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Extensive Geotechnical Instrumentation Program to Control Dike Raising Constructed on Soft Clay

(Program Instrumentasi Geoteknik Ekstensif untuk Mengawasi Kenaikan Tanggul di atas Tanah Lunak)

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ABSTRACT

In its quest of increasing potash production, Arab Potash Company (APC) decided to increase the size of their salt evaporation pans. The Dike 18 which is spanning a length of 13km and enclosing a pan area of 16.5km^2 was built between January 1996 and December 1997 as part of APC's expansion scheme. The foundation soils were predominantly varies from soft to very soft silty clay. From laboratory and field test results the undrained shear strength of the clay was between 28 to 40 kPa. An extensive instrumentation program was designed and implemented in order to control the dike raising during construction as well as to monitor the performance of the dike foundation during and after the construction. Instrumentations being installed included settlement spider magnets, level stations, standpipe and pneumatic piezometers. The major constraints of the instrumentation program were the large vertical settlements (2-3m) of the very soft clays, artesian conditions where sand and salt layers were present, high salinity of the groundwater and the development of sinkholes. Special installation and protection measures were developed to overcome these constraints. The performance aspects of the instruments were discussed and typical plots were presented.

Keywords: piezometers, soft clay, dike, evaporation pans

INTRODUCTION

Arab potash Company (APC), Jordan, was founded in the mid seventies at the southern limits of the Dead Sea, Jordan (Figure 1) to utilize the sea water (brine) for the production of Potash (KCl) which is used as fertilizer (Khlaifat et al., 2010). A larger number of salt pans are required in order to increase potash product. These salt pans are surrounded by large watertight dike structures built on soft to very soft silty clay (Lisan Marl) foundation. Dike 18 which is spanning of 13 km long and enclosing a pan area of 16.5 km^2 was built as part of this expansion scheme (GIBB Ltd, 1995a).

The Lisan Marl is an alternating layers of white (dominated by aragonite) lamina and grey (dominated by calcite) lamina. Gypsum, clay minerals (mainly koalinite), quartz, halite, and feldspar are also found in this formation. Typical thickness of Lisan Marl is approximately 120 m (Abed, 1985; GIBB Ltd., 1995c). Typical indices, strength and permeability parameters for the foundation soil are: moisture content (15–90%), PI (1–23%), LL (11–45%), Su (28–40kPa), effective strength parameters ($C'=0$, $\Phi=30^o$), horizontal permeability ($k_h = 5x10^{-6}$ m/sec), and elastic modulus ($E' = 65XSu$) (Madadha & Tabbal, 1997a).

The behavior and response of such difficult soil under the added loads during construction could only be quantified by means of highly sophisticated geotechnical instrumentation which was crucial to the success of the dike construction. Major challenges for achieving an effective instrumentation were large settlements, presence of artesian conditions where sand and salt layers were found, development of sinkholes (GIBB Ltd, 1995d) and the high salinity of the ground water (>300g/L). Less extreme installation conditions than what was encountered in this project have frequently resulted in low instrument survival rates.

FIG. 1 Geographic location

Consequently, a real potential danger existed that extensive instrumentation loss could occur at dike 18 and perhaps jeopardize its success. This paper presents a description of the instrumentation being used, detailing the equipment and installation techniques being employed and recording and presenting the observed performance of the various units during and post construction of dike 18.

INSTRUMENTATION EQUIPMENTS

Construction of Dike 18 required four types of performance systems which included internal deformation measurement, pneumatic piezometers, surface measurement, and standpipe piezometers. The instrumentation philosophy was to choose the correct instruments, instrument types and measurement systems wherever possible (GIBB Ltd., 1995b).

Twelve instrumentation lines were installed at 1km intervals along Dike 18 alignment (Figure 2). Nine pneumatic piezometers, one settlement extensometer magnets and three standpipe piezometers were installed at each instrumentation line. Four concrete monuments at both upstream (US) and downstream (DS) toe were installed and two level stations were installed at the dike crest and DS berm after the successful completion of the dike at 200m intervals.

A system of duplicate installations especially for pneumatic piezometer was employed. The survival rate of the instruments was overall excellent (Table 1).

