Frank Slide a Century Later: The Turtle Mountain Monitoring Project

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ABSTRACT: Turtle Mountain in southwest Alberta, Canada - the site of the 1903 Frank Slide - has been the focus of many studies over the past century. Geotechnical investigations have concluded that there is potential for a subsequent rock avalanche from the South Peak of Turtle Mountain. To reduce the risk associated with a second rock avalanche, the Government of Alberta initiated a two-year multi-disciplinary monitoring project in 2003. The Turtle Mountain Monitoring Project involves implementation of a predictive monitoring system comprising a variety of geotechnical, geophysical, hydrological and other instruments operating in near real-time. The system incorporates an integrated data management strategy linked to emergency response protocol. Site-specific alarm and warning criteria being developed on the basis of monitoring data from Turtle Mountain are the subject of a companion paper. The project represents a state-of-the-art application of geotechnical monitoring technology in an area of significant historical interest from a landslide perspective. Long-term monitoring is planned following completion of the current project.

1 INTRODUCTION

1.1 *Background*

The Frank Slide occurred at 4:10 AM on April 29, 1903 in what is now southwest Alberta. The slide lasted 90 seconds, and involved some 30 million cubic metres of limestone from the east face of Turtle Mountain. It covered an area 3 km^2 with an average depth of 14 m of rock debris, burying the south end of the town of Frank, the main road, and the CPR mainline, and damming the Crowsnest River (Stewart 1903). The slide killed about 70 people.

The 1903 Slide left two prominent peaks on Turtle Mountain (Fig. 1). South Peak comprises Paleozoic limestone, and rises about 1000 m above the valley floor to an elevation of 2200 m. Studies of South Peak conducted since the 1903 Slide have identified a rock volume of about 5 million cubic metres that could be the source of a future rock avalanche from Turtle Mountain.

The area of attendant risk (Fig. 2) is bounded by the 1903 Slide runout area, Bellevue to the east, and the Hillcrest cemetery to the south. This area currently contains residences, transportation corridors, recreational facilities, commercial buildings, historic sites, agricultural activities, and utilities. There are currently no land use restrictions outside the 1903 Slide runout area to prevent further development in this area (BGC 2000).

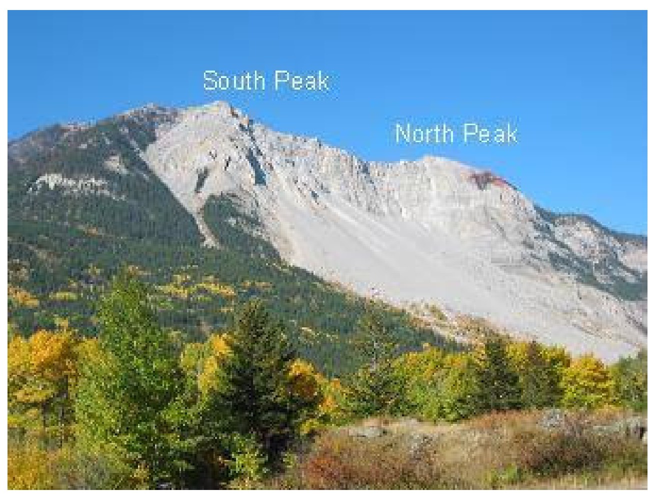

Figure 1. East face of Turtle Mountain showing the 1903 Frank Slide and the prominent North and South Peaks.

To reduce the risk associated with a second rock avalanche, a two-year multi-disciplinary monitoring project was announced by the Government of Alberta on April 29, 2003 – the 100th anniversary of the Frank Slide. The Turtle Mountain Monitoring Project involves implementation of a predictive monitoring system comprising microseismic, displacement, pore pressure, temperature, and other monitoring instruments operating in near real-time. The system incorporates an integrated data management strategy, including operational procedures and

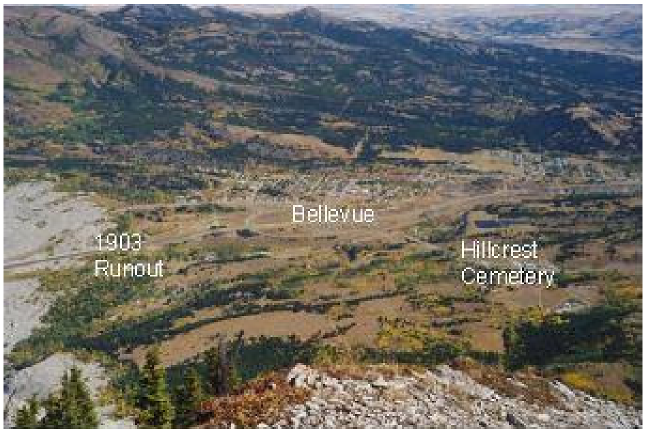

Figure 2. View looking east from South Peak of the potential runout area associated with a rock avalanche from South Peak.

planning guidelines linked to emergency response protocol. Site-specific alarm and warning criteria are being developed on the basis of background and baseline monitoring data from Turtle Mountain, and are the subject of a companion paper (Froese et al. 2005). The project represents a state-of-the-art application of geotechnical monitoring technology in an area of significant historical interest from a landslide perspective.

