associated response plan. The following sections discuss each of these items in detail.

Instrumentation

The instruments selected for long-term monitoring include inclinometers, tilt meters installed across slip joints in the elevator shafts, piezometers, and outflow monitoring from the horizontal drains. The locations of the selected instruments are shown on Figure 4.

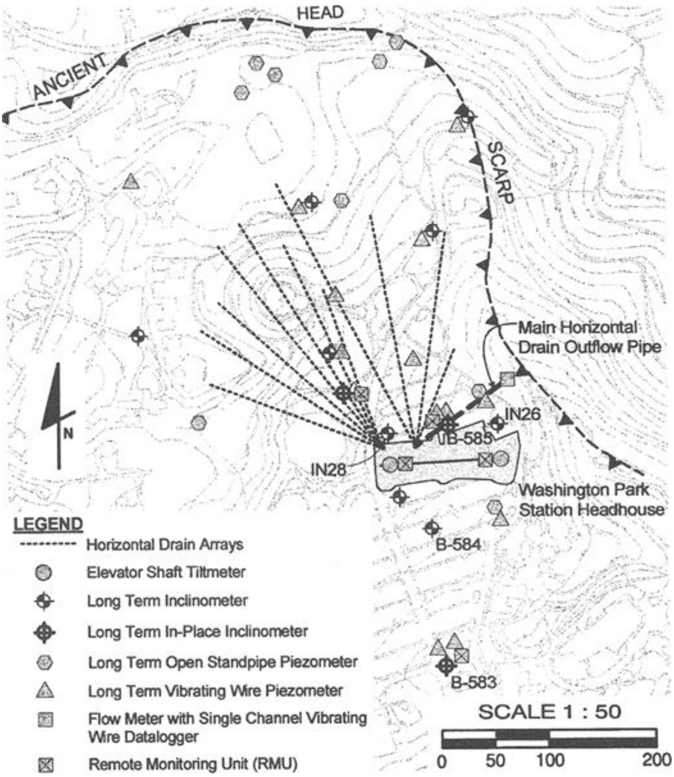

Figure 4 Long-term monitoring Instrumentation Plan

A summary of the different instrument types, their purpose, and the associated reading frequencies are presented in Table 2.

Table 2. Summary of Long-term monitoring Instrumentation

Instrument Type (Quantity)	Monitoring Purpose	Sensor Type	Reading Frequency
Inclinometers (10)	Movement in the landslide mass	Biaxial inclinometer probe (0.61 meter intervals)	5 Quarterly 5 Semi-annually
Inclinometers (3)	Movement at the slide plane	Electrolytic type in-place inclinometer	Every 4 Hours
Tilt Meters (2)	Movement across the slip joint in the elevator shafts	Two uniaxial vibrating wire tilt meters configured to provide biaxial monitoring	Evaluated every 60 seconds and logged for historical data every 4 hours
Open Standpipe Piezometers (11)	Piezometric head near the midpoint and base of the landslide mass	Water level read with electronic well sounder	3 Quarterly 8 Semi-annually
Vibrating Wire Piezometers (11)	Piezometric head near the midpoint and base of the landslide mass	Vibrating wire pressure transducers	3 Every 4 Hours 3 Quarterly 5 Semi-annually
Horizontal Drain Outflow Flow meter (1)	Flow from the horizontal drain outfall pipe	Multistage orifice standpipe flow meter with vibrating wire pressure transducer	Every 6 Hours

Inclinometers

All of the inclinometer casing installed, with the exception of one replacement instrument, is 6.99 centimeter (2.75 inch) outside diameter (O.D.) PVC casing manufactured by the Slope Indicator Company of Bothell, Washington. The one exception is a 8.48 centimeter (3.34 inch) O.D. replacement casing which was installed to achieve a longer design life at a location that has historically experienced larger rates of movement and offset. All of the inclinometer installations were placed in 10.2 centimeter (4 inch) diameter boreholes and backfilled to the surface with cement grout. Since all of the installations are highly visible, they were protected with steel or aluminum flush-to-grade monuments. The depths of the installations range from 24.5 to 46 meters (80 to 150 feet) with the deeper installations located upslope of the Station in the deepest portions of the landslide.

The three inclinometers that are considered to be the most critical for early detection of movements that could be damaging to the Station are outfitted with Model 56804020 electrolytic vertical In-place-Inclinometers (IPI's) manufactured by the Slope Indicator Company of Bothell, Washington. The IPI's are electronic sensors that measure tilt at one location within the inclinometer casing. The IPI's were positioned in the casing at the depth of the identified zone of movement.