SURFACE MEASUREMENT SYSTEM

The surface measurement system consists of a series of concrete beacons fitted with steel studs and centring devices installed on DS berm and crest to measure vertical displacements and on the US and DS toe to measure horizontal displacements (Figure 2).

TABLE 1. Instruments utilized at dike 18

Instrument type	Measured parameter	No. installed	No. functional
Concrete monuments	Horizontal displacement	356	356
Level station	Vertical displacement	260	260
Standpipe piezometer	Groundwater table	36	36
Extensometer	Settlement profile	84	84
Pneumatic piezometer	Pore water pressure	108	100

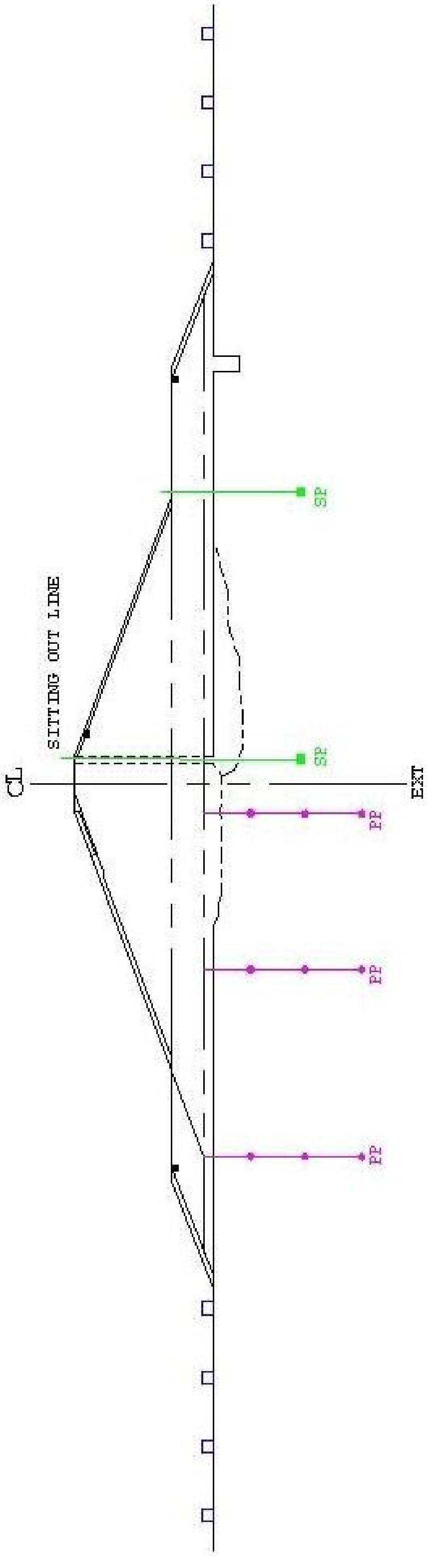

Figure 2. Dike 18 instrumentation configuration

Vertical Measurement System - Level Stations

Two concrete beacons for vertical measurements were installed every 200 m on the crest and DS berm along the dike. The results obtained from monitoring level stations were used to estimate the time required to increase the assumed freeboard allowance (i.e. five years based on trial dike results). The values for Dike 18 crest settlement were plotted with log time at each instrument section to determine the coefficient of secondary compression of the given section (Figure 3). The post construction settlement will then be estimated using equation 1 to predict the point at which topping up of the dike is required to maintain an adequate freeboard.

$$\Delta H = \frac{C_{\alpha} Log \Delta t}{H} \qquad (1)$$

where:

H : Thickness of consolidated layer below dike

ΔH : Post construction settlement at a given time increment

Δt : Post construction time increment

Horizontal Measurement System - Concrete Monuments

Four concrete monuments each were installed at both the US and DS toe and were repeated every 200m along the dike. The installation of the monuments was carried out ahead of dike construction. The lateral movement was measured using a tape extensometer consisting of a precisely tensioned heavy duty tape with a measurement precision of 0.05mm and accuracy of ± 0.2mm (Figure 4) to determine the behavior of the surrounding soil in the vicinity of the dike during construction; the horizontal displacements were plotted against dike height and time. The displacement obtained during dike 18 construction was less than those obtained from trial dike. This could be due to fast raising of trial dike which lead to mud waves formation. However, the smaller horizontal displacement in this case is a good indication that no sliding is expected.

