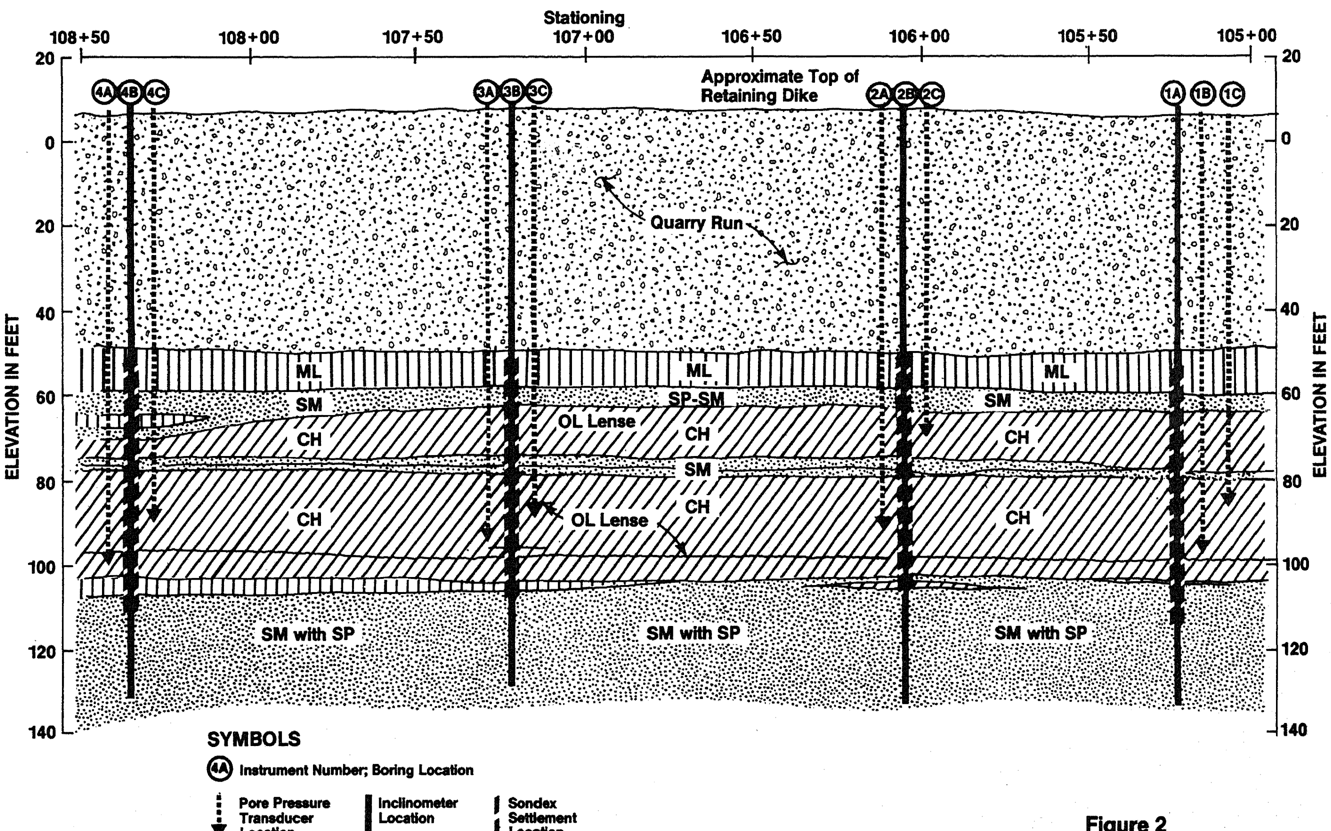

Figure 2
Generalized Soil Profile and Instrument Location

Geo-Slope Programming Ltd. of Calgary, Alberta. This program is written so that the accuracy of input data can be checked, the performance of the inclinometer probe can be evaluated, and a variety of data sets can be obtained and plotted.

