Instrumentation

John Dunnicliff

Introduction

This is the seventeenth episode of GIN. As promised in GIN-16, there are two articles following this column.

Automatic Control and Data Acquisition for 3D Deformation Measurements

I've recently become aware of two commercial versions of an optical survey system that can be used for automatic monitoring of deformation in three dimensions. Both are based on proven surveying technology and use Leica instruments, which have been enhanced by the addition of automatic tracking mechanisms, so that the survey instrument can be left in place and unattended. The system is programmed to make observations on targets, in a predetermined cycle at predetermined time intervals, and to output the data electronically. Applications include deformation monitoring of structures, excavations, slopes and dams.

One commercial version, the GeoMonitor, is available from Solexperts in Switzerland, and is described in the article that follows this column. Contact information is given at the end of the article. The other version, Cyclops (CYCLic OPtical Surveyor), is available from Sol Data in France. Contact information is:

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Pre-Installation Acceptance Tests for Vibrating Wire Piezometers - Concentrate on Checking the Zero Reading

In the September 1996 issue of *Geotechnical News*, on page 27, I discussed the need for testing vibrating wire piezometers prior to installation to ensure that they are reading correctly, and included some recommendations. In summary, my points were:

1. If the entire piezometer is not at a uniform temperature, it will give an incorrect reading. Depending on the manufacturer, it may take up to 2 hours to achieve this, after being moved from one temperature to another.
2. The pre-installation reading depends both on temperature and barometric pressure. If the pre-installation reading, corrected for these two factors in accordance with the manufacturer's instructions, differs significantly from the manufacturer's pre-shipment value, the manufacturer should be contacted.
3. If changes have occurred between factory and site, they are much more likely to be changes in 'zero' reading rather than changes in slope of the calibration plot.
4. I gave three possible methods for checking the slope of the calibration plot, prefaced with: "Although changes in slope of the calibration plot are unlikely, some users choose to verify that this has not occurred".
5. It is difficult to duplicate factory calibrations in the field. Pre-installation acceptance tests should therefore be regarded more as function checks than check calibrations.
6. For checking under water pressure, either the filter should be removed or the filter and cavity should be completely saturated with water.
7. For checking under water pressure, the piezometer should not be placed in a sand-filled bag.

In my view the above seven points are still valid. However, I would like to give much more emphasis to point 3 because I have found that some users are ignoring the need for a high-quality zero check. Recognizing this, in a recent specification I have written the following:

1. *A pre-installation acceptance test shall be performed on all vibrating wire piezometers, as specified herein, to check the zero reading.*
2. *The piezometer shall be placed in an indoor environment at a constant temperature of +/-2 degrees C, for a minimum period of one hour* [this time is adequate for all piezometers manufactured in USA, Canada and England, but should be reviewed with other manufacturers if the specification allows for acceptance of their piezometers], *to achieve thermal equilibrium. A piezometer reading shall then be made, together with a reading of temperature by using the internal temperature sensor, and a reading of barometric pressure by using a barometer with a minimum accuracy equal to +/-0.025 percent of the full-scale range of the piezometer.*
3. *The piezometer reading, when corrected for temperature and barometric pressure in accordance with the manufacturer's instructions, shall agree with the factory zero reading to within +/-0.5 percent of the full-scale range of the piezometer.*
4. *Piezometers that do not meet the above criterion shall be returned to the manufacturer.*
5. *After such pre-installation acceptance testing, vibrating wire piezometers shall not be subjected to shock.*

Note that the above wording does not call for a check on the slope, because I am convinced that if the zero hasnt changed, when checked as above, the crude checks that can be made while lowering the piezometer down a water-filled borehole (have you done your spellcheck on this word yet?) are not worthwhile. Note also that the fifth point will not satisfy specification purists, but I included it as a reminder of the obvious!

FMGM-99

The Fifth International Symposium on Field Measurements in GeoMechanics (FMGM-99) will be held in Singapore from December 1-3, 1999. This Symposium takes place once every four years, and has previously been held in Switzerland, Japan, Norway and Italy. Bulletin-1 for the Symposium is now available, and can be viewed on Website http://www.eng.nus.sg/civil/Conference/fmgm99. Alternatively, contact *Associate Professor Harry Tan Siew Ann, Secretary, FMGM-99, Department of Civil Engineering, National University of Singapore, Singapore. Tel: +65-8742278, Fax: +65-7791635, email* cvetansa@nus.edu.sg.

This is the major regular international meeting for those of us in the geotechnical instrumentation business. I hope to see you there.

Come to the Beach Party

The next in the series of instrumentation courses at Cocoa Beach, Florida, is scheduled for January 17-20, 2000. What better way to celebrate the millennium than to join us at this 'best of all places for a course', and in the middle of the Northern Hemisphere winter too! For technical content please contact me. For registration, price, and other issues, please contact:

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http://www.doce.ufl.edu/conf&sem.

A Puzzler

A challenge, but no prize! Please let me know if you have any ideas or solutions.

- An embankment on soft ground
- Concern for stability, with a possible failure surface primarily through one of the subsurface layers
- Open standpipe and vibrating wire piezometers in that layer. Enough of them to give confidence in the data, based on consistency
- After all piezometers reached equilibrium (settling down after installation, and after enough time for the open standpipe piezometers to overcome time lag), the vibrating wire readings of piezometric elevation were all much higher, by many feet, than the open standpipe readings.

This is a real-world puzzler, not an academic exercise.

Closure

Please send contributions for GIN to me at the following address:

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Salud! (Spain)

Automatic Control and Data Acquisition for Optical Digital Levels and Motorized Total Stations

Daniel Naterop

Introduction

Two notable developments in geotechnical instrumentation involve the Solexperts GeoMonitor data acquisition and monitoring system. One is the addition of motion-control motors to optical digital levels and the integration of the automated levels into the GeoMonitor System. The second is the integration of motorized Total Stations (theodolites) into the system to enable automated 3-dimensional displacement measurements. Unlike other systems used to monitor movement (e.g. hydraulic leveling systems, clinometers), there is relatively little installation effort required for these instruments because the measurement points (bar-code staffs for the level and miniprism targets for the Total Station) require no cable connection to the instruments.

The GeoMonitor System also acquires data from hundreds of other sensors such as piezometers, extensometers, or tiltmeters, enabling the monitoring of large and complex sites for a wide range of geotechnical problems. Alarms with several triggering options (telephone dialer, fax, pager, flashing lights, etc.) warn of measurements outside set limits. The system is ideal for monitoring slope stability, tunnel construction, dam safety, and excavations and their adjacent structures, for example.

Two projects are presented here in which these instruments, combined with the GeoMonitor System, were applied to monitor critical displacement; 1) tunneling under a railway/embankment dam in Switzerland, and 2) safety monitoring of a lock facility in Slovakia.

Hardware and Software for Data Acquisition and Monitoring

The measurement control center, shown in fig. 1, consists of a PC running the GeoMonitor software and an SGC (Solexperts GeoMonitor Controller). The SGC contains an analog to digital (A/D) converter, a "Watchdog" for se-

curity against system failure, and alarm switches.

The system can be controlled on-site or remotely via modem, and acquired measurement values can be transferred via modem to anywhere in the world for evaluation and external backup.

The GeoMonitor software controls the positioning of the levels and Total Stations, acquires the measurement data, and presents real-time graphical and numerical displacement by comparing measurement points to fixed reference points. Any movement of the instrument itself is compensated for in these calculations. Other analog measurements are also acquired (such as temurements are also acquired (such as temperature, atmospheric pressure, etc.). Measurements that are outside alarm criterion set within the program trigger alarms (pagers, faxes, telephone dialers, etc.).

Data Visualization Software (DAVIS) provides a graphic overview of the site, including instrument, sensor and measuring point locations, and data from all instruments and sensors. In addition, this software offers numerous options for data analysis and presentation, which are unique to geotechnical instrumentation and measurement.