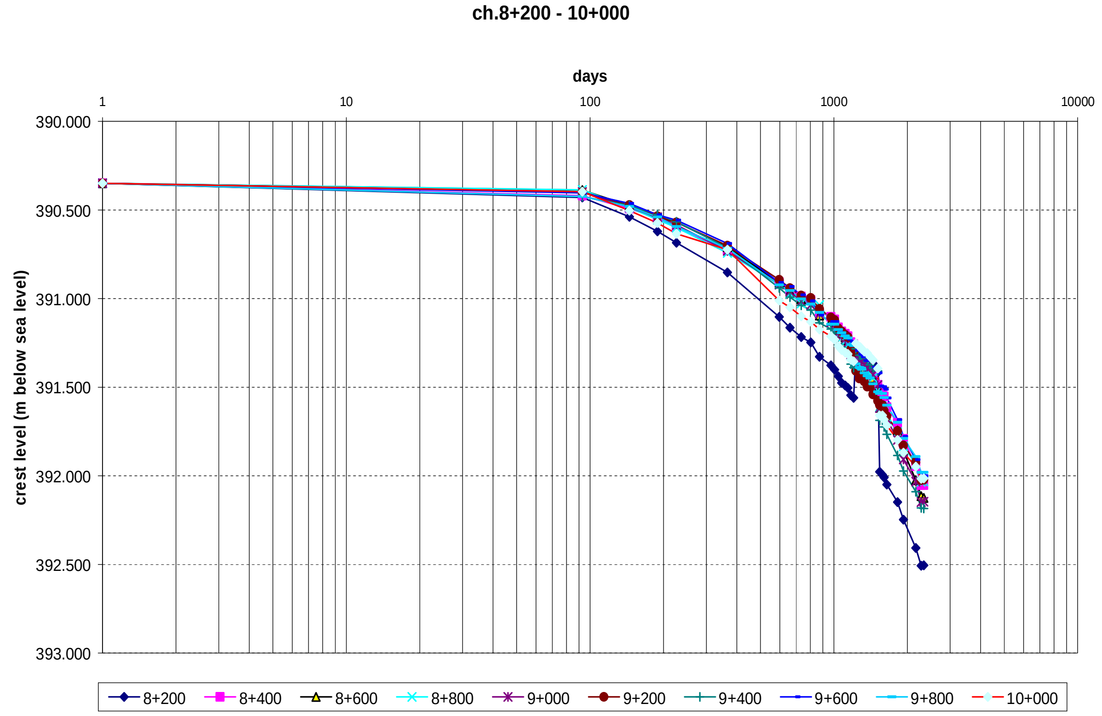

FIGURE 3. Typical results for vertical deformation monuments

FIGURE 4. Tape extensometer used in dike 18 monitoring

SOURCE: Soil Instruments Ltd., 1994

EXTENSOMETER SPIDER MAGNETS

Extensometer spider magnets were used for the measurement of settlement profiles below the foundation soil. This procedure is an essential requirement for evaluating pneumatic piezometer results. Settlement profiles were also used to better understand the soil deformation by back-analysis of the observed settlements for comparison of derived parameters with the design assumptions. The spiders magnets possess spring leafs attached to them so they can be fixed to the sides of boreholes and cause the spiders to settle in conformance with the surrounding soil. The vertical settlement measurement system was installed ahead of pneumatic piezometers and actual construction of Dike 18.

Vertical settlement measurement system (Figure 5) consists of vertical telescopic tubes, spider magnets and extensometer probe. The system components were installed such a way that they can move freely with the soil and relative to each other. Seven spider magnets were fitted around the telescopic tubes at 2.5m vertical distance between consecutive spiders. One such system was installed at each instrumented section. The extensometer probe was used during the monitoring stage to measure vertical movement of the spider to an accuracy of ± 3 mm in a 30 m deep hole. The top level of the access tubes were used as datum level.