Tilt Meters

One set of tilt meters was installed across a precast slip joint in each of the elevator shafts. The slip joint is a design feature for the elevator shafts to compensate for any shear movement along the failure plane of the ancient slide. The tilt meters provide immediate detection of total movements that exceed 0.64 centimeters (0.25 inches). They also measure smaller ongoing shear displacements to observe for trends that could indicate a developing rate of movement of concern. The locations of the tilt meters are shown on the elevation view of the Station, Figure 1. The tilt meters span the joint by means of a 51 centimeter (20 inch) long stainless steel bar with pivot joints on either end to allow the units to tilt in any given direction. The tilt meter assemblies consist of two Model 6350 uniaxial vibrating wire tilt meters that are welded together at 90 degrees to provide biaxial measurements. Geokon Inc, of Lebanon, New Hampshire manufactured the tilt meters and assembly.

Piezometers

Two different types of piezometers were used for long-term monitoring of the piezometric head within the landslide mass. These included open standpipe piezometers and vibrating wire pressure transducers. Dual instrument installations were used to monitor the piezometric head at both the midpoint and base of the landslide mass at three locations as shown on Figure 4. At these locations the vibrating wire transducer was placed at the base of the landslide and the open standpipe was used to monitor the piezometric head at the midpoint of the landslide.

The open standpipe piezometers consist of two 2.5 centimeter (1 inch) diameter PVC standpipes that were stacked, two per installation, one deep and one shallow with a bentonite seal between the two. The zones identified for monitoring were screened and backfilled with sand to provide a 4.6 meter (15 feet) screened and sanded monitoring zone. The vibrating wire transducers were installed in a similar configuration with the transducers wrapped in a protective cover, lowered into the boring, and buried directly near the base of a 3 to 4.6 meter (10 to 15 foot) thick zone of sand backfill. A bentonite seal was placed between the monitoring zones and the borehole was then backfilled with grout to the ground surface. The pressure transducers used were Model 4500 vibrating wire pressure transducers manufactured by Geokon Inc. of Lebanon, New Hampshire.

Horizontal Drain Outflow Flow Meter

The horizontal drain outflow pipe is equipped with a multistage orifice standpipe flow meter. The flow meter consists of a 20.3 centimeter (8 inch) diameter PVC standpipe with different sized orifice holes at three different elevations. Discharge from the horizontal drain outflow pipe flows into the 20.3 centimeter (8 inch) diameter standpipe, and the water head in the standpipe is measured. The flow rate from the outflow pipe is then calculated using the measured water head and an empirical orifice-flow equation. The orifice-flow equation relates the water head above the center of the orifice hole to the flow rate through the orifice.

Multiple orifice holes were used to allow for measurement of flow rates in the range of 0.095 to 3.5 liters per second (1.5 to 55 gallons per minute). When the water head rises above the lowest orifice hole, then the flow rate is calculated as the sum of the flow from each of the orifice holes. Therefore, for large flow rates near 3.5 liters per second, all three orifice holes are used.

The water levels within the 20.3 centimeter (8 inch) diameter standpipe are measured with a Model 4500AL, 17.2 kilopascal (2.5 pounds per square inch), vibrating wire pressure transducer manufactured by Geokon Inc. of Lebanon, New Hampshire. The pressure transducer is buried in pea gravel near the base of a perforated 10.2 centimeters (4 inch) diameter PVC standpipe that is placed within the 20.3 centimeter standpipe. The 20.3 centimeter diameter standpipe is also centralized within a 30.5 centimeter (12 inch) diameter PVC standpipe that is set in concrete in the ground. The outer standpipe provides protection for the flow meter and allows for the water discharged through the orifice holes to be collected and discharged further downstream. A 15.2 centimeter (6 inch) diameter outfall pipe is connected at the base of the 30.5 centimeter diameter standpipe to convey the water to the desired discharge point located 152 meters (500 feet) downstream.

The multistage orifice standpipe flow meter was selected rather than a weir plate or flume because of the site geometry constraints. The discharge from the horizontal drain outflow pipe exited on the side slope of a drainage ravine. Consequently, providing a level bench to install an open channel-type flow meter would have been difficult. In addition, access to the site was difficult and, therefore, adopting a design that would minimize the amount of heavy construction materials, such as concrete and steel, was advantageous.