This paper presents an overview of the Turtle Mountain Monitoring Project in the context of prior monitoring efforts, geotechnical investigations, and recent field studies. Instrumentation installed for the project, and plans for ongoing operation of the monitoring system, are also described.

2 GEOTECHNICAL CONSIDERATIONS

2.1 *Factors contributing to the Frank Slide*

The factors contributing to the 1903 Frank Slide have been identified as the geological structure of Turtle Mountain, deformation due to coal mining at the toe of the mountain, above-average precipitation in the months prior to the slide, water and ice accumulation in cracks at the top of the mountain, remote natural and blast-induced seismicity, thermal variations and freeze-thaw cycles, and karst development.


Figure 3. Turtle Mountain Anticline exposed in Hillcrest Mountain looking south across Drum Creek

The geological structure of the mountain, dominated by the Turtle Mountain anticline (Fig. 3) and several thrust faults, is considered the prime contributing factor (Cruden & Krahn 1973). However, mining-related deformation at the toe of the slide, in combination with water and ice accumulation in cracks, is considered a key trigger of the 1903 Slide. The relative importance of these contributing factors continues to be a source of debate amongst experts, and is one of the aspects being studied as part of the Turtle Mountain Monitoring Project.

2.2 *Geotechnical studies of South Peak*

The 1903 Slide created a network of deep subvertical tension cracks (fissures) at the crest of Turtle Mountain around South Peak (Fig. 4), extending to within a few metres of North Peak. Monitoring of these fissures commenced shortly after the 1903 Slide as a means of identifying the onset of a subsequent rock avalanche.

Between 1931 and 1933, three investigations of the stability of South Peak were conducted, including detailed mapping of the fissure network at the top of Turtle Mountain (Allan 1931, 1932, and 1933). Allan (1931) defined a large and a small "danger zone" associated with runout of a rock avalanche of 5 million cubic metres from South Peak. Based on these studies, the Provincial Government issued a Notice of Danger in February 1933 to residents in the small "danger zone" advising them of the potential risk associated with South Peak. Relo-

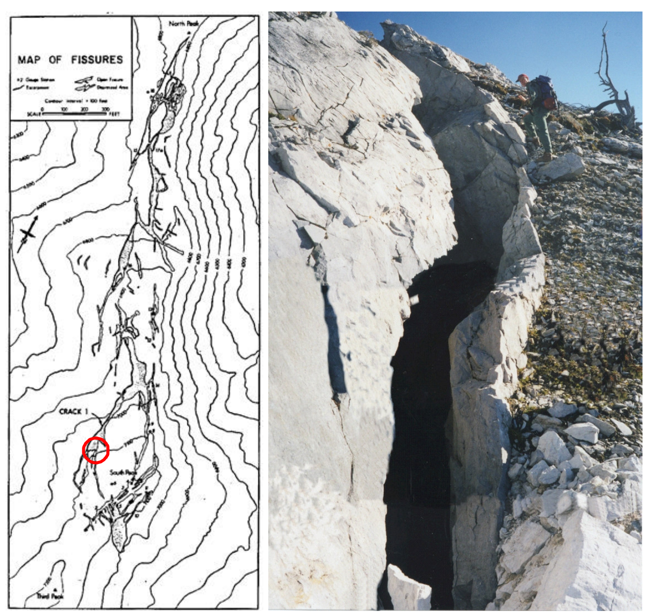

Figure 4: Junction of Crack 1 and a major splay on the west side of South Peak (right), and its approximate location shown by the circle on a reduced copy of Allan's fissure map (left)

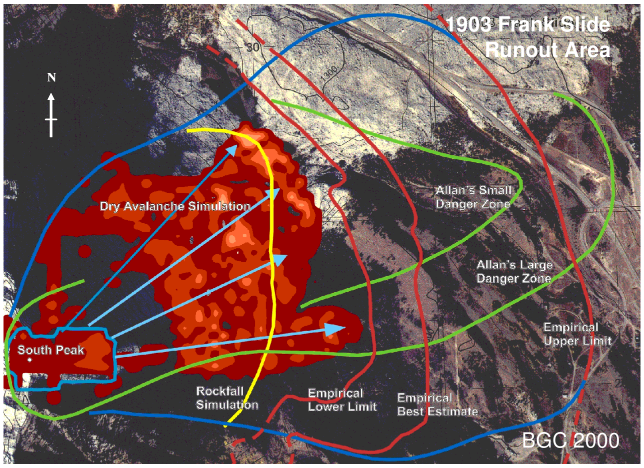

Figure 5: Summary of results from rockfall and rock avalanche analyses performed by BGC Engineering (2000) and earlier estimates by Allan (1931). The empirical upper limit represents the probable maximum hazard zone.

cation of residents to neighbouring communities started in 1934.