Immediately after the system was successfully installed and the grout set (used to back fill the borehole), base readings were taken before any fill was allowed in the vicinity of the installation.

Comparison between vertical settlements measured from extensometer spider magnets and settlements determined from borehole drilling: Vertical settlements were determined by drilling boreholes and the DS from Stage I level to top of zone 2 sand fill from which its elevation was determined. The settlement was calculated as the difference between top elevation of zone 2 sand fill at time of placement and its new elevation at time of drilling.

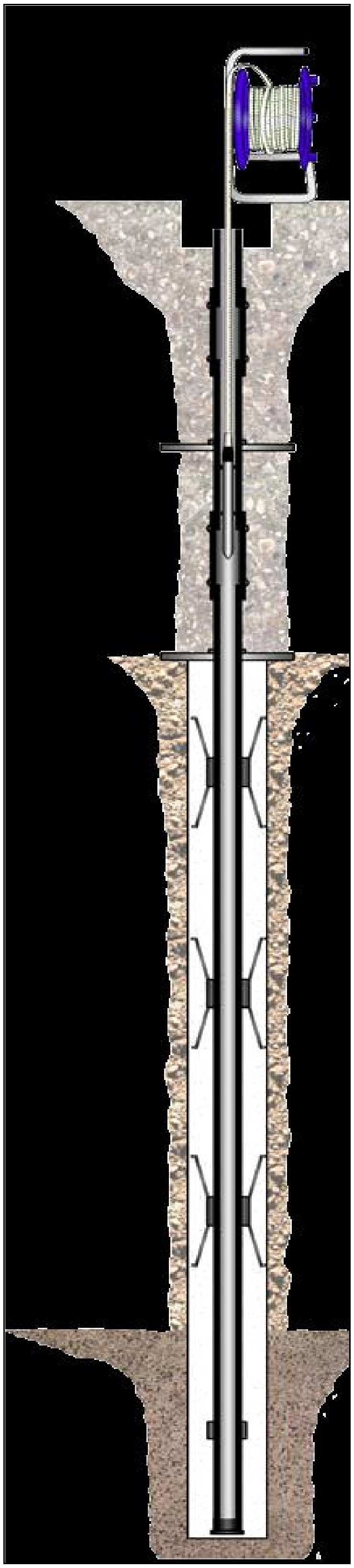

FIGURE 5. Extensometer system after releasing the spider magnets

Total settlement values obtained from borehole drilling were found to compare well with settlements obtained from extensometer spider magnets immediately before Stage II was about to commence. Typical results are shown in Figure 6.

Pneumatic Piezometers

Pneumatic piezometers were used for the measurement of pore pressure in low permeable soft clay. These instruments are called closed or constant volume piezometers and they possess short response time that they are able to reflect rapid variations in pore pressure due to surface loads (Knight, 1989). Nine piezometers were installed at each instrumentation section. The nine piezometers were arranged in three rows with three piezometers in each row. The depth of the piezometers being installed were 5m, 10m and 15m.

The pneumatic piezometer measurement system consists of low air entry piezometer tips, nylon twin tubing and digital readout unit. The tips used at Dike 18 are of the push type equipped with a diaphragm capable of recording-pressures in the range of (-5 to 350) mH_2O with an accuracy of ±0.20m. The permeability of the tips is approximately 3×10^{-4}m/s. Each piezometer was connected between its tip and the terminal apparatus by nylon twin tubing. The readout unit used to measure the pore pressure is the Pneumatic Bubbler Logger. The digital read out unit id capable of recording pressures between (0-35) mH_2O for an accuracy of ±0.035m and a display resolution of 0.01m. Before the actual installation, pneumatic twin tubing was cut to size, color coded, connected to piezometer tips, pressure tested and the tips were boiled in desired water and left to soak for at least twenty four hours prior to installation to ensure complete saturation. The push-in type pneumatic piezometer tips were fitted on a special rod adapter rod lowered to the bottom of the predrilled and cased boreholes (Φ=150mm) and pushed into the undisturbed soil below the depth of casing, Case 2. Extreme care was exercised at all times during pushing-in of piezometers to ensure that the diaphragm is not over stressed (McKenna, 1995). Careful monitoring of the diaphragm response was always carried out at all phases of installation to ensure precise and complete functioning of the piezometer tips connections and twin tubing operation.