The Sondex data were interpreted by determining the distance between the anchor ring and the reference rings. In November 1986 it was realized that the instrument cable used to record the depths of the Sondex rings was undergoing "negative stretch." Apparently as the cable aged some of its elastomers evaporated, making the cable stiffer and hence shorter under the same sensor probe weight. This problem was corrected by using a steel measuring tape to lower and measure the location of the Sondex probe.

The total pore water pressure was recorded by each piezometer. To evaluate the percentage of settlement that had occurred, it was necessary to determine the excess pore water pressure. This involved subtracting the hydrostatic component of pore pressure from the total pore pressure reading after applying a tidal correction. The tidal correction factor was determined by monitoring the pressure change over a tidal cycle on two occasions.

RESULTS

The instrumentation system has been monitored for over 400 days, as of mid-October 1987. During this period, the backlands area was filled, test piles were driven, and production piles were installed. Table 1 summarizes key events, dates, and elapsed time during the monitoring period.

Inclinometer profile plots for clusters 1, 2, and 3 at five different times after installation are shown in Figure 3. Two of the five profiles for each inclinometer show measurements before production piles were driven, and three show measurements after production piles were driven. These plots summarize the change in horizontal location of the inclinometer casing relative to initial installation. Movement to the right (positive values) indicates movement towards the main channel; i.e., outward from the axis of the dike. The depths shown on these plots are the distances below elevation +6 feet, which was the top of the dike at the time of installation.

Settlements for each cluster recorded during the Sondex program and during level surveys are summarized as a function of time since installation in Figure 4. Figure 5 shows the change in excess pore water pressure with time.

Table 1
KEY EVENTS DURING MONITORING PERIOD

Event	Date	Elapsed Time Dike	Elapsed Time Instrument
Start of dike construction	6/13/86	0	--
Dike at elevation +6 feet	7/20/86	37	--
Instrumentation installed	8/12/86 to 8/28/86	60-76	0
Test piles driven	10/01/86 to 10/27/86	110 136	34-50 60-76
Production piles driven	12/19/86 to 4/15/87	189 307	113-129 231-247
Whittier Narrows EQ	10/01/87	476	400-416
Last data set	10/14/87	490	414-430