Data Collection

Data collection for the long-term monitoring program includes both manual readings and automated data acquisition. As previously discussed, future movements within the vicinity of the Station are of greatest concern and require close monitoring. Other areas within the ancient landslide mass are also of interest to aid in the evaluation of any future movements that may adversely impact the Station. Therefore, long-term monitoring includes automated data collection at frequent intervals for those critical instruments in the vicinity of the Station. Less frequent data collection by manual methods is provided for those instruments that are valuable in maintaining a good historical record of movements within the overall landslide mass. In addition, real-time monitoring is provided for the tilt meters to allow for immediate detection of any critical shear movements impacting the elevator shaft structures.

Manual Readings

The manually read instruments include inclinometers, open standpipe piezometers, and vibrating wire piezometers. The reading frequencies for these instruments vary from quarterly to semi-annually as shown in Table 2.

The inclinometers are read at 0.61 meter (2 foot) intervals using a Slope Indicator Company accelerometer-type inclinometer probe. The data are stored in a portable Datamate readout unit for later download to a PC. Slope Indicator Company also manufactures the Datamate.

Water level data are collected from the open standpipe piezometers using an electronic well sounder with a graduated tape. The vibrating wire pressure transducers are read electronically by connecting the transducer leads to a vibrating wire readout box. The readout box energizes the sensor and reads its response as a frequency measurement. Since the frequency response of the sensor is directly related to pressure, the water pressure at the elevation of the sensor can be determined. The piezometric head is then calculated by adding the pressure, expressed in meters of water, to the elevation of the transducer. Geokon Inc manufactures the readout box used to read the transducers.

Automated Data Acquisition

Automated data acquisition is accomplished by the use of both intelligent remote monitoring units (RMU's) and a single channel datalogger. The locations of the RMU's are shown on Figure 4. The three locations around the Station each monitor one IPI and a shallow and deep vibrating wire piezometer. The two locations within the Station monitor the tilt meters in the west and east elevator shafts, respectively. The single channel datalogger is used to collect data from the horizontal drain outflow flow meter.

The RMU's consist of either a Model CR-10 or CR-10X automated datalogger as manufactured by Campbell Scientific Inc. of Logan, Utah. The CR-10X is a newer model with enhanced capabilities that was used for the real-time monitoring of the tilt meters, and one of the inclinometers and piezometer instrument groups. The Model CR-10 and CR-10X are a microprocessor controlled data acquisition units that can be programmed to collect and evaluate data independently of the other RMU's, and without direction from a central control unit. This distributed intelligence architecture provides significant advantages. With the intelligence distributed throughout the monitoring network, data can be collected and alarm notification initiated at multiple locations independent of each other. Therefore, if one or more of the RMU's cease to function, the remainder of the system continues to operate. This is important in providing a reliable system, especially for the real-time monitoring of the tilt meters. Of importance, a separate RMU was provided for each of the tilt meter assemblies for system redundancy.

The three RMU's located outside of the Station are configured to function primarily as dataloggers. The units collect data on the IPI's and vibrating wire piezometers every 4 hours. The data is then downloaded periodically for evaluation. The two RMU's within the Station are configured as data acquisition and control units that provide continuous monitoring for alarm conditions along with historical data collection functions. The units are integrated with the Station's Supervisory Control and Data Acquisition (SCADA) system so that if alarm conditions are detected, the operations personnel can be notified automatically. Real-time interrogation of the tilt meters and periodic downloading of historical data from a remote location is provided through the use of modem communications. The tilt meters are read and evaluated for alarm conditions every 60 seconds, and data is logged for historical purposes every 4 hours.

One Model LC-1 single channel datalogger, manufactured by Geokon Inc., is used to collect water level data from the vibrating wire pressure transducer installed in the horizontal drain outflow flow meter. The single channel data logger is a programmable unit that can collect and store readings on a predetermined time interval for later retrieval. The unit is concealed within the 30.5 centimeter diameter standpipe and provides reliable transducer readings every 6 hours. The single channel datalogger was selected for this application as an inexpensive way to collect reliable data on a frequent basis. Data is periodically downloaded from the unit for evaluation.

Data Evaluation/Management

Data from the long-term monitoring system is evaluated on a quarterly basis. This evaluation consists of reducing the data and plotting it for comparison with the historical data. The comparison is primarily used to make observations regarding the rate of movement and the corresponding conditions within the slide mass that are influencing the rate of movement. Trends of increasing rates of movement are of special interest.