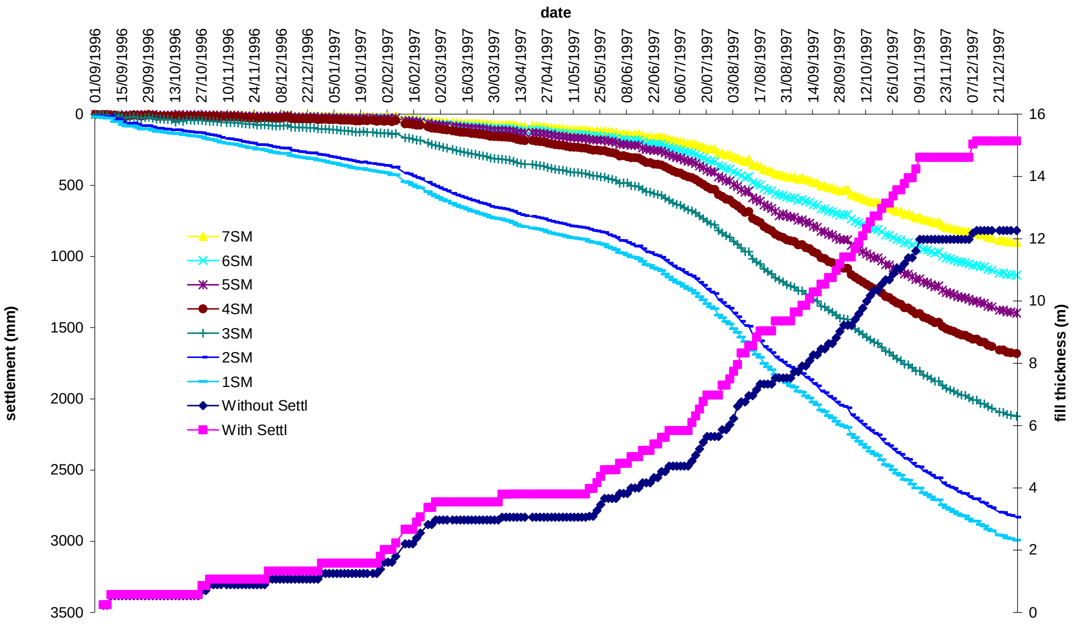

FIGURE 6. Typical extensometer readings

Piezometers installed in sand cells were placed within the borehole and surrounded with pre-saturated clean sand extended a distance of 0.5m beyond each end of the piezometer tip, thereafter, at least 0.5m of bentonite balls or pellets plug were immediately placed above pushed-in tips or sand cells after ensuring that the diaphragms were functioning properly. Two of the boreholes drilled for the installation of the 15m depth piezometers at Ch. 1+000 showed artesian conditions. The flow of water encountered prevented proper installation of the piezometer tips and therefore, it was decided to place the tips in pre-formed sand cells and plug the top of response section with pneumatic packers. At least 0.5m of bentonite balls or pellets plug was immediately placed above the installed packers after ensuring that the diaphragms were functioning properly. The boreholes were then backfilled with cement/bentonite grout while carefully withdrawing the casings (Mikkelsen, 2002). All pneumatic tubing were laid in trenches excavated to a maximum depth of 0.5m. The tubes were laid between two 100mm thick layers of soils free from particles that could damage the tubing. The tubing for the pneumatic piezometers were placed parallel to each other on zig zag path having an approximate wave length of about 2m with an amplitude of about 200mm to allow for large expected vertical deformation. Continuous checking of proper functioning of the system was carried out after each step of installation procedure until the twin tubing was successfully connected to the terminal unit. Pore pressure readings were repeated daily until equilibrium of pore pressure readings was reached usually during one week of monitoring. Base readings were then determined for each piezometer by determining the average pore pressure readings recorded in the last monitoring week after equilibrium was achieved. Upon establishing the base readings for the pneumatic piezometers and the extensometer spider magnets, earth works were allowed to commence in the vicinity of the specified instrumented section. One hundred and eight pneumatic piezometers were installed at twelve instrumentation lines of Dike 18. During Stage I construction, the pneumatic piezometers were monitored once daily; while during stage II, monitoring was carried out twice daily. An example of pore water pressure behavior as detected by pneumatic piezometers is shown in Figure 7.