Subsequent studies of the geotechnical hazard posed by South Peak were conducted by Agra Earth and Environmental (1998) and BGC Engineering (2000). The annual probability of occurrence of a rock avalanche from Turtle Mountain was estimated to be between 10^{-2} and 10^{-4} depending on the assumed contribution of coal-mining to the 1903 Frank Slide. With a population base between 1 and 100 people in the possible runout area, reduction of risk associated with a second rock avalanche from Turtle Mountain was considered warranted.

The 2000 study produced an updated estimate of the potential runout area associated with a rock avalanche from South Peak, and possible means of reducing the attendant risk. As shown in Figure 5, Allan's estimates of "danger zones" are generally consistent in distal extent with these recent estimates, but not in shape or lateral extent (Read et al. 2000).

Options identified to reduce risk within the probable maximum hazard zone associated with a rock avalanche from South Peak include consultation with those potentially affected by the hazard, restrictions on land use and development within the hazard zone, and installation of a predictive monitoring system. Mitigative measures such as engineered barriers, controlled blasting, or rock mass stabilization were not considered feasible given the large volume of the potential sliding mass (BGC 2000).

3 MONITORING

3.1 *Framework for monitoring*

Based on the recommendations of the geotechnical hazard assessment of South Peak (BGC 2000, Read et al. 2000), RSRead Consulting Inc. (RSRCI) was retained by Alberta Municipal Affairs in 2002 to develop a framework for monitoring the South Peak of Turtle Mountain. This planning framework was intended to provide a blueprint for possible future actions aimed at reducing the risk associated with a rock avalanche from South Peak.

The 2002 study included a review of options for landslide monitoring, a summary of historical monitoring of South Peak, a proposed predictive monitoring system for Turtle Mountain, and an overview of the associated operational logistics, implementation strategy, schedule, and costs. Read (2003) provides an overview of the monitoring framework report.

3.2 *Historical monitoring of South Peak*

Intermittent monitoring of Turtle Mountain has been conducted since 1903. Shortly after the Frank Slide occurred, reference mounds were installed to monitor changes in aperture of the major fissures at the top of the mountain (Dowlen 1903). Daly et al. (1912) recommended that monuments be established for future monitoring of fissures.

As part of Allan's studies, 18 manual gauging stations were established across major fissures in 1933. By 1994, eight of these stations had been destroyed by local rockfalls (Cruden 1986). Readings taken at six of these gauging stations in 1999 showed a maximum of 4 cm change from Allan's original measurements. The nature of movement associated with this aperture change (episodic versus gradual) is unknown.

Starting in 1980, several monitoring systems were deployed on Turtle Mountain. Two TM 71 crack motion detection (Moiré) gauges were installed in the major fissure (Crack 1) between South and Third Peaks (Kostak & Cruden 1990). Between 1980 and 1988, total movement of about 3 mm was detected by these instruments. Tape extensometer measurements across Crack 1 were also taken at nine different locations (Cruden 1986).

In 1981, Alberta Environment installed a seismic monitoring array on the east flank of Turtle Mountain. The array comprised six seismometers in two linked triangular sub-arrays (Bingham 1996). The system used low power radio telemetry to transmit data to an acquisition system at the Frank Slide Interpretive Centre (FSIC).

The seismic monitoring system recorded nearly 350 local events between 1983 and 1992 from different sources including local earth tremor events, rockfall events, blast events, teleseisms, sonic events, noise, and other unidentified sources. Source locations of these events were typically uncertain. It was concluded that induced seismicity is ongoing in Turtle Mountain, primarily west of the abandoned Frank Mine up to 1 km below surface (Bingham 1996). This seismicity is believed to be related primarily to deformation and stress relief within Turtle Mountain, and to ongoing collapse of the mine workings at the base of the mountain.

