A FRAMEWORK FOR MONITORING THE SOUTH PEAK OF TURTLE MOUNTAIN – THE AFTERMATH OF THE FRANK SLIDE

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ABSTRACT
The 1903 Frank Slide on Turtle Mountain in southwest Alberta 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. The potential runout from such an event could cover a large area where there are currently residences, recreational facilities, utilities and transportation corridors. A predictive monitoring/early warning system was previously recommended to address this geotechnical hazard. In response to this recommendation, a framework for future monitoring of Turtle Mountain was developed. The framework accounts for the geotechnical conditions on Turtle Mountain and historical monitoring efforts, and provides an integrated view of monitoring options, technical issues, as well as schedule and cost considerations. This framework establishes a context in which decisions regarding future monitoring can be evaluated from a systems perspective.

RÉSUMÉ
Le glissement Frank de 1903 sur la montagne Turtle au sud-ouest de l'Alberta a été l'objet de plusieurs études depuis une centaine d'années. Des enquêtes géotechniques ont conclu qu'il y a un risque futur d'avalanche de roches du sommet sud de la montagne Turtle. La zone de coulée potentielle d'un tel événement pourrait couvrir une grande surface où il y a présentement des résidences, des aménagements récréatifs et des corridors pour des entreprises de service public et de transport. Un système de moniteur / d'avertissement anticipé avait été recommandé pour aborder ce risque géotechnique. En réponse à cette recommandation, un encadrement pour surveillance future de la montagne Turtle avait été développé. Cet encadrement donne un compte rendu des conditions géotechniques sur la montagne Turtle, et les efforts l'historique de surveillance qui fournit une vue ensemble des options de suveillance, des questions techniques, d'un échéancier et des considérations de coût. Cet encadrement établit un contexte dans lequel des décisions au sujet de surveillances futures pouront être évaluées dans une perspective d'ensemble de systèmes.

1. INTRODUCTION

Turtle Mountain is located in the Crowsnest Pass in southwest Alberta. It is the site of the 1903 Frank Slide, a massive rock avalanche that dramatically impacted the area. The Frank Slide left two prominent peaks on Turtle Mountain (Figure 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 Frank Slide have identified a rock volume of about 5 million cubic metres that poses a geotechnical hazard to the valley below (Figure 2).

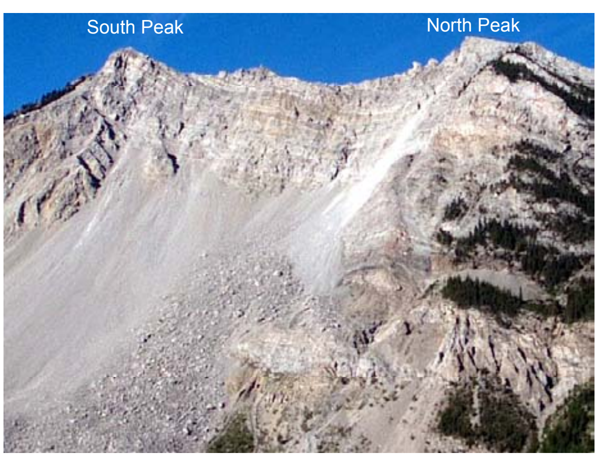

Figure 1. East face of Turtle Mountain showing the 1903 Frank Slide and the prominent North and South Peaks.

Figure 2. View of South Peak looking north towards Bluff Mountain from Third Peak.

The area of attendant risk (Figure 3) is bounded by the 1903 Frank 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. Further development in this area is also possible because there are currently no land use restrictions in place outside the 1903 Frank Slide runout area (BGC 2000).

Figure 3. View looking east from South Peak of the potential runout area associated with a future rock avalanche from South Peak.

Based on a geotechnical hazard assessment conducted by BGC Engineering Inc. (BGC) in late 1999 and reported in 2000 (BGC 2000, Read et al. 2000), a predictive monitoring/early warning system was recommended to reduce the risk associated with a future rock avalanche from South Peak. In response to this recommendation, 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 further actions aimed at mitigating the risk associated with a rock avalanche from South Peak.