Upon initial embankment loading, soils usually experience stresses lower than yield stresses since pore pressure rises more slowly than the applied stresses and the B coefficient is below unity.

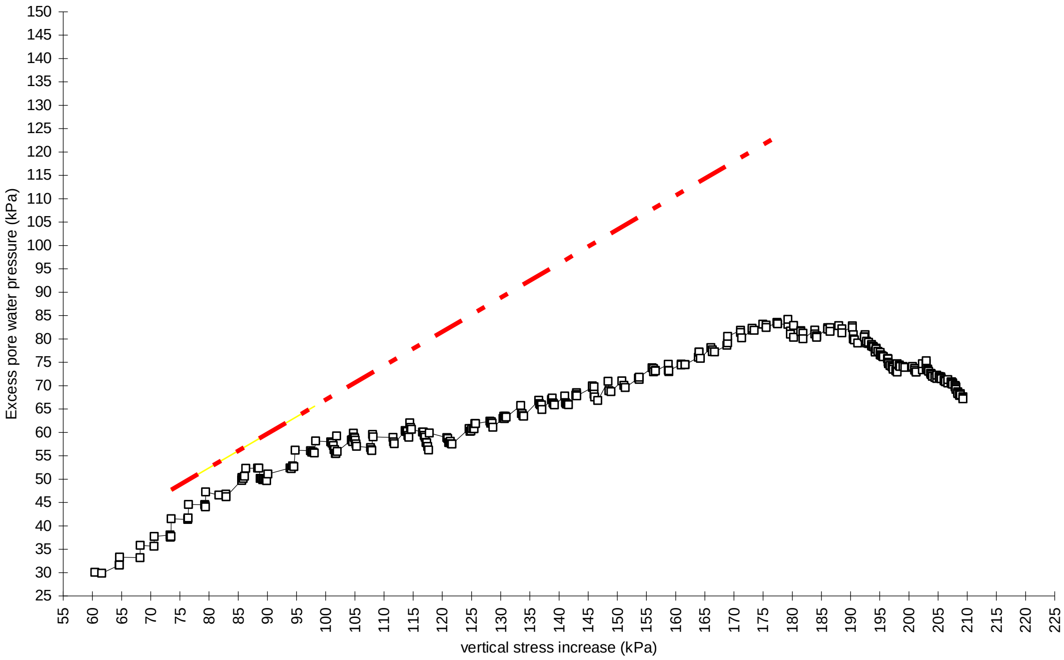

FIGURE 7. Pneumatic piezometer readings plotting

If yield is initiated in soft soils, pore pressure increase rapidly and B coefficient reach values equal or exceeds unity. If the zone of pore pressure increase is localized, the fill may not fail. However, with continued small loading increments, zones of yield spread very quickly thereby, causing sudden collapse. Few data exists to discover the rate at which sudden failure may develop after the initial rise of B coefficient to greater than unity. Therefore, proper assessment of pore pressure are only possible if sufficient measurements are made and carefully evaluated and linked with variations of vertical stress increase due to applied fill load. Furthermore, corrections to both the pore pressure readings and vertical stress increase to reflect actual construction conditions required careful consideration to arrive at accurate excess pore pressure values. To obtain accurate excess pore pressures, the depth of pneumatic piezometers, which measure total pore pressures, below the phreatic water level was required. Consequently, corrections were necessary to determine the excess pore pressure used in the B coefficient which is the main parameter for the control of dike raising. Pneumatic piezometer tip settlements were also estimated and compensated for using settlement profiles determined from extensometer spider magnets. Transverse settlements values were determined for each piezometer tip by settlement analysis assuming a Boussinesq stress distribution under the dike calibrated against the known extensometer spider magnet settlements. Excess pore pressure was then calculated as the difference between piezometer readings and base readings compensated for settlement.