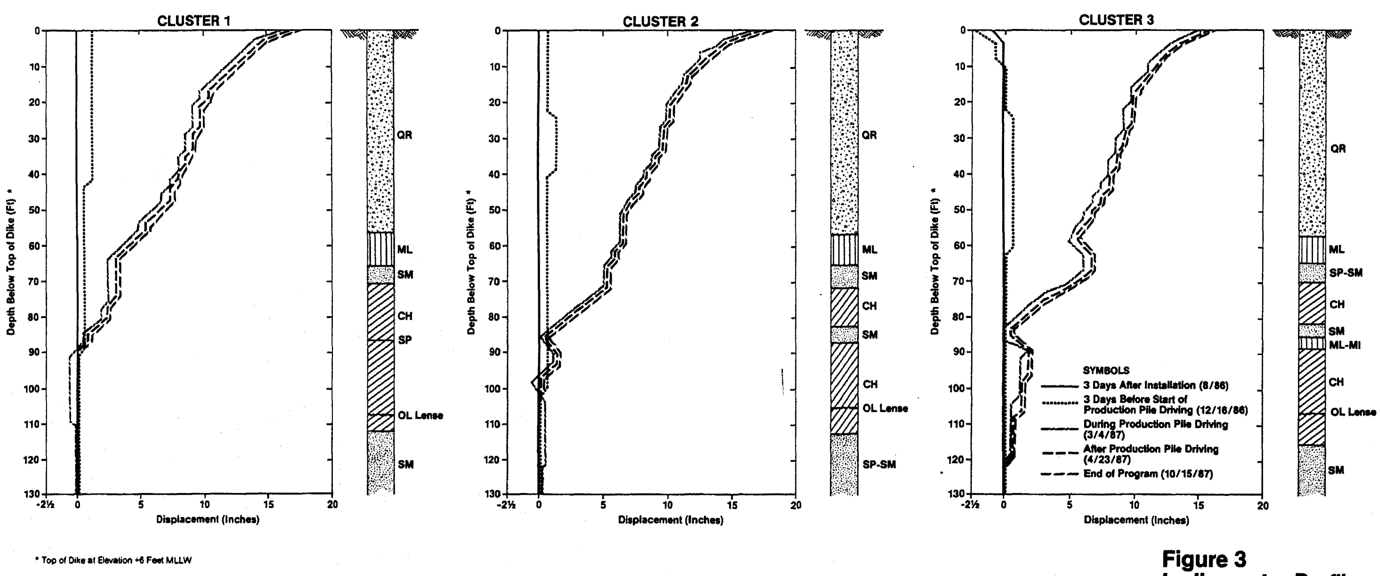

Figure 3
Inclinometer Profile Plots for Instrument Clusters

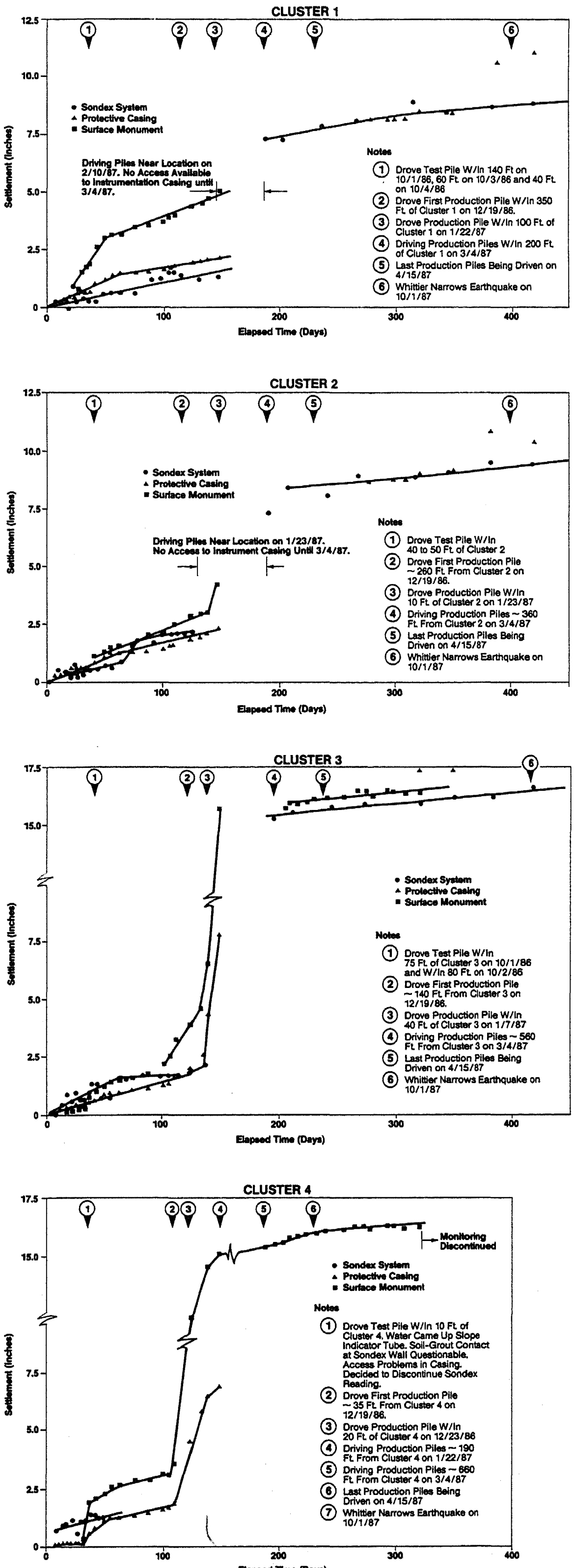

Figure 4
Settlement Results

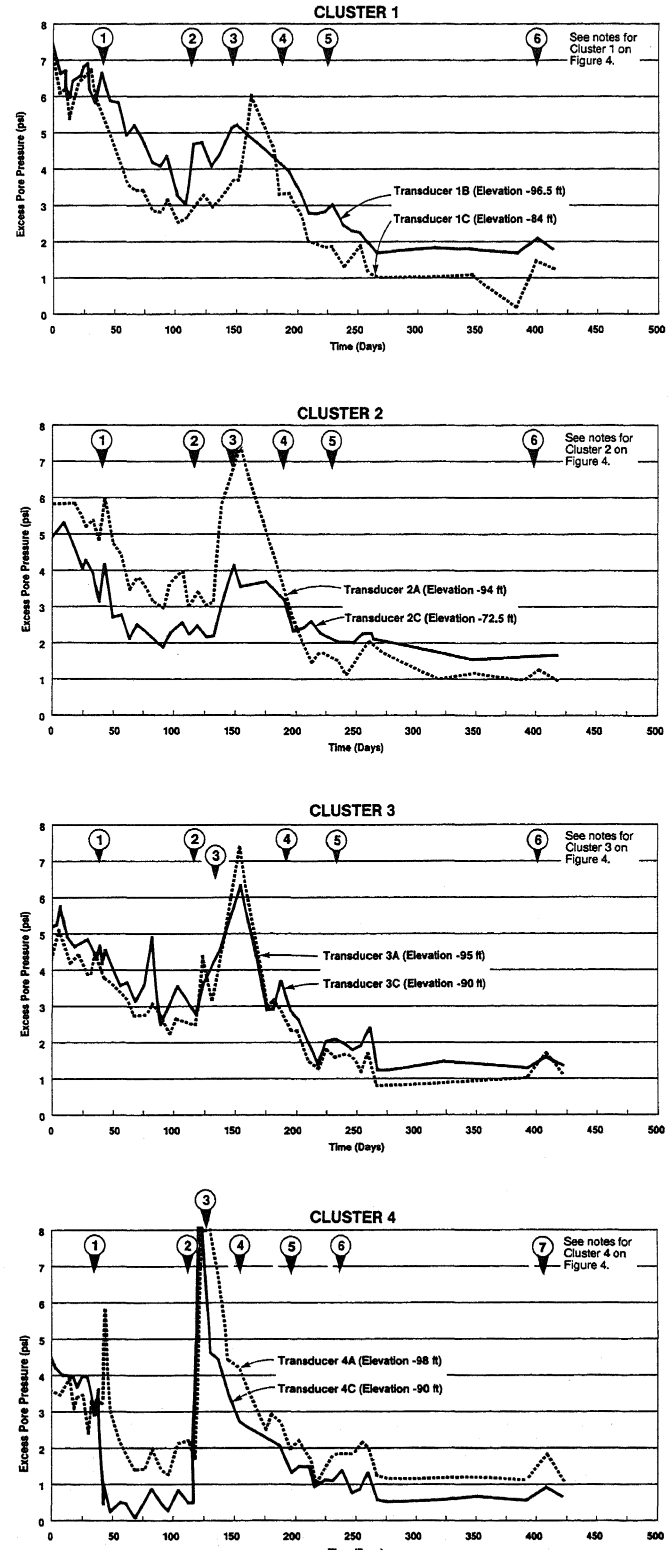

Figure 5
Excess Pore Pressure as a Function of Time

DATA REVIEW

The monitoring period was broken into four time periods for the purpose of data review. These periods include initial (baseline) conditions, before and after test pile installation, before and after production pile installation, and post construction.

Baseline Conditions

A set of data was collected for each instrument immediately after all instruments within the cluster had been installed. The baseline data represented conditions on the day that each cluster of instruments was read and, therefore, served as initial conditions for subsequent readings.

The baseline data did not represent initial conditions at the end of dike construction, since they were first monitored approximately 3 to 5 weeks after the dike reached an elevation of +6 feet. One of the objectives of the instrumentation program was to decide whether or not sufficient settlement and horizontal movement had taken place to install the production piles; therefore, it was necessary to estimate what the settlement and excess pore pressure would have been if the instrumentation had been installed before construction. This information was then used to decide how much additional pore pressure dissipation, settlement, and horizontal movement would have to occur before production piles could be driven.