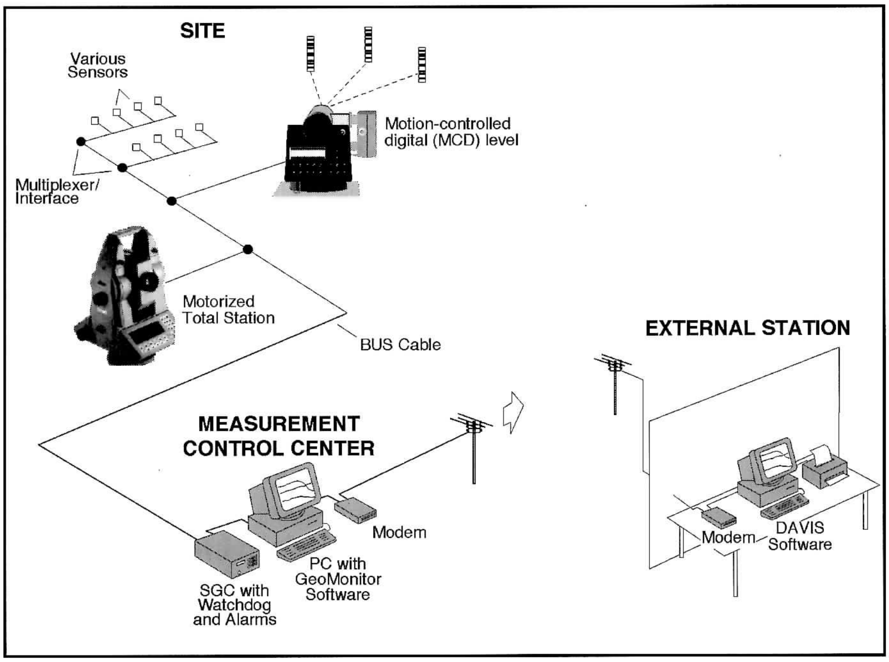

Fig. 1: GeoMonitor automatic monitoring and data acquisition system

Motion-controlled Digital (MCD) Levels

The continuous observation of vertical movement is crucial during projects such as tunnel construction in urban areas, grouting beneath foundations and safety monitoring of existing buildings adjacent to excavation work to detect settlement and heave at the earliest possible moment. A single Motion-Controlled Digital (MCD) level can automatically monitor a large area for settlement and heave, around the clock, with a minimum of installation effort.

Solexperts has developed software controlled motion-control units for several types of optical digital levels. Via software commands, the unit rotates the instrument and focuses the optics on measurement staffs. The motion-control units allow digital levels to be integrated as intelligent sensors into the data acquisition system.

Bar-code staffs, typically 0.5m long, are used as measuring points. The optical measuring principle enables measurement of staffs at distances from 2 to 100 m. For measurement at night, a spotlight mounted on the level illuminates staffs up to 40 m away (for greater distances, special illumination is required).

The accuracy achieved with digital levels depends primarily on the setup of the measurement system, e.g., distances between instrument and measurement points and stability of the reference points. Based on our experiences from various projects where distances between measurement points and the instrument are over 40 m, measurements are accurate to within 0.3 to 0.5 mm.

The MCD level itself is often placed in an area where vertical movement is expected. In such a situation, readings are made to a stationary reference point and movement of the level is compensated for in the real-time settlement calculations. In some projects, several MCD levels have been installed in a 'chain' to monitor large areas or structures, using on-line calculations to determine and display real-time settlement data for the entire system.

Monitoring Tunneling Activity Under a Railway Embankment with MCD Levels

The Bern-Zurich line is one of the main connections in the Swiss railway system. Along this line, in the region of Lenzburg, an overflow canal is being constructed to reroute overflow from a small river during periods of high water. A section of this canal had to be tunneled through an embankment, across which this railway line passes.

A tunnel with a diameter of approximately 3m was driven through the embankment by pipejacking under the protection of an injected shield. Solexperts was contracted to install a monitoring system which would continually monitor the stability of the embankment and the train rails throughout the tunneling phase, and which would automatically trigger alarms if critical settlements occurred.

The combination of the MCD level with the data acquisition and monitoring system was ideal for this project. From April to November 1997, a single MCD Zeiss DiNi10 level monitored 32 bar-code measurement staffs hourly (every 30 minutes during critical stages).

Most of the 50 cm-long staffs were attached to the train rails, using supports that did not interfere with train traffic (see fig. 2). Other staffs were mounted on light poles and railings along the body of the embankment. As a reference point, one measuring staff was mounted approximately 30 m from the axis of the tunnel, where it would not be affected by the tunneling activity. The MCD level was fixed to a wall on the crown of the embankment directly above the tunnel axis, enabling measurements at the greatest distances on both sides of the tunnel axis. Although the largest settlements were expected at this location, any movement of the level was compensated for, on line, in the absolute settlement calculations. Fig. 3 presents a layout of the site.

The MCD level and 32 bar-code staffs were installed before the onset of tunneling in order to establish the "normal" behavior of the embankment. During two weeks of pre-tunneling observation, only slight settlements were detected as a result of drilling boreholes for inclinometer casing.

During the second monitoring phase, the soil directly over the projected tunnel was stabilized with injections of a cement/bentonite mixture. Settlement of up to 12 mm was observed due to drilling of the first series of boreholes for grouting. Based on these measurements, the drilling method of the subsequent boreholes was adjusted. Instead of drilling all the boreholes from one side of the embankment, the boreholes were then drilled from both sides of the embankment in order to reduce uneven settlement and tipping of the railway tracks.

Unexpectedly large settlements of the embankment were recorded as soon as pipe jacking for the tunnel started. Jacking had to be halted several times because settlement and difference in settlements had reached or passed acceptable limits. During some of these interruptions, e.g. on the weekend of July 12th and 13th 1997, the train rails had to be elevated to correct for the large amount of settlement.

Within about 10 days after pipejacking was completed, virtually no further settlement was detected. At the end of 4 weeks, settlement reached a maximum of 68mm directly above the tunnel.

Fig. 2: Bar-code measuring staffs attached -to the train rails along the Lenzburg embankment dam

These on-line measurements with the MCD level and real-time calculations allowed the differential settlementof the embankment to be monitored around the clock. A graph of settlement with respect to position of measuring point is presented in fig. 4. In combination with the DAVIS Software, the system provided those responsible for the safety of the project with a continual overview of the measurement data, accessible by modem from the office.

Motorized Total Station

The advantages of the Total Station over the digital level are the ability to measure displacement in three dimensions and the ability to measure targets at greater distances, i.e. 1000 m or more. (However, Total Stations measure vertical displacement with slightly less accuracy than digital levels.) Total Stations have proven ideal for the monitoring of slope stability, among other applications.

Integration of the Total Station into the GeoMonitor System enables automatic control of the instrument, around-the-clock measurements and data acquisition, alarm triggering options, on-line calculation and plotting of displacement in relation to fixed reference points. As with the digital level, monitoring a site with a Total Station requires minimal installation, since no cables are needed to connect the measurement points to the instrument.

Displacement of the Total Stations themselves is detected and measurements are compensated on-line. At the same time, atmospheric temperature and pressure are measured to allow on-line correction of the distance measurements. With this system, point-specific displacement of less than 1 mm can be detected even when difficult conditions exist (large temperature fluctuations, strong winds, etc.) as in the Slovakian project described below. The system provides measurement results (coordinates and displacement vectors) for evaluation and interpretation immediately after each measurement is taken.

Accuracy achieved by Total stations depends on a variety of different factors, including:

- distances and angles between points to be measured and the instrument
- measurement mode, measurement and analysis procedures
- type of measurement target (prism)
- stability of reference points

Applying the instruments to measure structural deformation, we have achieved displacement measurement accuracy of 0.5 to 2 mm.

Automated Monitoring of a Lock Facility with Motorized Total Stations

The double-lock system Gabcikovo in Slovakia, shown in fig. 6, is one of the largest in Europe. Each lock chamber has a length of 275 m, a width of 34 m and a maximum difference between upstream and downstream water levels of 23 meters.