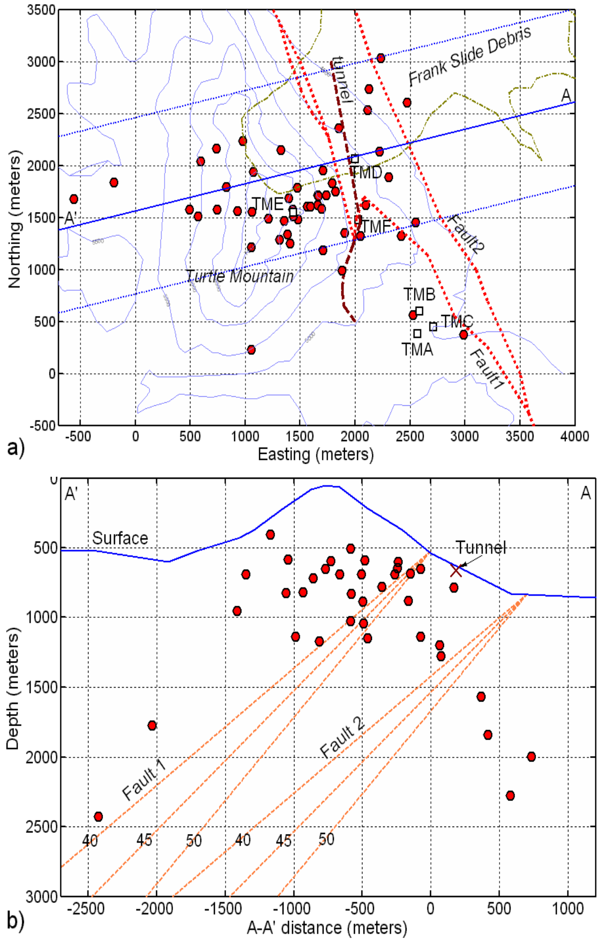

Figure 6: Microseismic results in (a) plan and (b) cross section through Turtle Mountain showing hypocentres of well-resolved events (Chen et al. 2005).

Recent work by Chen et al. (2005) reinterpreted these results, and shows correlation between event location swarms and some geological structures within Turtle Mountain (Fig. 6).

Subsequent monitoring of Turtle Mountain included displacement measurements using high-precision photogrammetry (Fraser & Gruendig 1985; Chapman 1986), electronic distance measurement (EDM) surveys (Anderson & Stoliker 1983), and strain gauges (Peterson & Cruden 1986). Meteorological observations were also recorded at a solar-powered weather station on the mountain. Regular monitoring of Turtle Mountain was discontinued by the early to mid-1990's. Historical instruments and monitoring stations were located and inspected in 1999 as part of a field investigation (BGC 2000). It was found that many of the instruments had been vandalized or destroyed (Fig. 7).

In addition to quantitative measurements, observations, and anecdotal evidence (Allan 1933; Kerr 1990; Cruden 1986; and Bingham 1996) indicate that rockfalls have been ongoing from the steep scarp left by the 1903 Slide, and from the northeast side of South Peak. Of those rockfalls observed, debris has in some cases reached, but not crossed, the Crowsnest River at the foot of the mountain (consistent with predictions from geomechanical analyses). A rockfall of about 15,000 tonnes from the vicinity of North Peak occurred on June 3, 2001. Active collapse of mine workings at the base of the mountain was also observed in 2001 (M. Field, Alberta Community Development, pers. com.).

Figure 7: Defaced photogrammetry target (left) and vandalized Moiré crack gauges (right) observed in 1999.

These observations and measurements confirm that ongoing deformation and microseismic activity are occurring at various locations on and within Turtle Mountain.

3.3 *Predictive monitoring of South Peak*

Past monitoring of Turtle Mountain has been sporadic and relatively short-lived, generally involving manual readings and intermittent analysis. There has been limited coordination of past research projects, and no commitment to ongoing funding for long-term monitoring. The result has been inconclusive information on the background levels of deformation and microseismic activity expected as a result of normal climatic variation versus significant changes associated with the geological and man-made structures (i.e., mine openings) within Turtle Mountain.

The implementation of a predictive monitoring system followed by committed long-term monitoring is expected to provide the data required to identify trends in deformation and microseismic activity associated with degrading stability conditions on Turtle Mountain.

The four objectives of a predictive monitoring system on Turtle Mountain are to advance or improve public safety, public education, scientific research, and tourism/economy in the Crowsnest Pass. Such a system is envisioned as an integrated collection of different types of instruments communicating in near real-time to a data acquisition/processing control centre at FSIC, and other designated sites. Public safety is the primary concern; educational, research, and tourism/economic aspects are lower in order of priority.