The 2002 study included a review of landslide monitoring, a description of options for a predictive monitoring/early warning system for Turtle Mountain, and an overview of the associated operational logistics, implementation strategy, schedule, and costs. This paper describes the monitoring framework, and gives an brief overview of geotechnical conditions on South Peak, and monitoring efforts that have been undertaken in the 100 years since the Frank Slide.

2. OBJECTIVES

A monitoring system on Turtle Mountain is envisioned to include a number of different types of instruments communicating in near real-time to a data acquisition/ processing centre located at the Frank Slide Interpretive Centre (FSIC), and possibly to other designated sites. Such a system would improve or influence public safety, public education, scientific research, and tourism and the local economy. Public safety is the primary concern; educational, research, and tourism/economic aspects are lower in order of priority.

The public safety role of the monitoring system is to measure changes in conditions that affect the potential for a rock avalanche from South Peak, and to provide early warning of extreme conditions to authorities responsible for emergency preparedness. The public education role involves raising the level of awareness of the general public about natural hazards and their potential impacts. The scientific research role of the system is to provide long-term monitoring data that can be used to gain a better understanding of the mechanisms associated with rock avalanches, and to advance the state-of-technology in landslide monitoring. Finally, a monitoring system that terminates at the FSIC has the potential to increase tourism to the Crowsnest Pass area, and may consequently benefit the local economy.

3. OBSERVATIONS FROM THE FRANK SLIDE

The Frank Slide occurred at 4:10 AM on April 29, 1903. The slide lasted about 100 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 limestone rubble, burying the south end of the town of Frank, Alberta, the main road, and the CPR mainline, and damming the Crowsnest River (Stewart 1903). The slide killed about 70 people.

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, seismic activity in 1901 and blast-induced seismicity, thermal variations and freeze-thaw cycles, and karstification (i.e., progressive dissolution of limestone). The geological structure of the mountain (Figure 4) 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 event.

4. GEOTECHNICAL STUDIES OF SOUTH PEAK

The 1903 Frank Slide created a network of deep subvertical tension cracks (fissures) at the crest of Turtle Mountain around South Peak (Figure 5), extending to within a few metres of North Peak. Monitoring of these fissures commenced shortly after the Slide. as a means of identifying the onset of a subsequent rock avalanche.

Figure 4. Turtle Mountain Anticline exposed in Hillcrest Mountain looking south across Drum Creek (BGC 2000).

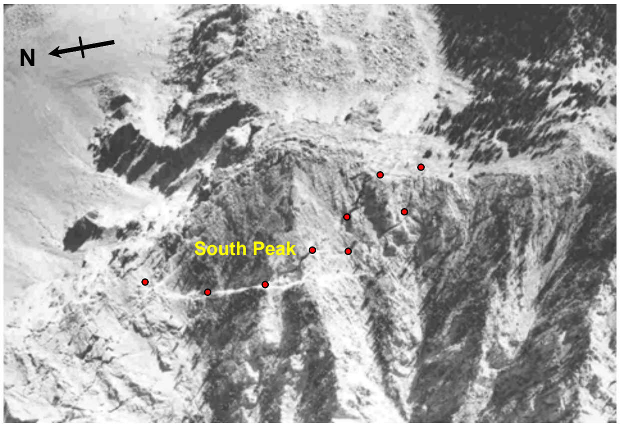

Figure 5. Aerial photograph showing the major fissures encompassing South Peak. Crack 1 and associated splays are identified by the series of filled circles on the aerial photograph.

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). A reduced copy of Allan's fissure map is shown in Figure 6. 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. Relocation of residents to neighbouring communities started in 1934.

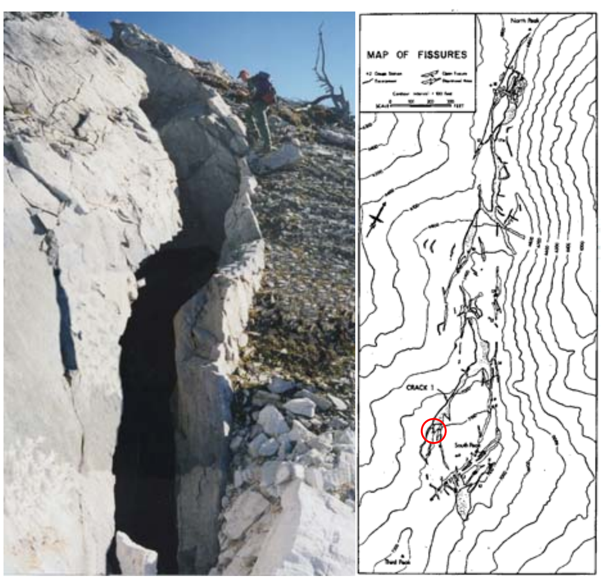

Figure 6: Junction of Crack 1 and a major splay on the west side of South Peak observed in 1999 (left), and its approximate location shown by the circle on a reduced copy of Allan's fissure map (right) (BGC 2000).