Solexperts and the Slovakian daughter company, Geoexperts, were concontracted by the operators of the lock system to develop a measurement program for geotechnical monitoring and instrumentation for the lock chambers and the surrounding foundation soil. The objective of instrumentation and monitoring is to detect deformation and displacement in the concrete structure (blocks and lock gates) during operation of the locks, and to determine the relationship between deformation and water levels within the lock and in the surrounding soil. An additional objective of monitoring activities is to ensure the safety of the entire dam and lock facility.

The data acquisition and monitoring software was installed on the control center computer for controlling the 2 Total Stations, for the continuous acquisition of measurement data from all sensors, and for on-line calculation and analysis. Approximately 80 measuring points for the two motorized Leica TCA 1800 Total Stations were mounted on measuring pillars located on the lock walls and gates. These measuring points consist of passive reflectors (miniprisms) which are monitored continuously and automatically for position (X and Y) and level (Z).

Using readings from 4 reference points, position and level changes of the two Total Stations are detected and automatically compensated. At the same time, atmospheric temperature and pressure are measured to correct the distance measurements on-line. The measurement results (coordinates and displacement vectors) are available for

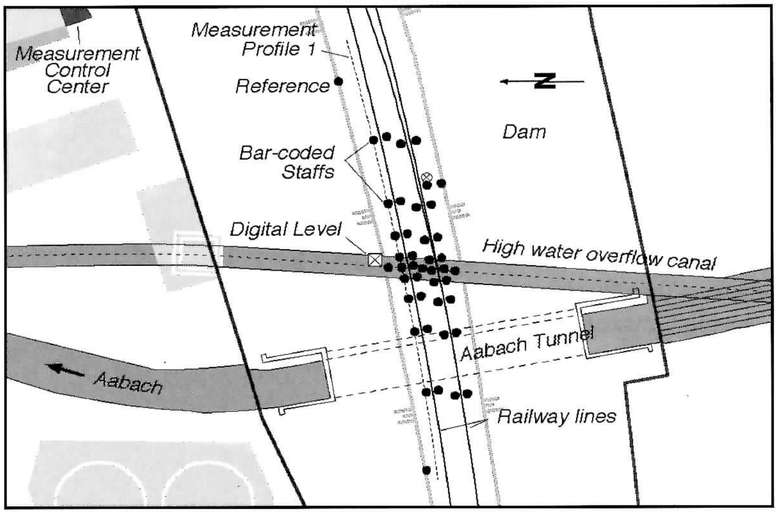

Fig. 3: Layout of the measuring points and the motion controlled optical digital level

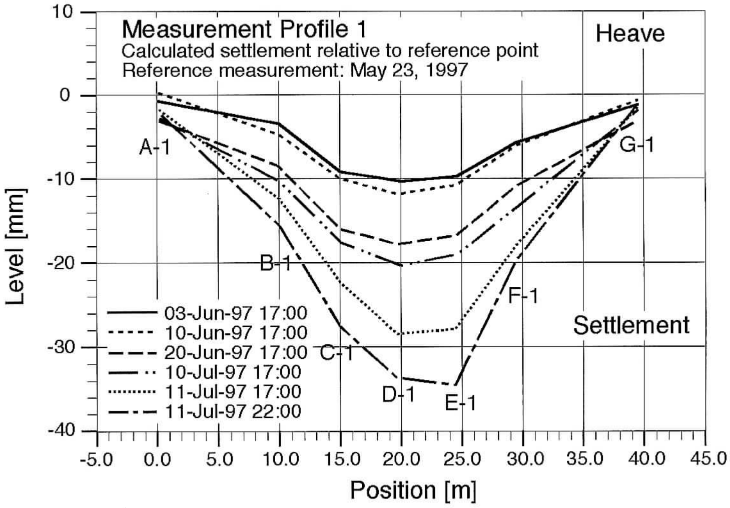

Fig. 4: Calculated settlement relative to a reference point; settlement increased on July 10 and 11 during the first phase of driving the tunnel

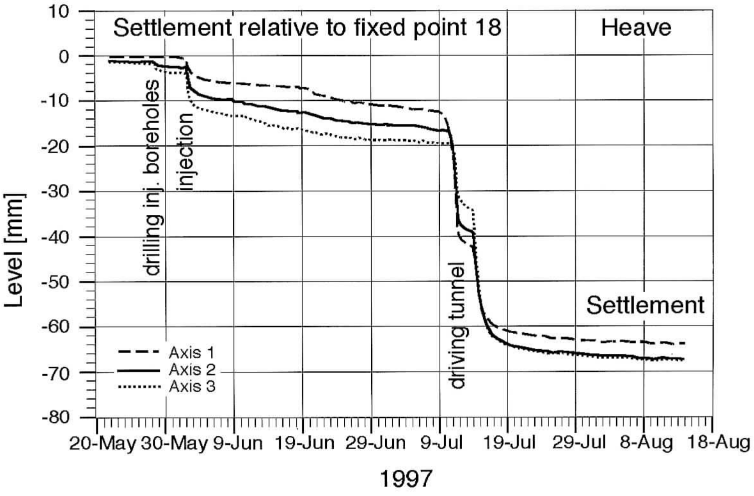

Fig. 5: Settlement corresponding to the individual stages of construction (DAVIS graphic

Fig. 6: The Gabcikovo lock system

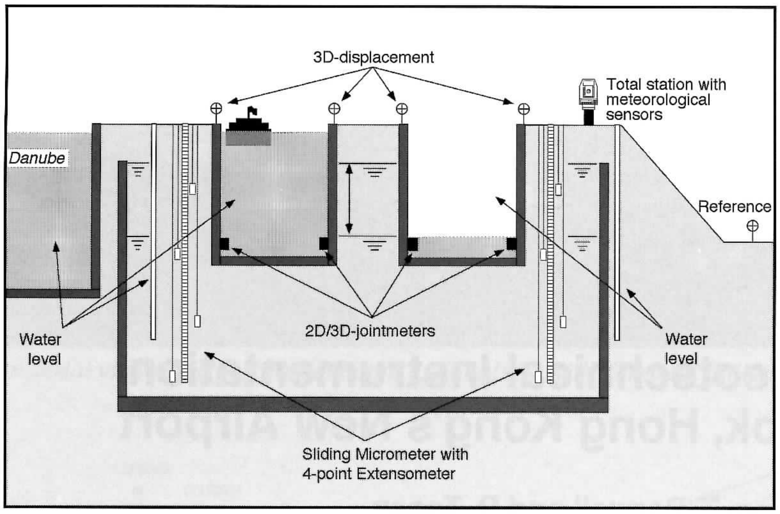

Fig. 7: Schematic cross-section of the locks showing instrumentation

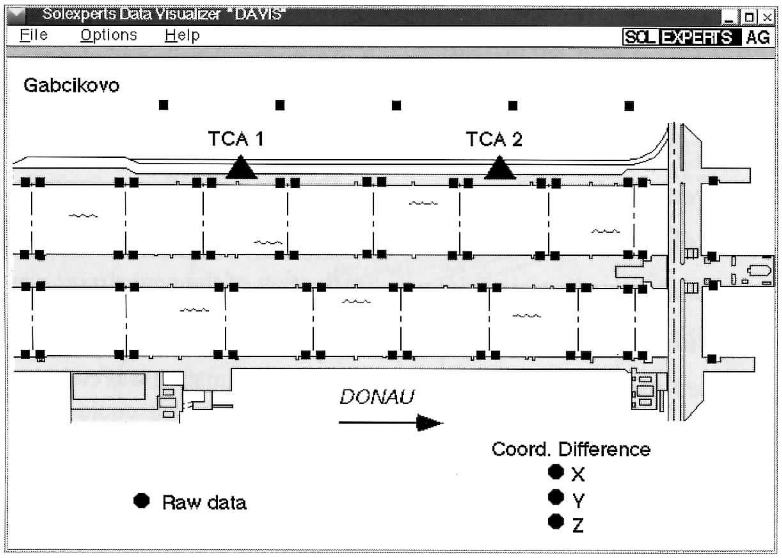

Fig. 8: Site-specific DAVIS window showing sensor types and locations

evaluation and interpretation immediately after each measurement is taken.