The manually collected inclinometer data is downloaded from the Datamate into a database software tool called DMM®. Another software tool called DigiPro® is then used to plot and evaluate the inclinometer data. Slope Indicator Company manufactures both of these software tools. The plots that are generated include cumulative deflections verses depth, and time-history plots of the movements at specific depth intervals. The cumulative deflection plots indicate the depth at which the movement is occurring and the time-history plots are used to evaluate the rates of movement, and magnitudes of movement.

Data from the IPI's, tilt meters, piezometers, and horizontal drain outflow flow meter are entered into a Microsoft Excel® spreadsheet for reduction and evaluation. Time-history plots are generated for each of the instruments. The time-history plots for the IPI's and tilt meters are used to evaluate rates of movement trends and total accumulated deflections for the tilt meters. The horizontal drain and piezometer data are evaluated along with rainfall data to identify trends of increasing piezometric head and changes in flow rates under different climatic conditions.

The results of the data accumulation and evaluation are presented in a quarterly report that is provided to Tri-Met operations personnel for review and assessment

Integrated Warning System and Alarm Response Plan

The purpose of the integrated warning system is to provide advanced warning of shear movements along the elevator shaft slip joints that exceed 0.64 centimeters (0.25 inch). The threshold of 0.64 centimeters was based on the design tolerance for the guide rail supports for the high-speed elevators. If the total cumulative movement at the slip joint exceeds 0.64 centimeters, then the guide rail supports need to be adjusted to maintain safe operation of the elevators.

System Design

The architecture for the advanced warning system is presented on Figure 5. The tilt meter assembly is located in the stairwell portion of the elevator shafts and extends across the slip joint as shown. Transient protection is provided for the tilt meters at a junction box that is located in the stairwell. A roughly 70 meter (230 foot) long shielded signal cable connects the junction box with the RMU, which is located in the lower Headhouse level of the Station as shown on Figure 1. The signal cable is protected inside a 5 centimeter (2 inch) diameter metallic conduit. The junction box at the RMU location provides transient protection for the RMU. Components for the RMU include the CR10X, a 12VDC battery power supply with 110VAC trickle charger, a vibrating wire interface unit that reads the tilt meters, and the modem communication equipment. The SCADA system interface consists of a latching relay that is energized by the CR10X when an alarm condition occurs, and an alarm box that provides visual confirmation of the alarm condition and a manual reset button to unlatch the relay. The relay provides a closed contact that is recognized by the SCADA system as an alarm. The SCADA system then provides a visual and audible notification to the personnel located at the primary operations center 24 kilometers (15 miles) away. The primary operations center is manned 24 hours a day.

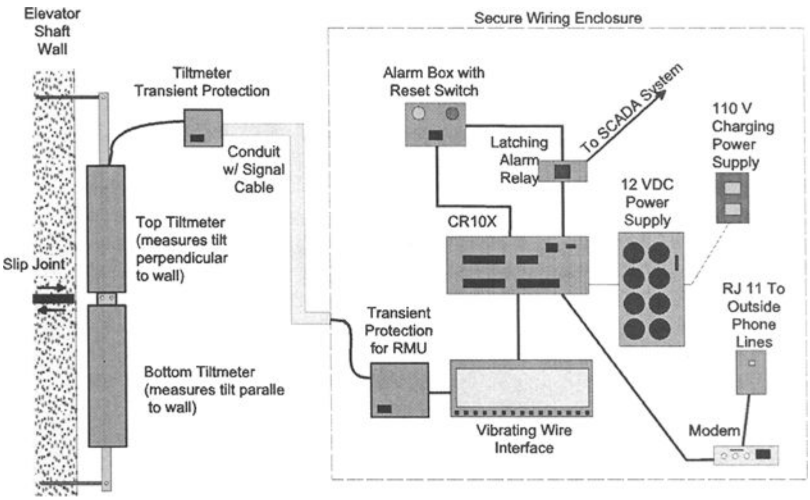

Figure 5 Monitoring System Schematic

Alarm Level Detection

In the event that the tilt meter readings indicate a cumulative total vector movement of 0.64 centimeters (0.25 inch), then a portion of the CR10X's operating program becomes activated and begins an alarm subroutine. The alarm subroutine averages the next five sequential readings and verifies that the average value is equal to or greater than 0.64 centimeters. Based upon the averaging routine, the CR10X will screen out erroneous or anomalous data points to prevent the occurrence of a false alarm. When the CR10X confirms that the alarm is real then it will latch the relay and personnel at the primary operations center will be notified by the SCADA system. The CR10X also begins logging the data every 60 seconds. The data may be remotely viewed by personnel through the modem communication link. If the average value does not exceed the alarm level, then the CR10X returns to its normal operating procedures.