3.4 *Critical monitoring parameters*

In developing a predictive monitoring system for Turtle Mountain, monitoring systems and approaches used by BC Hydro at hydroelectric sites in British Columbia (Moore et al. 1991), experimental monitoring systems used to monitor brittle rock failure in Switzerland (Willenberg et al. 2002), and other types of systems were reviewed. Based on this review and observations from the 1903 Frank Slide, the critical monitoring parameters associated with Turtle Mountain were identified as:

- Shear deformation along joints and flexural slip surfaces,
- Extensional deformation across subvertical tension cracks and joints near South Peak,
- Deformation and induced seismicity due to mine collapse at the toe of the potential sliding mass,
- Seismicity induced by progressive development of a basal sliding surface,
- Natural seismicity that might act as a triggering mechanism for a rock avalanche,
- Pore pressure at the basal sliding surface and at various depths in the rock mass,
- Temperature at various depths in the rock mass,
- Precipitation at the top of Turtle Mountain,
- Surface temperature and other climatic data; and
- Outflow at springs connected to the fracture network on South Peak.

As in the case of the Wahleach power tunnel (Baker 1991), it is entirely possible that a continuous basal sliding plane does not currently exist beneath South Peak, but may develop progressively with time. As such, microseismic monitoring in combination with deformation monitoring is considered an important diagnostic component of the monitoring system. Additional system components to measure climatic data and outflow are also needed to help diagnose causative mechanisms associated with observed data trends (e.g., freeze-thaw effects, pore pressure increase due to ice-damming of fissures, and temperature variations).

4 THE TURTLE MOUNTAIN MONITORING PROJECT

4.1 *Project synopsis*

On April 29, 2003, during the ceremony commemorating the 100th anniversary of the Frank Slide, the Government of Alberta announced that it would commit $1.1 million to implement a state-of-the-art monitoring system on Turtle Mountain. The Turtle Mountain Monitoring Project was established as a collaborative effort between the Government of Alberta, contractors, Universities, stakeholders and interested third parties. Ongoing communication with stakeholders and the public was considered an integral part of the project.

Three Alberta government departments were involved in the project. Emergency Management Alberta, through Alberta Municipal Affairs, was responsible for initiating and administering the project. Alberta Geological Survey, through the Alberta Energy and Utilities Board and in conjunction with selected contractors, was tasked with providing necessary technical expertise to implement the monitoring system. Alberta Community Development agreed to house part of the system at FSIC.

The monitoring framework developed for Turtle Mountain (Read 2002) was used as the basic blueprint for the project. The project timeline was compressed from the proposed 3 years to about 20 months as a result of necessary project start-up activities and a major forest fire in Crowsnest Pass in summer 2003.

Development of the monitoring system was originally planned around the idea of three consecutive implementation phases, using information from earlier phases to help refine plans for the later phases. The first phase involved replacing the existing seismic stations and weather station on Turtle Mountain, and establishing a control centre at FSIC. The second phase involved deploying electronic or laser-based distance measurement systems, differential GPS-based instruments, and a series of crack gauge monitors to assess surficial deformation and aperture changes in the major fissures around South Peak. The third phase involved deploying borehole-based instruments to measure displacement, pore pressure, temperature, and microseismicity. Outflow monitoring at springs near the toe of the mountain was also planned as part of the third phase.

Several supporting investigative studies and repeated surveys were planned to provide new site-specific characterization data, compile historical monitoring data and information on mining development, assess the influence of mine collapse on the stability of South Peak, and assess gross deformation patterns using radar-based satellite imagery.

The three implementation phases were scheduled for completion between April 1, 2003 and March 31, 2005. The compressed timeline associated with the project required reorganization of field activities and overlap of the three implementation phases. Eighteen distinct work packages involving eleven contractor/subcontractor companies, two Universities, and several Government agencies, were defined to complete the project over the approved time frame.

The Turtle Mountain Monitoring Project is expected to be followed by ongoing long-term monitoring in order to define baseline deformation and microseismic characteristics of the site, and developing trends that might indicate degrading stability conditions.

4.2 *Microseismic monitoring systems*

Two complementary microseismic systems were installed as part of the Turtle Mountain Monitoring Project: a surface-based system and a borehole-based system. These systems both communicate with the control centre at FSIC via two-way radio telemetry operating at 2.4 GHz.

The surface microseismic system was designed and deployed by Gennix Technology Corp. of Calgary, Alberta between October 2003 and March 2004. Six motion sensing stations (Fig. 8) were installed at various locations on Turtle Mountain. Three 28 Hz triaxial geophones connected in series were cemented into outcrops at each of the stations. Station locations were selected on the basis of array design analysis and consideration of sunlight available to provide solar power.