Additional instruments were installed at the site, as illustrated in fig. 7, for geotechnical and hydrogeological monitoring and for ensuring the safety of the facility. These instruments, which include piezometers, pressure transducers, 2-D and 3-D jointmeters and extensometers, were also integrated into the system for data acquisition.

The project-specific Data Visualization (DAVIS) Software is installed at the site, and at two external offices which connect to the measurement control center via modem. This software assists with overseeing the monitoring of 434 active sensor channels (actual measurements from sensors and instruments) and 388 calculated channels, and for organizing, displaying and plotting the large amounts of data. An example of one of the windows is shown in fig. 8. With a mouse click, data from one or several sensors are presented in list format, as graphs, or as displacement profiles with vectors of position changes of the measurement points.

Monitoring the instruments and sensors automatically in combination with linewise deformation measurements (Sliding Micrometer) has proven to be a very efficient system for geotechnical observation, obtaining data and ensuring safety at the Gabcikovo Lock facility. The large number of measurements within a short period of time, as well as on-line calculations and compensation, enable detection of previously unavailable correlations. For example, the movement of the lock wall during filling and emptying (each taking about 15 minutes) correlated strongly with the change in water level within the lock and in the surrounding soil.

Lessons Learned

- It became clear during the projects described above that systems must be installed early enough to allow changes in the setup. It is not always possible to predict conditions that will affect readings from the instruments; often only after a series of measurements over several days or weeks do they become known. Compensating for external influences may require further instrumentation and an extended period of time for testing.

- Experience showed that temperature changes within a structure are delayed compared to surface and air temperatures, a fact that becomes especially important when forces are to be calculated based on strain measurements and when measurements are to be temperature compensated.
- High-precision settlement measurements (e.g. of a building near a deep excavation) often should coincide with groundwater level and/or pore-water pressure measurements within the same monitoring system. This enables the effects from construction to be distinguished from the effects of changing groundwater level.
- The quality of geodetic measurements (not only automated measurements) depends strongly on the stability of the selected reference points. Surveying these points before automatic monitoring starts helps to optimize the layout.
- Through these projects several improvements were made in the software, especially with alarm features. It is now easier to eliminate false alarms by disregarding erroneous readings and by setting 'soft' and 'hard' alarm limits.
- Finally, as most geotechnical engineers already know, Murphy's Law plays a part in any project. Therefore, extra time, testing and care are called for.

Summary

Compared with other systems used for measuring displacement, geodetic instruments have the advantages of minimal installation requirements, few cables and a high level of accuracy. Automating the measurements and data acquisition from geodetic instruments, within a system that continuously monitors hundreds of other geotechnical instruments and sensors, makes it possible to monitor large and complex sites for numerous geotechnical parameters with maximum safety and a minimum of personnel and costs.

To automate optical digital level measurements, it was necessary to develop motion-control and focusing motors, and then to integrate the instrument into a data acquisition system. A subsequent development was the integration of motorized Total Stations into the same system. The on-line calculations and compensations of measurements from these instruments make real-time displacement information available for immediate evaluation and decision making, in an easy-to-use graphic format.

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Overview of Geotechnical Instrumentation at Chek Lap Kok, Hong Kong's New Airport

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INTRODUCTION

Construction of the reclamation for Hong Kong's new airport at Chek Lap Kok was essentially complete in July 1995. The platform on which the airport has been constructed has a total area of 1248 ha of which 938 ha is newly reclaimed land and the remainder comprises the former islands of Chek Lap Kok and Lam Chau, see Figure 1. The reclamation is underlain by between 10 and 30 m of alluvial sands and clays. The material used in the reclamation (up to 30 metres thick) comprises rockfill obtained from the excavation of Chek Lap Kok, Lam Chau and the adjacent Brothers Islands and also marine sand from borrow areas located within Hong Kong waters.

Settlement of the reclamation will occur as a result of primary consolidation and secondary compression of the alluvial clay below the site and also creep compression of the recently placed fill materials. Reclaimed land in Hong Kong is usually left dormant for a few years to allow for a significant proportion of the consolidation and creep to occur prior to follow on construction. However, construction of the new airport was a fast-track project and construction of the airport facilities commenced shortly after the reclamation was completed. Significant settlement could therefore be expected both during construction of these facilities and throughout the operational life of the airport.

The prediction of settlement has received a high priority on the project. As

Oblique aerial view of Airport Reclamation as July 1997 with Terminal Building in the foreground.

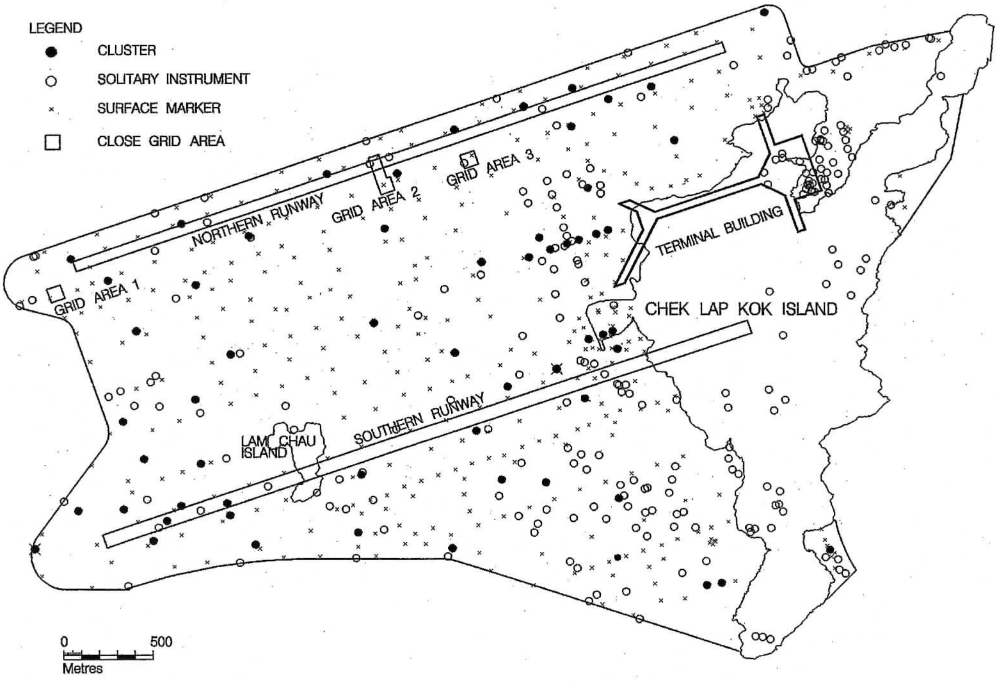

Figure 1. Instrumentation Summary Plan.

part of the overall strategy for assessing settlement, an extensive range of surface and sub-surface geotechnical instruments have been installed and monitored throughout the construction project.

This article presents an overview of instrument types used on the project. The day-to-day monitoring regimes are described including a description of calibration procedures. Finally a description is given of the instrumentation database which has been developed to both store and process the large quantity of data that has been collected during the project. Details of the reclamation design, construction and performace are set out in Plant et al. (1998).

INSTRUMENTATION WORKS

Instrumentation works were carried out under a series of major civil works contracts with instruments being installed predominantly under sub-contracts rather than under direct contract to the Airport Authority (the Authority). As is common practice in Hong Kong instrumentation installation for the majority of the works, was conducted by a specialist instrumentation contractor subcontracted by the main contractor.

The Authority's role included design of the instrumentation systems, preparation of works specifications, a review of all installation method statements and regular audits of installation activities. The installation of geotechnical instrumentation was carried out under a quality assurance scheme where quality control activities and hold points were defined and agreed for critical stages of the installation procedure.