Based on the ratio of measured excess pore pressure to the estimated value of initial excess pore pressure, the average degree of consolidation was estimated to range from 60 to 70 percent at the time of baseline monitoring. This suggested that 6 to 8 inches of settlement had probably occurred before the instrumentation system had been installed.

Test Pile Installation

Test piles were installed during October of 1986, approximately 35 to 75 days after instrument installation. The rate of soil settlement before test pile installation was fairly small. Typically 1/2 inch or less of soil settlement was recorded by the Sondex system. This is consistent with pore pressure data, which suggested that much of the excess pore pressure had dissipated before the instrumentation was placed.

Typically, the test piles were driven 40 feet or more from the nearest instrument cluster (Figure 2). A test pile was driven approximately 10 feet from cluster 4 on October 2, 1986. During installation of the test pile, water from the pile jetting operation was observed to spout from the top of the inclinometer casing. Later when an attempt was made to obtain inclinometer readings in cluster 4, sediment was found to be accumulating in the casing. The cluster 4 location was subsequently abandoned.

The effects of test pile driving included increased settlement and excess pore water pressure. The amount of settlement ranged from less than 1/2 inch to more than 2 inches; excess pore pressures increased by several pounds per square inch (psi). The settlement was most pronounced for the surface monuments. Very little settlement was recorded by the Sondex system. This suggests that most settlement resulted from densification of the quarry run material. No visible effects occurred in the inclinometer readings.

It was concluded from these measurements that test pile driving caused localized increases in pore pressure in the fine-grained soil and localized settlement of the quarry-run material, but no permanent horizontal movement or noticeable increases in fine-grained soil settlement.

Production Pile Driving

Production pile driving began on December 19, 1986, and concluded in mid-April of 1987. During this period over 500 piles were driven. Driving was initiated approximately 25 feet south of cluster 4 and continued north along the dike section passing cluster 3 on approximately January 12, 1987; cluster 2 on approximately January 23, 1987; and cluster 1 on February 10, 1987.

By the start of production pile driving approximately 1.5 to 2.5 inches of settlement had been recorded by the Sondex settlement system and by taking elevations on the top of the protective casing. This meant that total settlement from the start of dike construction was roughly 8 to 11 inches. The required amount of settlement before pile driving could begin was estimated to be 9 to 10 inches; hence the settlement data suggested that production pile driving could begin with minimum risk. Excess pore water pressure data indicated that excess pore pressures were less than 3 psi by December 19, 1986. This corresponded to an average consolidation of 80 percent, which was greater than the 70 percent required for production pile driving to start. Inclinometer data suggested that horizontal movement of the soil between installation and the last recording date before production pile driving varied from 1/2 to 3/4 inch in the fine-grained soil. An additional 1/2 to 1 inch of horizontal movement apparently occurred in the quarry-run material.

Production pile driving had significant effects on all of the instrumentation. Settlement data indicate that 5 to 15 inches of soil settlement occurred as a result of production pile driving. Settlement at clusters 1 and 2 was approximately 5 inches, whereas settlement at clusters 3 and 4 was nearly 15 inches. Survey data for the surface monument and the instrumentation casing clearly showed that settlement increased as pile driving approached.

Excess pore pressures increased dramatically during production pile driving. At cluster 4 the excess pore pressure was 35 psi immediately after driving. A maximum pore pressure in excess of 30 psi was also recorded at cluster 3. These levels of pore pressure nearly exceed the effective overburden stress at the transducer elevations. Dissipation times for the excess pore pressures were greater than 2 months.

The inclinometer data show that 13 to 15 inches of movement occurred at the top of the quarry-run dike during production pile driving. This movement decreased somewhat linearly with depth, with no appreciable movement occurring below elevation -80 feet. Closer inspection of the inclinometer data suggests that the steel protective casing in the quarry-run material rotated approximately 1 degree during production pile installation and that the soil beneath the quarry-run material displaced approximately 4 to 5 inches.