The total vertical stress increase (analyzed separately for each stage of construction) was estimated for each piezometer tip based on Boussinesq stress distribution. Again proper compensation was applied for the settled piezometer tips.

Datum of stress distribution model for the Boussinesq analysis was assumed on the ground surface. Consequently, further compensation was necessary to implement the difference between the settled fill mass and the replace mud mass in the vertical stress increments at each piezometer tip. The phreatic water level was another important factor affecting the excess pore pressure determination. In several locations water was observed accumulating near the US toe of the dike indicating a marked rise in the phreatic water level. Such phenomena gives false high values of excess pore pressures and corresponding large B values. Compensation for the phreatic water surface was estimated and applied by excavating "pits" near the US toe of dike, then measuring the water rise after the initial pneumatic piezometer installations. The phreatic surface was further confirmed from monitoring the standpipe piezometers installed at the DS berm. The ratio of excess pore pressure (Δu) and total vertical stress increase ($\Delta\delta_v$) is termed B – $\Delta u/\Delta\delta_v$. The B value was calculated from measurements carried out during dike construction. Limiting B values used during Stage I was B=0.7 under the middle third of the dike and B=0.5 elsewhere. These limits were changed during Stage II since significant consolidation of the soil occurred before Stage II construction actually started. The new limits were set at B=1.0 and were modified by the designer to account for the increase in effective stresses due to significant consolidation of the foundation soils below the dike between completion of Stage I and starting of Stage II. Graphs of excess pore pressure against the total vertical stress increase at each pneumatic piezometer tip were plotted from which the controlling B coefficient was evaluated. Typical daily report summarizing all monitoring, compensation and final calculation procedure and results for the pneumatic piezometers and extensometer spider magnets are shown in Table 2. The report indicates incremental layers, total fill height, base readings for both pneumatic piezometers and extensometer spider magnets, pore pressure readings influence factors based on Boussinesq solutions for spider magnets at different depths and piezometer tip, telescopic tube elevation, total settlements for each stage of construction and the B coefficient,

SUMMARY

Extensive geotechnical instrumentation has been used successfully used for the foundation monitoring and control of dike fill (raising) during construction. The foundation monitoring data is essential to be read, processed and interpreted so that appropriate actions are taken during the construction process to control the dike fill raising to ensure satisfactory foundation behavior during and after completion of dike construction. Consequently, effective instrumentation was crucial to the success of Dike 18 construction. Effective instrumentation posed a major challenge in view of the anticipated large vertical settlements (2-3m), artesian conditions where the sand and salt layers are found and the high salinity of the groundwater (density >1.25gr/cm^3). Other problems included the development of sinkholes and rutting during construction and the need to bring instrumentation tubing, connections and risers progressively up through and across within the dike fill. The instrumentation program was very carefully designed and implemented to successfully overcome these problems. Instrumentation procedures used to reduce the risk of failure included:

1. The use of a specifically designed instrumentation to accommodate large vertical settlements, i.e., 1m every 3m and telescopic tubing.
2. Replacement of faulty and damaged instruments during installation and commissioning of instruments.
3. Duplication of method of measurement by using two or more different instrument types or similar instruments to those used in previous studies to check or/and compare results from instruments with results of another instruments or/and results from a certain instrument with results obtained using the same instrument in previous studies.
4. Extensive use of on-site checking after each step of installation as well as re-calibration of instruments.
5. Use of extensive protective measures before, during and after instrumentation installation was successfully used.

   Vertical settlements were measured using extensometer spider magnets and were found to compare well with settlements obtained from borehole drilling to determine actual settlements along the dike.
6. Investigations were carried out during construction of Dike 18 to determine if the 15m deep silty clay layer is of sufficiently low permeability that could act as a barrier to excessive seepage from the salt pan if sinkholes are developed near the dike alignment during construction. The results of the investigations indicated that no special modifications were required and that Dike 18 construction should continue as scheduled. However, close and extensive monitoring should continue during the initial filling of the salt pan for

signs of leakage. A system of surveillance should be established to monitor ground water levels and flows from springs downstream of the dike during salt pan filling.

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