The instrumentation was installed to monitor settlement of the reclamation during construction and during the operation of the airport reclamation. Data obtained from the instruments was used to predict long term total settlement, differential settlement, identify areas where estimates of settlement exceed design criteria thereby substantiating ground treatment works, measure the effect of ground treatment (primarily surcharge), estimate construction levels, evaluate operational issues and predict maintenance requirements (e.g. resurfacing of runway pavements).

Instruments were generally installed in clusters across the platform with isolated instruments such as inclinometers/extensometers located along the sea-wall. A cluster normally consisted of 4 piezometers set out within approximately 15 metre spacing around a central inclinometer/extensometer. The piezometers comprise a combination of vibrating wire and pneumatic piezometers installed in the alluvial clay layers and standpipe piezometers with Casagrande tips installed in the fill and basal sand and gravel layer. Field measurements from clustered instruments were better suited for the calibration of analytical settlement models as consolidation of specific layers could be related to excess pore water pressure measurements in both the consolidating clay layers and the interbedded drainage layers. Sub-surface instrument clusters were installed at approximately 60 locations across the platform as shown in Figure 1. A summary of the instruments installed to date is set out in Table 1.

Table 1. Summary of geotechnical instrumentation installed

Extensometers/Inclinometers	
Induction type extensometers	97
Magnetic extensometers	33
Rod extensometers	11
Piezometers	
Vibrating wire	177
Pneumatic	44
Push-in piezometers (vibrating wire)	19
Heavy duty (vibrating wire)	8
Open standpipe or observation well	137
Surface Markers	
Surveyed by contractor	1521
Surveyed by Airport Authority	2311

INSTRUMENTATION EQUIPMENT

Extensometers

Three different types of extensometers have been installed at different stages during the reclamation and airport construction.

- **Inductive -** During construction of the reclamation the extensometers were of the Sondex® inductive type. In this system a flexible corrugated sleeve, to which steel target rings are attached, is placed over a rigid inner core of 70mm diameter inclinometer casing. This system was installed immediately behind the reclamation face and was selected for its ability to accommodate and measure significant vertical strains and also the lateral spreading movement of the expanding reclamation.
- **Magnetic -** Following completion of the reclamation a limited number of magnetic extensometers were installed. These have up to 10 annular spider magnets threaded over 70mm diameter rigid inclinometer casing. These were located at positions where long term monitoring of the reclamation settlement would be possible. A number of these extensometers have now been modified to allow readings to be recorded automatically.
- **Rod -** As part of the southern runway construction contract the contractor had to install automated extensometers for future long-term monitoring of the airfield areas. The contractor selected an automated rod extensometer system for this purpose.

Inclinometers

The inclinometers access tubes were an integral part of the inductive and magnetic extensometer systems. The access tube consists of 70mm diameter flush coupled PVC pipes with 4 guide grooves on the inside wall to guide the inclinometer probe for lateral displacement monitoring.

With the exception of the instruments located adjacent to the seawall the inclinometer function was subordinate to the extensometer measurement capability. Most instruments were therefore located in areas of special interest with regard to settlement.

Piezometers

Various types of piezometers were installed in the reclamation, usually clustered in association with the inclinometer/extensometers. These installations varied according to construction constraints and the ground conditions at each cluster location. The types of piezometer used were;

- **Pneumatic** - Installed at locations where short-term monitoring was anticipated and the piezometer would be destroyed due to future excavation and construction work carried out by follow on contracts.
- **Vibrating Wire** - Installed at locations where long-term monitoring was required, future works would not interfere and the piezometers could be automated in the longer term.
- **Standpipe or Observation Well** - These instruments were initially used to determine water levels in the reclamation fill. Their application was later extended to determine excess pore water pressure in the alluvial sand and gravel horizons below the reclamation.
- **Push-in** - Vibrating wire "drive point" piezometers were installed near other piezometers in clusters around the magnetic extensometers as previously described. They were introduced to complement or verify the readings of other piezometers in soft-to-firm consolidating clays.

Surface markers

Surface markers across the platform consist of galvanised steel rods embedded in concrete. The rods extend about 100mm above ground level. In general surface markers were installed on a 200m by 200m grid across the reclamation. Close grid monitoring with markers at 10m centres on a 90 by 90m grid were established at three locations to monitor differential settlement at the reclamation surface.

INSTALLATION

Subsurface instruments

The planned levels at which to install piezometers and settlement targets on the extensometers were revised according to the soil profile determined during the drilling of the boreholes. The first borehole at each cluster location was for the extensometer as this was required to be drilled and logged through to the underlying bedrock. The target depths could then be determined from the preliminary log while the installation crew prepared the extensometer. During the installation of the extensometer the design team could work out the optimum levels for the piezometers clustered around the extensometer. Good teamwork and cooperation between designer and contractor was essential as up to 7 drilling rigs were working at the same time.

Instruments were initially installed on the reclamation at an intermediate level, usually about +4mPD, to obtain early data on the behaviour of the reclamation. These instruments later had to be extended as the reclamation was raised to the final level of approximately +6.5mPD. To maintain continuity of readings, additions to the inclinometer casing had to be in 0.5m increments to

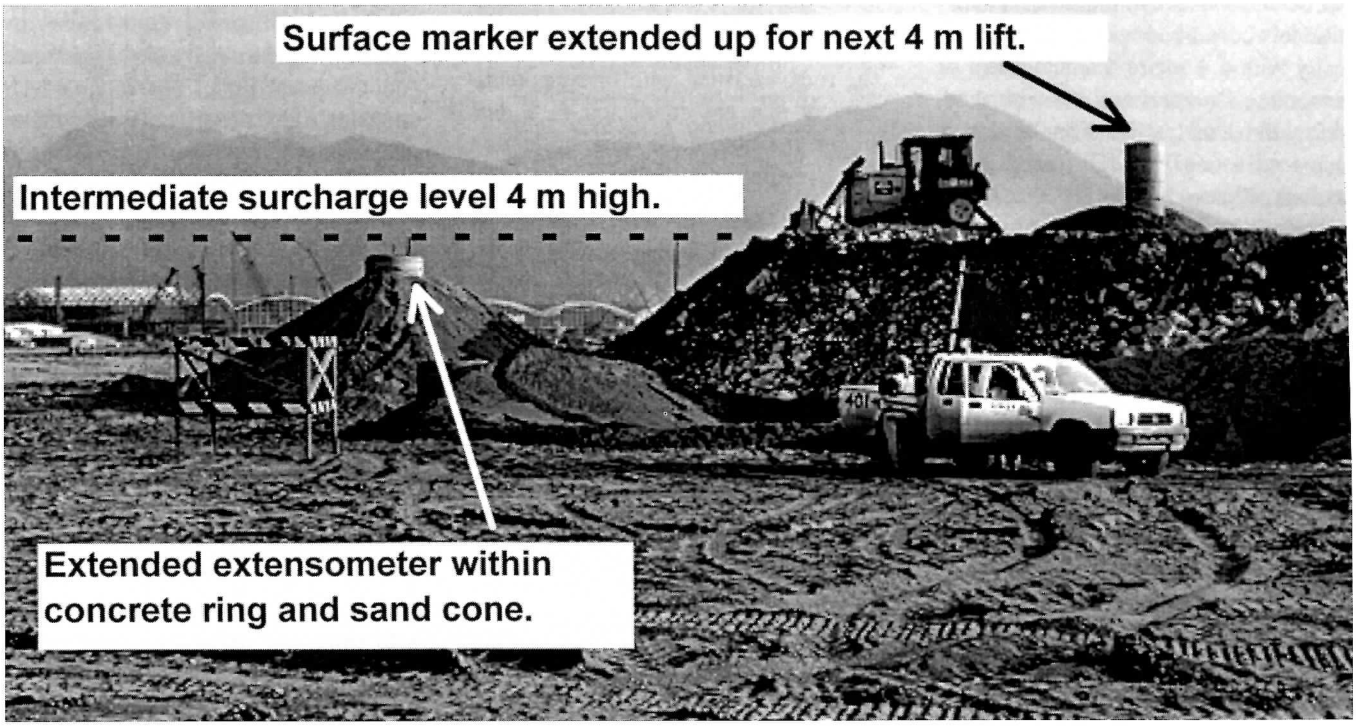

Figure 2. Surface marker and extensometer extension up through surcharge.

coincide with the wheel spacing of the inclinometer probe. To avoid adding electric cable or pneumatic tubing to the downhole piezometers the instrumentation specialist sub-contractor installed the instruments with cable or tubing long enough to reach the formation level. It was relatively simple to add PVC tubing to extend the Casagrande piezometers. Steel and wood barriers originally used to protect the instruments were later replaced with one metre diameter steel or concrete rings, backfilled with sand. This method of protection was particularly useful where instruments were temporarily covered with fill.