Post Construction

The last production pile was driven on approximately April 15, 1987. Since that date numerous construction activities have taken place at the project site, but none of these involved subsurface work such as pile driving or the addition of appreciable foundation loads. With the exception of the Whittier-Narrows earthquake on October 1, 1987, the foundation soil was subjected to constant stresses from the dike and backland fills during this post-construction period.

Pore pressure values from mid-April to mid-October of 1987 continue to decrease slightly or are relatively constant. The magnitude of the excess pore pressures as of October 14 was typically 1.5 psi or less. This represents roughly 90 percent consolidation or more. At least a portion of the remaining excess pore pressure could be attributed to uncertainties in correcting for tidal pressure effects. One excursion occurred consistently on all records approximately 400 days after the start of monitoring. This slight increase of approximately 0.5 psi was measured at about 2:45 p.m. on October 1, 1987, approximately 7 hours after the Whittier-Narrows earthquake. The epicenter for this earthquake was over 20 miles from the project. These excess pore pressures returned to levels recorded before October 1, 1987, by the next data recording period, which was 2 weeks later.

Results of Sondex measurements suggest that approximately 1 inch of settlement has occurred in the soil since the end of production pile driving. The rate of Sondex settlement appears to be decreasing with elapsed time, consistent with the normal consolidation and secondary compression processes. Settlements from the protective casing are generally consistent with the Sondex data. Significant jumps in the protective casing data in September are thought to be caused by construction activities. No increases in settlement were noted after the Whittier-Narrows earthquake.

Inclinometer data suggest that approximately 1 inch of outward movement has occurred at the top of the dike since mid-April. Less than 3/4 inch of outward movement has been recorded in the fine-grained soil (below elevation -60 feet) during the same period. No horizontal movement was detected during the earthquake.

DISCUSSION OF RESULTS

Results of the instrumentation program were relatively consistent with settlement predictions for dike and backlands loads. These predictions were based on results of laboratory consolidation tests and three-dimensional elastic stress estimates. The computer program FEADAM84 (Duncan et al., 1984) was also used to estimate stresses for different stages of construction. The magnitude of settlements and lateral soil movement during production pile driving was, however, much greater than anticipated. This observation, along with the observed pore pressure increase during the Whittier-Narrows earthquake warrants additional comment.

Production Pile Driving

It was clear from the recorded data that production pile driving caused very large increases in pore pressure. These increases were attributed to the combined effects of soil displacement during driving and the large jetting pressures that were used to assist in pile installation. While both conditions can logically result in pore pressure increase, the magnitude of increase was surprising. It was originally postulated that the vent channel associated with jetting would minimize the cavity expansion component of pore pressure increase. This vent channel was also expected to dissipate most excess pore pressures immediately after the end of pile driving. Pore pressure data indicate that excess pressures did not immediately dissipate. Rather, they dissipated in much the same manner as was recorded for dike loading. This suggests that the entire area underwent a pore pressure increase.

A substantial amount of settlement was also recorded as a result of pile installation. Changes in pore pressure in the soil do not appear to explain the magnitude of these settlements. It is believed that at least some settlement could be due to remolding and actual loss of soil during the pile jetting sequence.

Up to 13 inches of movement in the quarry run material were recorded. Movement of the steel casing probably resulted from a combination of (1) densification of the quarry-run material, (2) lateral stresses from the fill material on the shoreward side of the dike, and (3) pore-pressure-related losses in bearing support beneath the channel side of the dike. Movement of the soil in excess of an inch starts approximately at elevation -80 feet. This indicates that the lower clay layer was being stressed sufficiently to deform. Movement seems to increase in the upper clay layer that exists between elevation -65 and -75 feet. It is postulated that immediately after pile driving shearing forces induced by the sand fill behind the dike temporarily exceeded the strength of this clay layer. This would require that a loss in soil strength occurred somewhere along the shearing plane during pile driving, possibly at the toe of the embankment where overburden stresses were low and high pore pressures had developed. This loss in soil strength could have resulted from a combination of liquefaction within the sand layer, high pore pressures within the clay layer, and material loss during jetting. Figure 6 illustrates this concept.