Subsequent studies of the geotechnical hazard posed by South Peak were conducted by Agra Earth and Environmental (1998) and BGC (2000). The findings of the 2000 study provided a more accurate estimate of the potential runout area associated with a rock avalanche from South Peak, and possible means of mitigating the attendant risk. Allan's estimates of "danger zones" are consistent in distal extent with these recent estimates, but not in shape or lateral extent (Read et al. 2000).

5. HISTORICAL MONITORING OF SOUTH PEAK

Intermittent monitoring of Turtle Mountain has been conducted since 1903. Shortly after the Frank Slide, 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 gauging stations were established in 1933 across major fissures. By 1994, eight of these stations had been destroyed by local rockfalls (Cruden 1986). Readings taken at six of these gauging stations in 1999 (Table 1) showed little change from Allan's original measurements, or from those taken in 1994 by Bingham (Alberta Environment, pers. com.).

Table 1. Crack deformation readings.

Station #	Crack Aperture (m)		
	Sep. 1999	Aug. 1994	Jul. 1933
2	0.530	0.489	0.503
4	1.016	1.016	1.021
5	1.289	1.278	1.250
7	2.680	2.678	2.652
11	0.826	0.825	0.823
13	1.010	1.008	1.006

Source: BGC (2000)

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 (Figure 8) to transmit data to an acquisition system at the 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.

Figure 8. Seismic station (left) and weather station (right) near the summit of South Peak (BGC 2000).

Figure 9: Defaced photogrammetric targets (left) and vandalized Moiré crack gauges (right) observed during the 1999 BGC field investigation (BGC 2000).

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 caused by ongoing collapse of the mine workings at the base of the mountain.

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 (Figure 8) 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 damaged or destroyed (Figure 9).

In addition to quantitative measurements, observations, and anecdotal evidence (Allan 1933; Kerr 1979; 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. 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.).

6. MONITORING SYSTEM DESIGN

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 projects, and no commitment to ongoing funding for long-term monitoring.

In developing a monitoring framework for Turtle Mountain, monitoring systems and approaches used by BC Hydro at hydroelectric sites in British Columbia (Moore et al. 1991), and experimental monitoring systems used to monitor brittle rock failure in Switzerland (Willenberg et al. 2002) were reviewed. Conceptual designs for three monitoring system options were developed to address the different monitoring objectives in a logical way.

6.1 Data Requirements

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. Based on observations from the 1903 Frank Slide and review of other rock avalanches in brittle rock, the important parameters to monitor include:

- 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 (if any).

6.2 Monitoring System Options

The conceptual monitoring system options developed as part of the framework for Turtle Mountain monitoring include an educational system, an investigative system, and a predictive system. These options build sequentially on one another, with the educational system being the most basic option, and the predictive system offering full functionality for early warning. The conceptual layout of these various systems is shown schematically on an aerial photograph of Turtle Mountain (Figure 10). Each monitoring system option is described separately below with reference to the conceptual layout.

6.2.1 Educational System

The educational monitoring system is intended to increase public awareness of natural hazards. The system would employ shallow surface seismic sensors deployed in strategic positions to provide near real-time monitoring of natural and induced seismic events in Turtle Mountain. Sensors would be high frequency (~28 Hz) triaxial geophones, each located in a concrete lined pit. Each sensor would communicate to a seismic data acquisition system. All acquired data would be time-stamped by a dedicated GPS clock and transmitted by radio to a control centre at the FSIC in near real-time.