Surface markers

Although a relatively simple procedure the extension of surface markers rods required strict control to ensure continuity and reliable data. A system using 3 galvanised steel rods known as 'A', 'B' and 'C' were introduced to allow vertical extension of surface settlement at any point where ground levels were raised. The 'A' and the 'B' rods were installed at an intermediate level directly after reclamation with the top of the rod 'A' about 100mm above intermediate ground level and rod 'B' installed usually in 2 metre lengths which would be extended to the final reclamation level. This rod was protected typically with a 1 metre diameter steel or concrete ring that was filled with sand. After the final reclamation level was achieved a third rod 'C' was then installed adjacent to the 'B' rod. Thus monitoring of the settlement at the initial intermediate level could continue on the 'B' rod while settlement at the new formation level was maintained on the 'C' rod. Obviously it was critical to know the extensions added to each of the 'B' rods. Good communication was required between all parties to ensure that any adjustments were accurately recorded.

Instrument extension

Ground improvement, by means of surcharging with temporary stockpiles of fill materials, was used on areas of the site which would be sensitive to long term settlement. During surcharging operations instruments were extended upwards with placement of the surcharge and then lowered again when the surcharge was removed (Figure 2). As with the original extensions the most important part of the operations was to know exactly the lengths of rods and tubing extended and subsequently cut and to ensure that the corrected lengths were accurately entered into the database.

READOUT UNITS

Due to the size of the site and the quantities of instruments installed, three sets of readout units were purchased for each system.

Inductive probe extensometers

These were initially monitored with a probe attached to a readout cable with 1 metre graduations. The cable was read against a reference head that had a metre steel rule attached to it, thereby giving millimeter reading resolution but only centimetre accuracy. This was later upgraded to a conducting ribbon tape readout with 1 mm graduations which improved the ease and accuracy of monitoring and the repeatability of readings to better than 2mm.

Magnetic extensometer

These readouts are tape type readouts with 1 mm increments.

Rod extensometer

The rods are fitted with linear potentiometers that are connected to a data logger for automatic data collection with a resolution of 0.01mm.

Inclinometer monitoring

Monitoring has been carried out using a system consisting of a biaxial inclinometer probe, 150 metre maximum depth control cable and data logger readout system that enables the operator to perform data checks immediately on site.

Vibrating wire piezometer

A data logger readout which enables the operator to view and store readings directly on site is used to take measurements.

Pneumatic piezometer

The readouts have a digital display with the option of viewing results in psi or kPa units. The recording is manual.

Open standpipe and observation well

An ordinary dipmeter is used to measure the depth to the water level.

Dataloggers

In addition to the above, dataloggers have been used with the vibrating wire piezometers where a relatively high frequency of data readings has been required. Examples of the use of the datalogging include pumping tests, falling head permeability tests, dewatering works, monitoring tidal influence and relating ground water level to rainfall. The loggers used for this purpose are:

- one 10 channel
- one 3 channel
- four single channel

INSTRUMENT CALIBRATION AND SITE FUNCTION CHECKING

Inclinometers and Extensometers

Inclinometer sensor calibration was carried out in accordance with the manufacturer's recommendations. This required that some of the readout equipment be returned to the manufacturer annually. To perform function checks on the inclinometer and extensometer monitoring equipment the Authority constructed a checking frame and a control hole. The inclinometer checking frame consists of three 1 metre lengths of inclinometer tube set at approximately vertical,-10 degrees and +10 degrees from vertical, cast into a concrete block 1.5m (long) 1.2m (high) and 0.5m (wide).

The control hole was drilled on the existing island through predominately rock material to a depth of 47 metres. An inclinometer / extensometer tube with 40 steel target rings fixed at 1 metre intervals and magnetic datum targets fixed at 5 metre intervals was installed in the borehole and the borehole backfilled with cement grout.

The control hole was required as, with time, the inductive probe extensometer readouts began to give erratic results. Eventually as a result of breakdowns there was a requirement to interchange units between installations and in doing so large variations in monitored data were also noted. Close examination of the cable and measurement between the 1 metre cable markers with a steel rule showed errors of up to 40 mm between individual markers in some cases. As the Authority had already used these probes extensively throughout the site there was a need to devise a way of calibrating each readout and producing a calibration factor for each cable marker. The depth and separation of each ring was determined by monitoring the control hole with three individual tape type readouts. After establishing the depth and separation of each target ring the cable type readouts were checked against the true depth and differences between these readings were taken as the calibration factor.

The control hole also served as an excellent training tool for newly recruited technicians who were unfamiliar with the monitoring equipment and procedures.

Piezometers

In addition to full calibrations of the piezometers a final function check was carried out on the pneumatic, vibrating wire and push-in piezometers prior to installation. This was carried out during installation by filling the installation borehole casing with water and taking measurements at 5 metre intervals as the piezometer was lowered to its installation depth. The push-in piezometers required continuous monitoring throughout the driving process to ensure that the pressure applied to the diaphragm did not exceed 100% of the piezometers full working range of the pressure transducers.

MONITORING

Construction Phase

During construction of the reclamation three teams of two technicians carried out monitoring. One team monitored piezometers, the second extensometers and the third inclinometers. During construction of follow on facilities only two teams of technicians were required. Following opening in July 1998 this has been reduced to one team who are responsible for monitoring the long term performance of the reclamation.

The platform was divided into two sections, north and south, for day to day instrument monitoring. This allowed a set of equipment to be dedicated to each section of the site and for the third set to be kept as a backup and for use during installation checks. This also simplified the storage of base data for on-site checking without exhausting the memory capacity of the loggers.

- **Extensometers -** Initially the extensometer data was hand written on data sheets. This procedure was time consuming and introduced transcription errors when keyed into the database files. To improve efficiency, palm top computers with spreadsheet software were purchased to which the data could be downloaded directly on site. The palm top computers also allowed the technicians to compare newly saved data with previous data while still at the instrument. Generally the extensometers were monitored monthly, however the frequency was varied and in some cases extensometers were monitored daily at critical locations, for example during surcharging.
- **Inclinometers -** Inclinometer data was recorded directly into a data logger and downloaded to the database on the same day. Monitoring schedules were set at monthly intervals for a period of six months after installation and later extended to every three to six months depending on movement monitored and location on the site.
- **Piezometers -**The piezometers were monitored on a weekly basis. The vibrating wire piezometers were read into portable data loggers which was then downloaded to the geotechnical data base. Data loggers were connected to individual piezometers for periods when there was a requirement for increased frequency of monitoring. The pneumatic piezometer readings were hand written to a data sheet and then later keyed into the database. The standpipe and Casagrande piezometer data were dipped weekly. Vibrating wire piezometers connected to a data logger were lowered down the access tube when there was a requirement for increased monitoring frequency.