There are a number of components associated with each surface seismic station, including a microprocessor, power control unit, A/D converters, a GPS antenna and receiver, a radio transceiver and a telemetry antenna. Each station is powered by four 12V deep-cycle batteries, charged by a 100W solar panel. One station near the old Frank Mine entrance (River Station) is also powered by a wind turbine as this location is the most shaded of all of the stations.

In addition to the three channels of input from the geophone, the microprocessor receives timing and positional data from a GPS receiver whose antenna is mounted on the solar-panel mast. Seismic and GPS data are wirelessly transmitted to the control centre at FSIC.

The FSIC control centre has four separate installations: 1) the roof-mounted antenna assembly to receive digital data from the mountain stations, 2) an administration and analysis workstation, 3) an equipment rack housing the central network switch, and three computers (one for data acquisition, one for web serving, and one for SQL and file storage), and 4) a computer-based display centre on the FSIC exhibition floor.

Figure 8. Typical surface seismic station installed on South Peak of Turtle Mountain.

The data received at FSIC are transferred via cable to the equipment rack network hub. Data from all sensors are processed in near-real-time on the acquisition computer and then inserted into an SQL database on a database server system.

In addition to the surface seismic system, two 28 Hz triaxial geophones supplied by Weir Jones Engineering Corp. of Vancouver, BC were installed by AMEC Earth and Environmental in an air rotary drillhole completed to a depth of 62.5 m on South Peak. The borehole was drilled using a helicopter portable drill rig (Fig. 9) operated by Bertram Drilling Limited of Carbon, Alberta.

The subsurface geophones were positioned at 23.9 and 38.2 m depth. The lower geophone was grouted in place by first setting an inflatable borehole packer to isolate the upper portion of the borehole from large cavities visible by televiewer. Geophone signal cables were routed through watertight conduit to data acquisition equipment in an instrument enclosure near the South Peak borehole.

The acquisition board and GPS module for the subsurface seismic system digitize seismic sensor and GPS data, and send data via ethernet cable to a network hub at the South Peak surface seismic station. Data are merged with the surface seismic data and sent to FSIC using the existing telemetry equipment at South Peak.

At the FSIC control centre, the data acquisition computer receives via wireless ethernet the telemetered data transmitted from the South Peak acquisition system, merges the data from the surface and subsurface seismic systems, and runs event detection, source location and visualization software to analyze seismic events. These data are stored as event files, and interpreted data associated with each event are stored in the SQL database.

Figure 9. Air rotary drill used on South Peak during installation of subsurface geophones.

4.3 *Deformation monitoring systems*

Several deformation monitoring systems were designed and deployed as part of the Turtle Mountain Monitoring Project to provide redundant measurements of rock mass movement.

A series of 20 vibrating wire crackmeters (Fig. 10) were installed by Danaus Corp. of Edmonton, Alberta between October 2003 and November 2004. These instruments were located in eight clusters across major fissures on the west side of Turtle Mountain downslope of South Peak. Five of these clusters had crackmeters installed in triplets to determine a true movement vector.

Of the installed crackmeters, five were donated to the project by Dr. Neal Iverson of Iowa State University following completion of a precursor research project. A lightning strike in July 2004 destroyed six of the installed instruments, necessitating replacement of these crackmeters and installation of lightning protection. Data from all crackmeters are captured by a Campbell Scientific CR-10X datalogger installed on South Peak, and transmitted via 900 kHz radio telemetry to the Provincial Building in Blairmore, then relayed via a 5 GHz radio link to FSIC for storage in the SQL database.

Although protective metal snow roofs were installed at each crackmeter cluster to shed snow, several instruments were affected by drifting snow and ice build-up in late 2004. Further protective measures are planned next field season.

To supplement the information from crackmeters, a robotic optical survey system was deployed by Danaus Corp. in 2004. A computer-automated Trimble theodolite was mounted in a protected area at FSIC, and ten prisms (Fig. 11) were mounted at strategic points on South Peak and Third Peak. Readings of the position of each prism are taken hourly, and relative changes in position between each prism on South Peak and that on Third Peak

Figure 10. Vibrating wire crackmeters installed across a major fissure. The metal snow roof is to protect the instruments.

Figure 11. Combination theodolite prism and GPS antenna mounted on a concrete pillar near South Peak.

(considered a stable benchmark) are calculated. These data are stored in the SQL database

In addition to these prism installations, six GPS stations were erected by Danaus Corp. in the vicinity of South Peak in summer 2004. Each station comprises a reinforced concrete pillar mounted with a dual metal plate assembly and a fixed GPS antenna (Fig. 11).