The optimal locations for sensors would be determined through an array design analysis. Seismic stations would be located on stable ground to provide good coupling to the rock mass, and fixed positions in space. Ideally, all six existing seismic stations would be replaced, and relocated to provide better spatial coverage of the mountain. A minimum of five stations would be required for reasonably accurate source locations. A single station could be installed as a demonstration of the technology, but would not provide accurate source locations. It would, however, provide basic information on seismicity in Turtle Mountain, and could be augmented with other seismic stations in the future.

A modular design of the seismic stations would facilitate the addition of future stations to the monitoring network. Some advantages could be realized by establishing a central seismic data acquisition system on the mountain linked by cable or by wireless communications to multiple sensor installations. However, this approach would reduce redundancy in the overall monitoring system, a possible risk to the installations. In addition to the seismic sensors, a refurbished weather station would be installed near South Peak to record precipitation, temperature, barometric pressure, and wind speed. These data could be collected by a separate datalogger, or possibly by the seismic data acquisition system if sensors were close to the seismic station.

The educational monitoring system option is limited because it does not measure surface or subsurface deformations, and provides only broad seismic coverage of Turtle Mountain. It is therefore not considered a predictive monitoring/early warning system, but could provide the backbone for such a system.

6.2.2 Investigative System

The investigative monitoring system is expected to increase understanding of the failure mechanisms and the kinematics associated with the potential sliding mass, and to develop a baseline dataset that would be used to design subsequent instrumentation for a predictive monitoring system. In addition to the shallow seismic array and weather station proposed for the educational monitoring option, this system would incorporate intermittent and continuous surface displacement measurements.

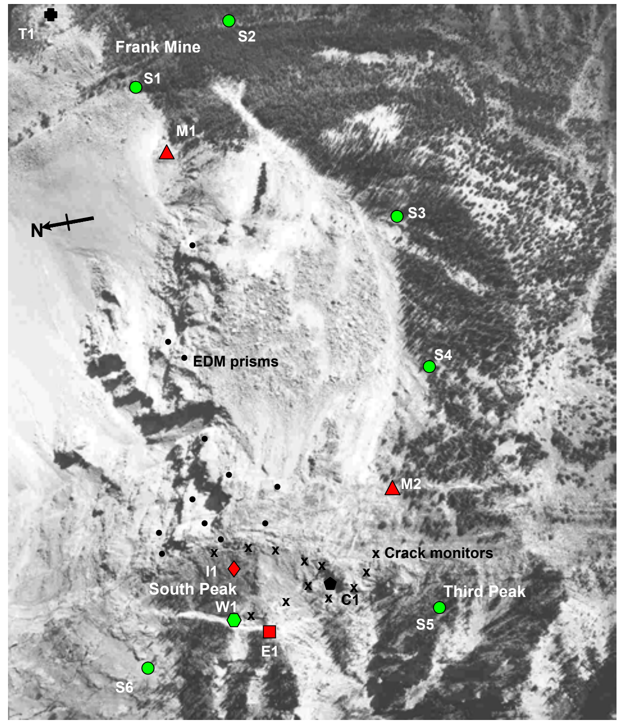

Figure 10: Conceptual monitoring system layout: Phase 1 includes seismic stations (S) and a weather station (W); Phase 2 includes an EDM total station and prisms (T) and crack monitors (C); Phase 3 includes microseismic (M), inclinometer (I) and extensometer (E) boreholes.

Electronic crack gauge monitors would be installed strategically around South Peak, focusing on Crack 1, but providing coverage of the other major fissures identified by Allan (1931). The locations of these instruments would be determined through a field reconnaissance using GPS technology. Where possible, these instruments would be installed deep in fissures to avoid surface disturbance and minimize the risk of vandalism. Based on Allan's gauge stations, it is estimated that 12 crack monitors would be required initially to gain an understanding of the relation between crack aperture changes and other measured parameters. These sensors would be datalogged at a central station, and data would be transmitted by radio to the control centre at the FSIC.

In addition to these continuous measurements, satellite radar interferometry or repeated photogrammetric surveys could be used to provide periodic assessments of surface deformation in the study area. Photogrammetric surveys would require repainting or replacing the existing photogrammetric targets, and reviewing the previous methodology used to calculate changes in position of the various targets. Successive satellite images or aerial photographs would be required for each method, respectively, along with resources to analyze and interpret the results. Alternatively, EDM surveys of existing prisms on the west side of South Peak and new prisms on the east side of South peak visible from a stable position near the base of Turtle Mountain could be repeated regularly to assess movement. Placement of prisms could entail rappelling in fairly dangerous conditions.