Long-term monitoring

In order to accommodate restricted access to instruments, after airport opening, automation of instrument clusters has been carried out. This has ensured that regular measurements of instruments are conducted with additional benefits facilitating smoothing of results to reduce tidal affects. Automation required civil works to centralise the instruments and house the datalogging devices in addition to the installation of rod extensometers and conversion of Casagrande piezometers. A significant cost saving was realised by automating existing magnetic extensometers. Two data logging devices were used according to the type of automated extensometer. In addition to logging compression, the datalogger also records excess pore water pressure readings for up to 8 vibrating wire piezometers at each cluster. The two systems used to automate the measurement of compression of set layers are:

- **Rod extensometers -** Automated using a Multi Point Borehole Extensometer (MPBX) head. The MPBX consists of 6 linear potentiometers that measure individual rod displacement.
- **Magnetic extensometers -** Automated using an Automated Magnetic Extensometer Controller unit (AMEC). This unit consists of a system module that instructs a transport assembly to raise and lower 8 reed switch probes that detect and record the change in level of magnetic targets.

QUALITY PROCEDURES AND TRAINING

At the start of the project the Authority produced a geotechnical instrumentation manual that covered the operation, interpretation and day-to-day maintenance of the instruments used on site. A set of quality and standards procedures were produced for each instrument type. These procedures included the preparation of monitoring equipment, monitoring and downloading procedure, battery recharging, cleaning and general maintenance of the instruments. New technicians were required to have a full understanding of the procedures and generally worked with a senior technician for the first month on site.

The instrumentation engineers arranged a series of training lectures for the technicians that dealt with the operating principles of individual instruments, reporting, and interpretation and analysis of instrumentation data.

THE AUTHORITY'S INSTRUMENTATION DATABASE

Introduction

The processing and dissemination of instrumentation results has been a priority function of the geotechnical section of the Authority. Up to date results were necessary for in-house reviews of the platform performance, ground improvement works and for consultants and works contractors for both design and control of construction.

The Authority's instrumentation database has evolved from simple independent spreadsheets for each instrument to a system whereby the raw field data is maintained on a central database from where it is processed, analysed and reported by a suite of programs dedicated to each instrument type. Macro driven workbooks were developed for this purpose using spreadsheet software.

Database development

Spreadsheets were originally adopted as the most suitable format to store the instrumentation results. Data loggers and hand held loggers used to capture the data in the field supported this file format and staff were familiar with the software. Processing of the results and generation of graphs were originally accomplished by individual spreadsheets replicated for each instrument. Updating and reformatting of the charts and tables was required as new field results were added. This arrangement was initially easy to manage as the instruments were few in number and the circulation of results was restricted to a small group. As further instruments were installed and the requirement to provide the results to a growing number of consultants arose, a much less labour intensive system was required which would avoid duplication of analytical processes and provide:

- standardised report quality output
- multiple access to results in an updated format
- additional plots
- bulk processing facilities
- quality assurance check facilities.

This resulted in a dedicated multiple linked spreadsheet system being developed to process the data for each instrument type. This arrangement is referred to as a workbook.

Workbook database setup

The basic principle of the workbook is that field data is temporarily copied from the original field data files onto a suitably formatted worksheet. Linked sheets then reference and process this data to generate standardised results as both and updated charts and tables. A graphic representation of a workbook layout is provided in Figure 3.

Automation of the workbooks is achieved by a series of macros which are activated from tailor made pull down menus. The workbooks are therefore accessible to engineers with limited computer experience.

Workbook database programs

Four primary workbooks have been produced to process the field data for the (I) Casagrande, (ii) vibrating wire and pneumatic piezometers, (iii) magnetic and (iv) inductive extensometer and the automated rod extensometers. A number of additional or secondary workbooks have also been developed which are used in conjunction with the primary workbooks. The secondary workbooks are divided into two groups that either provide information to the primary workbooks or source information from primary workbooks in order to carry out additional interpretative analysis. Secondary workbooks have been setup for two reasons. Firstly as a base processor to link and combine data

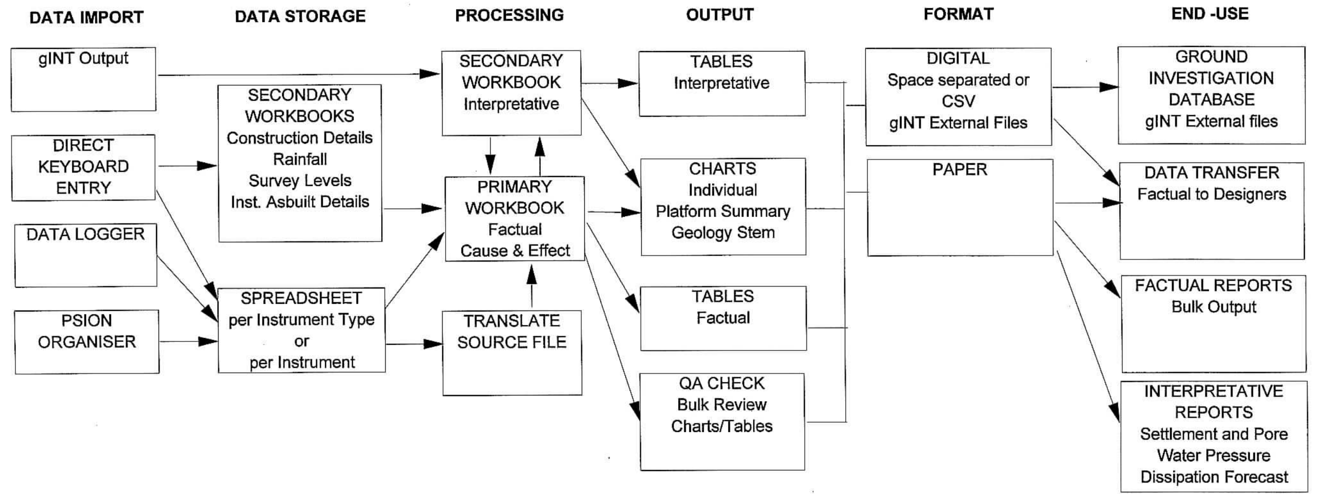

Figure 3. Schematic view of the workbook instrumentation database system.

from more than one of the instrument types. Secondly to provide special features which, if included in the primary workbook, would slow down more commonly used operations.

The workbooks have been further developed to include facilities for bulk reviews of the field data, batch processing and generation of factual tables and charts. Examples of workbook output are given in Figures 4, 5 and 6.

In order to integrate survey measurements with as-built records, where instruments were being extended or trimmed (up to eight times), workbooks were developed and presented to contractors. These workbooks fulfilled the database function for instrumentation as-built data and surface marker survey records and were pre-programmed with routines to update records, print as-built records and transfer data in a digital format. Up to date reviews of continuous settlement trends for the surcharged areas are therefore achieved as a result of the compatibility of the workbooks used by the contractor and workbooks used by the Authority to interpret the results.

INSTRUMENTATION DATABASE/ GROUND INVESTIGATION DATABASE

The instrumentation database is not a stand alone system. It has been developed to ensure compatibility with the Ground Investigation Database, gINT, a commercially available geotechnical database software program. External files are, for example, automatically generated in an appropriate format to be read by the gINT program while templates have been developed in gINT to provide information to the workbooks to facilitate borehole stem plots adjacent to instrumentation results, Figure 6.