The GPS antenna receives satellite-based time and positional data, which is stored and transmitted via telemetry to FSIC or, for those stations on the west side of Turtle Mountain, via a 900 kHz radio link to the Provincial Building in Blairmore, then via a 5 GHz radio link to FSIC. Data are stored in the SQL database, and compared to measurements taken at a fixed FSIC base station to calculate movement.

As part of one of the major work packages for the Turtle Mountain Monitoring Project, AMEC Earth and Environmental (in cooperation with Durham Geo Slope Indicator) installed 10 surface-mounted tiltmeters in the vicinity of South Peak in October 2004 to detect angular deformations.

Each tiltmeter is designed to measure tilt in a vertical plane, therefore the installation surfaces were selected to be as close to vertical as possible, striking in the same direction as the possible tilt direction. The signal cable for each tiltmeter was conveyed via protective conduit to a Campbell Scientific CR-10X data logger in an instrument enclosure near the borehole collar. Data were transmitted via telemetry to the Provincial Building in Blairmore, and then relayed to FSIC. Measurements of angular deformation are stored in the SQL database at the FSIC control centre.

AMEC Earth and Environmental was also responsible for the installation of four surface-mounted extensometers in October 2004. The cable associated with these instruments (Fig. 12) is anchored to bedrock at one end, then pinned to the ground surface. A suspended weight at the fixed upslope end of the assembly provides a constant load to the metal cable, which is housed inside a protective plastic sheath. Rock mass deformation results in a change in position of the suspended weight, which is recorded as movement. These instruments are expected to be sensitive down to 1 or 2 mm.

Extensometer locations were selected such that the head assembly (upslope end) and anchor (downslope end) were installed in exposed bedrock, with the extensometer cable roughly parallel to the possible direction of movement. The signal cable from the head assembly of each extensometer was run through protective conduit to the Campbell Scientific CR-10X data logger at the enclosure near the South Peak borehole. Displacement data from these instruments is transmitted to the control centre at FSIC via the Provincial Building in Blairmore.

To complement these other deformation systems, a TDR cable installation was originally planned for the South Peak borehole to determine the depth of a possible basal sliding plane. The hole did not reach its target depth of 120 m due to fractured rock conditions, so the TDR cable installation was aborted.

Figure 12. Typical surface extensometer head assembly with housing removed to show suspended weight.

4.4 *Climatic monitoring systems*

The original weather station installed on South Peak in the 1980s was refurbished by Danaus Corp. in December 2003. The weather station (Fig. 13) monitors barometric pressure, air temperature, relative humidity, wind speed, wind direction, solar radiation, precipitation, and rock temperature near the station. Additional temperature data are measured by each of the vibrating wire crackmeters. These data are collected on a Campbell Scientific CR-10X data logger near the weather station and transmitted to the FSIC control centre by radio telemetry via Blairmore.

To complement the weather station data with subsurface information, a 14.3 m long thermistor string with seven temperature measurement points was installed in the borehole drilled on South Peak. These instruments are expected to provide information on the depth of influence of freeze-thaw cycles, and correlations between melting and rock mass movement.

Figure 13. Refurbished weather station on the west side of South Peak.

4.5 *Hydrological monitoring system*

Hydrological monitoring for the Turtle Mountain Monitoring Project is focused on pore pressures at depth in the rock mass, and outflow from a spring at the entrance to the old Frank Mine.

A single vibrating wire piezometer was installed at 21.1 m depth in the South Peak borehole by AMEC Earth and Environmental. Two other piezometers of this type were deployed in one of the major fissures as part of the precursor Iowa State University research project. These three instruments provide pore pressure data that are collected by Campbell Scientific data loggers on South Peak, and transmitted to FSIC by radio telemetry via Blairmore.

The entrance to the old Frank Mine was identified as the location of a spring. As the mine workings are connected to the fracture network on Turtle Mountain, monitoring of outflow from this spring provides insight on the connection between precipitation events on the mountain and outflow. Variations in outflow response times during the year may indicate changes in the fracture network, possibly associated with freezing and ice-damming of cracks.

Matrix Solutions of Calgary, Alberta fabricated and installed a metal weir across the outflow path from the mine entrance (Fig. 14). A Keller pressure transducer installed inside a piece of screened PVC pipe bored into the streambed provides a continuous measure of water level. Data from the outflow monitoring system are collected on a Campbell Scientific CR510-55 datalogger connected to the telemetry system at the nearby surface seismic station (River Station). Data are transferred by radio telemetry to FSIC and stored in the SQL database.

Figure 14. Outflow weir installed at the Frank Mine entrance.