The investigative monitoring system option is limited because it does not provide information on subsurface deformation or pore pressure, and provides only broad seismic coverage. While it does provide the means of correlating seismic and surface deformation data, it is not considered a predictive monitoring/early warning system. It can, however, be incorporated into such a system.

6.2.3 Predictive System

The predictive monitoring system is intended to provide quantitative measurements of critical parameters related directly to the stability of South Peak. These data would be used to predict large-scale slope failure, and to provide early warning to identified emergency response personnel. A predictive monitoring system would measure seismicity, surface deformation, subsurface deformation, pore pressure, temperature, climatic data, and possibly outflow data.

In addition to instruments installed for the investigative monitoring system, at least one and as many as three vertical inclinometer boreholes would be drilled through the potential sliding mass into stable ground. Preliminary estimates suggest that boreholes would have to be about 120 m deep, depending on the exact drilling location. Inclinometer boreholes would be diamond-drilled by heli-rig to provide core for geological characterization. A televiewer log and possibly other downhole logs could be run to characterize the rock mass and identify major discontinuities. There is some inherent risk in positioning a drill rig on the potentially unstable rock mass on South Peak, but this is unavoidable for the inclinometer hole.

Following characterization, inclinometer casing would be run into the borehole along with TDR cable, and other instrument cables, outside the casing. One or more vibrating wire piezometers would also be installed, either strapped outside of casing, or installed near the bottom of the borehole in a sand pack that would extend through any identified basal shear zone. Vibrating wire thermistors could also be installed at several depths strapped outside of casing to provide a temperature profile with depth. Once positioned, the inclinometer casing and cables would be grouted in place. Manual inclinometer probe surveys could be conducted over an initial one year period, and periodically thereafter, to provide an indication of the shear displacement profile with depth. Once discrete shear zones were identified, a string of biaxial in-place inclinometers would be installed at the depth of shearing to provide continuous measurements of shear displacement. These could be temporarily removed for subsequent probe surveys.

At least one borehole extensometer is considered necessary to measure the relative downslope movement of the disaggregated rock mass comprising South Peak. This would require an inclined borehole drilled from the west side of South Peak downslope of Crack 1 through the open fissures. Diamond-drilling would produce core for geological characterization. Permanent drill casing would be required near the collar of the borehole to bridge the gap posed by Crack 1. An initial estimate of 50 to 100 m for the extensometer borehole would allow the extensometer to cross most of the open fissures at depth and would allow placement of anchors within discrete blocks. Loss of circulation of drilling fluid would likely be a problem because of the fractured nature of the rock mass. Therefore, there is a risk of high bit wear and possible complications with drilling this hole.

An alternative would be to drill an inclined borehole from the bottom of the cliff below South Peak into stable rock, using the bottom-most anchor in stable rock as the reference for movements. This arrangement has the advantage of providing measurements near the middle of the sliding mass and a stable reference anchor at depth in the mountain, but requires drilling from a potentially dangerous position. Likewise, a sensing station located in this region would be at risk from rock falls.

A subsurface array of triaxial accelerometers would provide focused coverage of the potential basal sliding plane, and induced microseismic activity associated with progressive failure. Between six and eight triaxial accelerometers would be deployed in two dedicated microseismic boreholes each approximately 60 m long. If possible, these boreholes would be drilled through stable rock so as to avoid complications with drilling through the fractured rock mass of the potential sliding volume.

An alternative to dedicated accelerometer boreholes is to lengthen the planned inclinometer boreholes to allow placement of a string of 3 to 4 triaxial accelerometers in the stable rock beneath the potential sliding mass. This alternative has the disadvantage of seismic cables passing through the potential sliding volume, and therefore being susceptible to damage and dysfunction as a result of shear displacement of several centimetres. Furthermore, the seismic sensing station in this case would be located on unstable ground.

7. OPERATIONAL LOGISTICS

Aside from monitoring system design, operational logistics associated with a functional predictive monitoring/early warning system include data management, quality assurance, early warning criteria, and emergency response protocol.