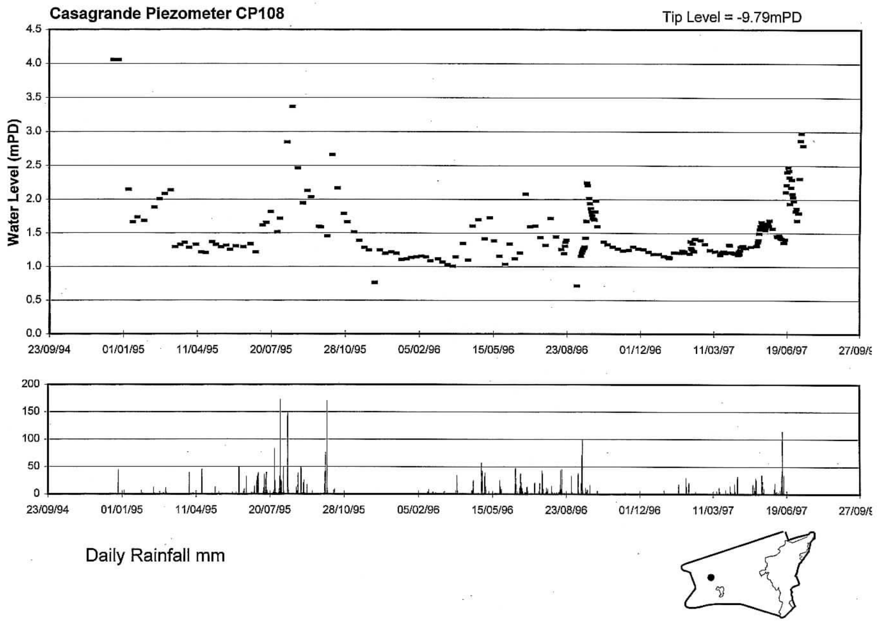

Figure 4. Casagrande piezometer workbook output.

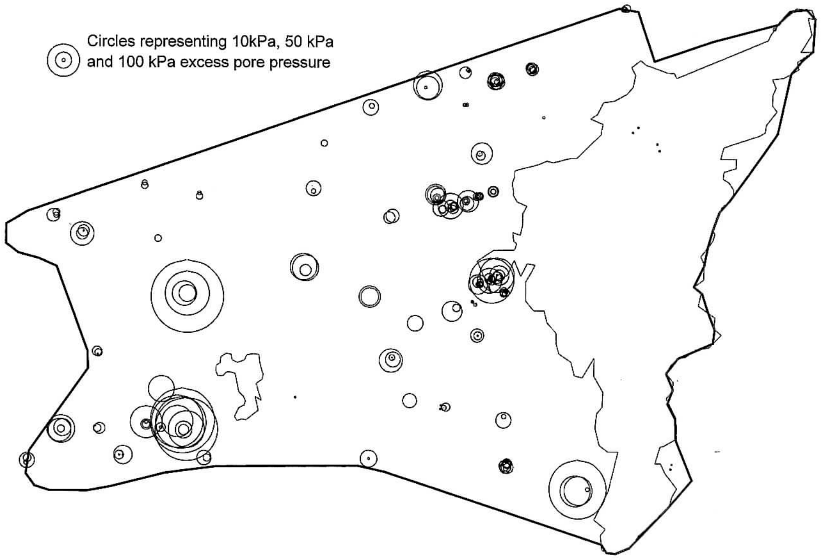

Figure 5. Piezometer workbook output summarising piezometer results for weeks monitoring.

CONCLUSIONS

The following points summarise the more important lessons learnt and the conclusions drawn from the experience gained on the airport project.

- The selection of instruments installed on the airport reclamation was based on their proven performance on other projects. In general this policy has resulted in reliable data being obtained throughout the project despite the difficulties associated with the environment on a fast track construction site. A good deal of effort was required to protect the instruments during construction. About 15% of the instruments have been accidentally destroyed, an unusually good result for such a rapidly developing multi-contract project.
- A significant number of the instruments have been extended up through stockpiles of rockfill and subsequently cut down when the stockpile was removed. In one area extensometers installed from a ground level of +6mPD and anchored in rock at a level of -40mPD were first extended through rockfill to a level of +13mPD and subsequently cut down to a level of -3mPD in an excavation for a cut and cover tunnel. It was possible to obtain high quality data throughout this whole process. The success can largely be attributed to the cooperation between the civil contractors and the instrumentation team.

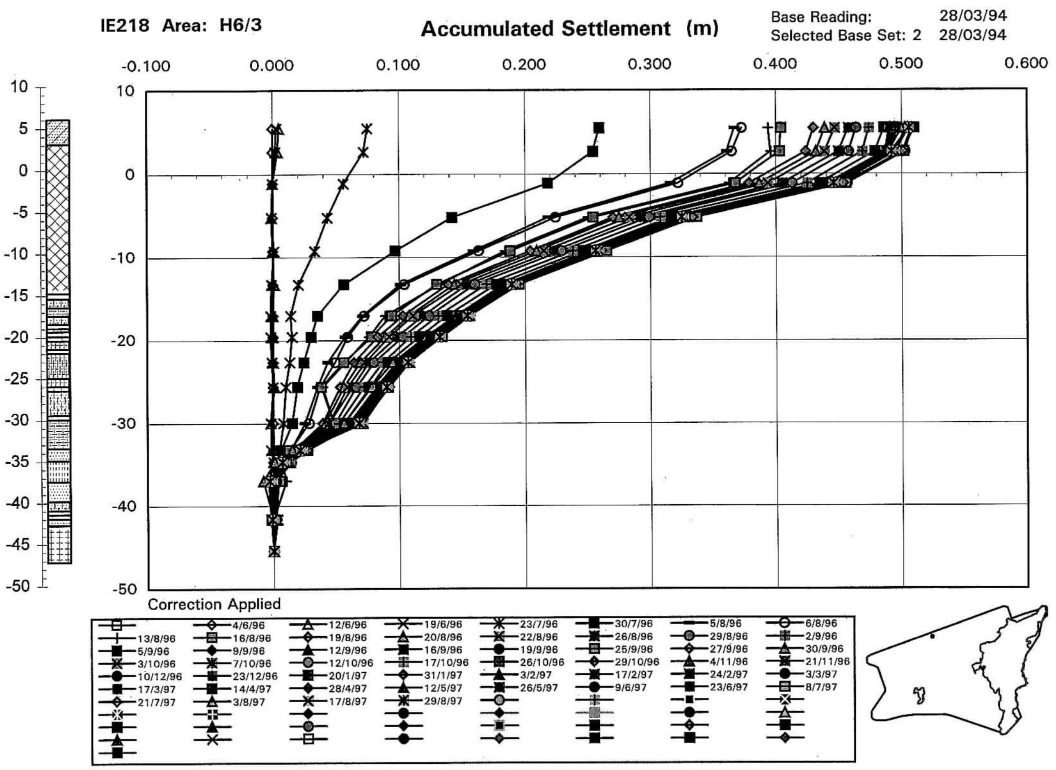

Figure 6. Extensometer workbook output including geological log.

- A well-defined system for maintaining records of as-built instrumentation has been critical to the success of the instrumentation works.
- As is prudent on a project of this nature a certain amount of redundancy was included in the overall scheme for the instrumentation. In addition, the opportunity of installing different types of extensometers and piezometers and comparing the results from each type has given confidence in the reliability of the data.
- The cable type probe for the inductance extensometer was the only piece of equipment to give significant problems during the project. With usage the control cable connecting the probe to the signal indicator stretched which resulted in the 1m graduation marks on the cable moving. However, it should be noted that the probes were used on a daily basis for a number of months before the problem started to appear. The use of standard ribbon tape probes remedied this situation and allowed measurement repeatability of 2mm to be achieved on a routine basis.
- The control hole has been most useful in ensuring compatibility between extensometer readouts and also enabled ongoing calibration as the graduated cables stretched with time. The control hole has been especially important on a site of this size, where it is not possible to have individual readout probes dedicated to specific groups of instruments.
- The down the hole probes and attached cables operated in a harsh environment and a thorough daily maintenance routine of cleaning was necessary to ensure equipment operation and repeatability of results throughout the project.
- Instrumentation integrity tests formed an integral part of the installation process with recalibration checks carried out thereafter on a regular basis as required for each instrument type.
- Measurement systems and procedures that allow field checks and downloading facilities that require no additional data handling of recorded data have proved to be invaluable.
- The option to carry out field checks and regular reviews of all instrumentation monitoring has meant that results can be disseminated to clients and works contractors with a high degree of confidence.
- The workbook programs have been successful for factual processing of data, interpretation and review of performance against expected trends, summarising platform results and maintaining a quality assured data set. The inherent features of the spreadsheet software have served to produce report quality output while automation by use of macros has ensured that users have not needed to be particularly computer literate.

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