Whittier-Narrows Earthquake

The Whitter-Narrows earthquake appears to have caused an increase in pore pressures within the fine-grained soil of approximately 0.5 psi. The magnitude of this increase is somewhat surprising, given the distance from the epicenter and the magnitude of the earthquake (M=5.9).

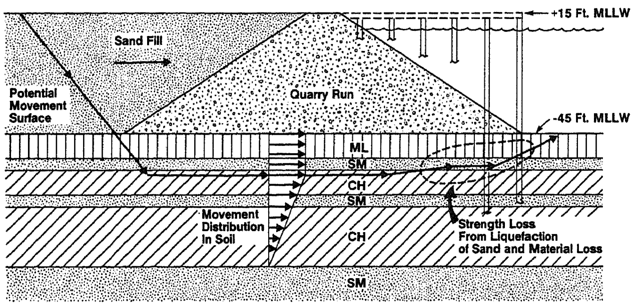

Figure 6
Potential Mechanism for Dike Movement

It was estimated that accelerations at the top of the dense sand layer, nearly 100 feet below the ground surface, would be less than 0.05 g. The shearing strain in the fine-grained soil was estimated to be as high as 0.05 percent. This level of shearing strain was apparently high enough to result in residual excess pore pressures. The level of pore pressure increase was small enough that no horizontal or vertical movements were recorded with the Sondex settlement system and the inclinometer system.

CONCLUSIONS

Results of the instrumentation program were used to decide that production piles could be driven beginning in mid-December of 1986. Instrumentation data collected before and after production pile driving indicated that ground movements occurring during production pile driving were within tolerable levels in terms of pile capacity. Data also suggested that the wharf-dike system should continue to perform satisfactorily in the future.

The following additional specific conclusions were reached during this instrumentation program.

- The instrumentation proved to be relatively easy to install and very reliable from the standpoint of operation. The only change in monitoring procedure involved using a steel measuring tape rather than the Sondex instrument cable to measure depths.

- Baseline measurements taken approximately 3 to 5 weeks after completion of the dike to an elevation of +6 feet indicated that 60 to 70 percent of the excess pore pressure had dissipated in the various fine-grained soil layers beneath the dike by the start of the monitoring period and that 6 to 8 inches of settlement had occurred. Pore pressure readings determined that excess pore pressures were from 4 to 8 psi, representing 60 to 70 percent consolidation.

- Test pile driving caused localized buildups in excess pore pressures. These pore pressures dissipated quickly. Settlement also occurred. Most of the settlement appeared to be within the quarry-run material.

- Production pile driving caused large increases in pore pressure, significant settlement, and lateral movement. The amount of pore pressure increase was as high as 35 psi. Nearly 10 inches of settlement occurred at some cluster locations. Inclinometer data showed that approximately 12 inches of lateral movement occurred at the top of the dike and from 4 to 5 inches in the soil beneath the dike.

- Very little settlement or horizontal movement has taken place since the end of production pile driving. Settlements have typically been less than 2 inches; lateral movement has been less than an inch. Excess pore pressures are generally less than 2 psi. Secondary compression of the soil appears to be under way.

The instrumentation program was a significant benefit to the Berths 225-229 project. For future projects involving the same design issues, consideration should be given to installing a similar instrumentation array to monitor soil behavior. If feasible, instrumentation used in any future array should be installed before dike construction.

ACKNOWLEDGMENTS

The instrumentation program described in this paper was performed for the Port of Los Angeles Harbor Department. Mr. Richard C. Wittkop served as the Project Manager for the Port of Los Angeles. His interest, as well as the excellent cooperation of General Construction Company, the contractor on the project, contributed significantly to the success of the project. Other CH2M HILL participants included Mr. Bradley P. Erickson, overall project manager; Dr. David Nyby, geotechnical engineer during design; and Mr. Art O'Brien, geotechnical engineer for instrumentation planning.

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