7.1 Data Management

A well-defined data management plan is required before any data are acquired from a monitoring system. The plan should detail the types of data being measured and the format of such data. Database selection and customization is a major consideration. All data are time-stamped so they can be sorted sequentially. Data visualization would involve near-real time displays at the FSIC, and accessible via the internet through a dedicated website. Comparison of collected data to alarm criteria would be carried out automatically at a user-defined interval to determine alarm conditions for individual sensors. Ongoing regular review of the data by qualified individuals would be required to identify developing trends and anomalous data. Alarm conditions would require immediate review of data and subsequent action defined by emergency response protocol.

7.2 Quality Assurance

During the initial commissioning of a monitoring system, standard operating procedures should be adopted and followed for component installation, wiring, calibration, diagnostic checks, and maintenance. There should also be procedures for regularly checking the overall functionality of the system, including sensor operation and alarms. These procedures should include both automatic system diagnostic checks of each station, and manual inspection to check for damage. A regular maintenance schedule should also be developed for installed instruments, and their associated data acquisition and transmission components. Project records are required for each installation and subsequent calibration, diagnostic, and maintenance operations. A strategy and procedures to cover the event of system component failure should also be developed beforehand. The system should have built-in redundant components and/or signal transmission routes to ensure system reliability and security. In addition, the onset of a rock avalanche on Turtle Mountain must not cause premature failure of the monitoring system.

7.3 Alarm and Early Warning Criteria

A predictive monitoring/early warning system requires data analysis and logic that determines 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 to indicate different levels of potential risk.

While there are examples in the literature of different criteria for assessing alarm thresholds, these criteria are site-specific. Because no two sites are identical, alarm thresholds for individual sensors must be based on site-specific baseline data (D. Baker, BC Hydro, pers. com.). 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. These types of alarm thresholds would require pre-processing of seismic event data.

7.4 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. In the Province of Alberta, the municipality is responsible for preparing integrated plans, procedures, and mutual assistance programs to deal with emergencies. The Municipality of Crowsnest Pass Peacetime Emergency Operations Plan provides procedures for prompt and coordinated response to peacetime emergencies affecting the municipality. There is no unique municipal emergency response plan related to a rock avalanche from Turtle Mountain (i.e., the plan follows an all-hazards approach). Development of specific emergency plans and planning guidelines that include a monitoring system is considered a key component of a predictive monitoring phase.

8. LONG-TERM MONITORING

Long-term monitoring is essential for continued reliance on a monitoring system installed on Turtle Mountain. This will require an ongoing funding commitment from stakeholders and other interested parties to maintain the system, upgrade or replace components as required, and to conduct ongoing analysis and reporting of the recorded data. Qualified personnel would be responsible for the monitoring program, and would address issues arising from the program on a round-the-clock basis.

The long-term monitoring plan would involve regular site visits to manually inspect instruments and stations, and to visually check geotechnical conditions on Turtle Mountain. Readings from all sensors would be checked daily by staff at the FSIC to identify possible system malfunctions or sensors operating out of range. Any observed anomalies would be reported immediately to personnel responsible for the system to initiate diagnosis and repair of the system. Appropriate responses to alarms would be defined in detail in an emergency plan. Data would be analyzed weekly, or more frequently during critical periods, to identify trends that might indicate decreasing stability of South Peak. Data would be summarized monthly in a short data summary report. An annual report would summarize the key observations and data trends to establish if conditions on Turtle Mountain are deteriorating from year to year.

9. CONCLUSIONS

Recent geotechnical hazard assessments have identified the potential for a large rock avalanche from the South Peak of Turtle Mountain. Based on previous monitoring and recent observations, deformation and induced seismicity from progressive collapse of the old mine workings is ongoing within Turtle Mountain. Past monitoring of the mountain has been sporadic and short-lived, and has typically involved manual readings and intermittent analysis. Vandalism has also been a serious problem.

Based on this information, a staged approach to deploying a long-term monitoring system has been proposed. The various stages of deployment address specific objectives including public safety, education, scientific research, and tourism. A system that combines seismic and deformation data with precipitation, pore pressure and temperature measurements is considered the best option for a predictive monitoring/early warning system. Microseismic monitoring is considered a key component of such a system. Long-term monitoring will require ongoing financial commitment for data measurement and analysis, and system maintenance. Specific emergency response plans are also needed to successfully operate a monitoring system.

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