Response Plan

When personnel at the operations center receive notification from the SCADA system, a response plan is initiated. The response plan is in the form of a flow chart that is kept at the operations center. The plan includes the following action steps in the event that an alarm condition is detected by the system.

If an alarm condition is detected by the tilt meters in both elevator shafts, then the operator immediately:

1) notifies the appropriate Tri-Met personnel,
2) dispatches someone to the site to inspect the structures for signs of movement or damage, and
3) downloads the data from the RMU's for evaluation.

If an alarm condition is detected by only one of the two RMU's, then the operator:

1) dispatches someone to the site to inspect the elevator shaft and appropriate tilt meter and RMU for signs of damage,
2) notifies the appropriate Tri-Met personnel immediately if the structure shows signs of movement or damage and downloads the data for evaluation,
3) notifies the appropriate personnel if the warning system equipment is damaged or malfunctioning, or
4) resets the alarm relay at the RMU if a false alarm has been verified.

Alarm Acknowledgement Procedure

When the latching relay is energized by the CR10X, the green light on the alarm box is turned off and the red light is turned on to indicate an alarm condition. The relay interface was intentionally designed to be reset manually at the alarm box location to ensure that a visual inspection of the system is made following any alarm detection event. The relay must be reset by manual action of the reset button on the alarm box panel and cannot be reset remotely using the modem communication link. When the relay has been successfully reset, the red light is turned off and the green light is turned back on.

SYSTEM PERFORMANCE SINCE INSTALLATION

The system has performed well since its completion in 1998. No alarms have been detected to date by the warning system and the rates of movement indicated by the instrumentation surrounding the Station have been consistent with the predicted values, as indicated below in Table 3.

Table 3
Total Post-construction Movement and Creep Rates Between July 1996 and December 1999

Inclinometer	Total Movement centimeters (inches)	Annual Creep Rate centimeters/year (inches/year)
B-585	0.20 (0.08)	0.05 (0.02)
B-584	0.15 (0.06)	0.05 (0.02)
B-583	0.15 (0.06)	0.05 (0.02)

Two design functions that have proven to be especially beneficial are the SCADA interface and the dial-up modem communications link. These two functions have enhanced the performance of the system for the following reasons:

Simplicity

As is typical for a large capital construction project by a local transit agency, many of the engineering staff who had intimate knowledge of the system left the project in 1998. The rail maintenance-of-way (MOW) staff then assumed the responsibility for operations and maintenance. The challenge was to provide an easy-to-understand interface for the MOW staff who are not design engineers. The addition of a simple alarm notification through the SCADA interface, and a clear response plan allows the staff to feel more comfortable in their ability to recognize and respond to an alarm condition at the Washington Park Station. Although an alarm event has not yet occurred at the Station, the SCADA interface has been tested and proven to perform very well for alerting the MOW staff.

Remote Access to the Elevator Shaft RMU's

As the Station construction was nearing completion, there were concerns about the ability to monitor the tilt meters from multiple remote locations to allow for rapid response to an alarm condition, and to minimize the cost of regular data collection. The addition of modems for the two RMU locations along with two dedicated telephone lines made remote communication possible.

With the modem communication link, the geotechnical consultants, as well as Tri-Met staff, can access the deflection data off-site from their office desktop computers using the PC208W® software by Campbell Scientific Inc.. Having the ability to access the deflection data off-site reduces the cost of data collection by minimizing the number of required site visits to download data. More importantly, however, is the ability for the Tri-Met engineering staff to immediately connect to the RMU's and evaluate the data when an alarm condition is detected by the operations center.

CONCLUSIONS

For some projects, moving to a site with ideal geotechncial engineering conditions is not an option. The Washington Park Station is a good example of a project where difficult geologic conditions had to be incorporated into the design and operation of the facility. The long-term performance monitoring provides a level of assurance that the Station will perform in a safe manner, and that if necessary, a timely response will be available to allow emergency actions. Further, the accumulated data would allow for the design and implementation of remedial measures to enhance stability of the landslide mass, if ever needed in the future.