4.6 *Other monitoring systems and related studies*

In addition to these continuous monitoring methods, satellite radar interferometry (InSAR) is being investigated by Atlantis Scientific as a complementary tool to identify deformation over the area encompassed by the new digital elevation model of Turtle Mountain. Repeated photogrammetric surveys of existing repainted targets were deferred due to budget limitations. However, this technique could be used to provide additional periodic assessments of surface deformation in the study area.

Supporting studies conducted under the Turtle Mountain Monitoring Project include surface and subsurface characterization of structural geology and fracture patterns on Turtle Mountain from surface mapping and televiewer logging of the South Peak borehole (Alberta Geological Survey and University of Calgary), compilation of mine opening information into a GIS-based system for visualization and analysis of the effects of mine opening collapse on stability of South Peak (University of Alberta), compilation of historical monitoring data (University of Alberta), and evaluation of ground-penetrating radar as a means of characterizing subsurface fractures on Turtle Mountain (University of Alberta).

5 OPERATIONAL LOGISTICS

5.1 *Data management*

A well-defined data management strategy is critical to ensure long-term data integrity. The database is accessible through a three-tier web-based interface designed for expert users, technical users, and the general public. The database can only be changed using the expert access protocol. Visualization of recent data can be accomplished using the other two access protocols. Ongoing regular review of the data by qualified individuals is required to identify developing trends and anomalous data. Alarm and warning conditions require immediate review of data and subsequent action defined by emergency response protocol.

5.2 *Quality assurance*

During the initial commissioning of the monitoring system, standard operating procedures will be in place and followed for future component installation, wiring, calibration, diagnostic checks, and maintenance. Quality assurance procedures for regularly checking the overall functionality of the system, including sensor operation and alarms, are also necessary. These procedures include both automatic system diagnostic checks of each station, and regular manual inspection to check for damage.

5.3 *Alarm and warning criteria*

Predictive monitoring systems require data analysis and logic that determine when a warning should be given. According to Bell (2001), emergency warning should never be based on the results of only one sensor reading. Typically, warning logic is based on majority vote, and allows for sensor and transmitter failures in alarm determination. Alarm thresholds can be programmed to consider absolute readings, relative changes in readings, or rate of change in readings. Several alarm thresholds for each sensor can be defined.

Alarm thresholds require site-specific baseline data. A combination of criteria based on total displacement, velocity, and acceleration is possible for the displacement sensors. Likewise, alarm criteria based on pore pressure, precipitation, or other measurements can be established. Alarm thresholds for seismic data can be developed on the basis of event magnitude, event frequency, localization (clustering) of events, or some combination of these parameters. The initial alarm and warning for the Turtle Mountain Project will be based primarily on displacement measurements. Froese et al. (2005) describe the development of alarm thresholds for Turtle Mountain.

5.4 *Emergency response protocol*

Emergency response protocol is a vital link between long-term monitoring of Turtle Mountain and response to a warning of a rock avalanche from South Peak. The relevant legislation related to Emergency preparedness for this project includes the Federal Emergency Preparedness Act (1985), the Alberta Disaster Services Act (1995), and supporting regulations. The Municipality of Crowsnest Pass Peacetime Emergency Operations Plan provides procedures for prompt and coordinated response to peacetime emergencies affecting the municipality. Development of specific emergency plans and planning guidelines based on the monitoring system is part of the project being undertaken by AMEC Earth and Environmental.

6 LONG-TERM MONITORING

Long-term monitoring of Turtle Mountain will require ongoing funding to maintain the monitoring system, to upgrade or replace components, and to conduct ongoing analysis and reporting of the recorded data. The long-term monitoring plan involves regular site visits to manually inspect instruments and stations, and to visually check geotechnical conditions on Turtle Mountain.

Readings from all sensors are to be checked daily to identify possible system malfunctions or sensors operating out of range. Any observed anomalies are to be reported immediately to qualified personnel to initiate diagnosis and repair of the system. Data are to be analyzed weekly, or more frequently during critical periods, to identify trends that might indicate decreasing stability of South Peak. Data are to be summarized monthly in a short data summary report. An annual report will summarize the key observations and data trends to establish if conditions on Turtle Mountain are deteriorating from year to year.

7 CONCLUSIONS

Recent studies of the South Peak of Turtle Mountain have identified the potential for a large rock avalanche. Based on previous monitoring and recent observations, deformation and induced seismicity are ongoing on and within Turtle Mountain. Past monitoring of the mountain has been sporadic and short-lived. The Turtle Mountain Monitoring Project has implemented a combination of deformation, microseismic, hydrological and climatic monitoring systems suitable for planned long-term monitoring. This project represents an integrated state-of-the-art application of geotechnical monitoring technology in an area of significant historical interest. The multi-disciplinary focus of the project addresses issues of public safety, scientific research, public education, and local tourism/economy.

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