 

Strategies towards design of next-generation Early Warning Systems (EWS) for rapid mass movements

A White Paper arising from a workshop organized by the project TRAMM – Triggering of Rapid Mass Movements – in January 2013

Workshop participants:

A. Berne, A. Ferrari, F. Frank, U. Gruner, J. Haeberle, N. Hählen, Ch. Huggel, A. Kos, P. Lehmann, B. McArdell, D. Or, M. Sättele, M. Schleiss, S.M. Springman, M. Stähli, D. Tobler, A. Van Herwijnen

0. Background

Rapid mass movements (RMM) pose a substantial risk to people and infrastructure. Reliable and cost-efficient measures have to be taken to mitigate this risk. One of these measures includes establishing and advancing the State of Practice in the application of Early Warning Systems (EWS). These have been developed during the past decades. Broadly, EWS have been defined as "the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss"[1]. Integral EWS include four main elements: a) knowledge of the main hazards and of the vulnerabilities of people and infrastructure; b) technical components to monitor and/or forecast the hazards; c) dissemination/communication lines for issuing warnings; and d) plans and capacities for action by authorities and those at risk. We focus on the **technical components** of EWS in this document, i.e. the prediction and timely recognition of imminent hazards, as well as on monitoring slopes at risk and released mass movements.

Scientists and engineers from the TRAMM (Triggering of Rapid Mass Movements in Steep Terrain[2]) research project and representatives from cantonal authorities and private companies discussed the current state and future needs of Early Warning Systems (EWS) for rapid mass movements at a workshop on 14-15 January, 2013. The participants agreed that the importance of EWS in managing natural hazards and providing safety to inhabitants and infrastructure is rapidly increasing. As a result of these discussions, the views and visions of this group with respect to the future development and application of EWS were summarized in the form of a 'White Paper'.

Specific objectives of this document are (i) to highlight the needs for functional EWS from a practitioners' point of view, (ii) to report on current innovations in the research on rapid mass movements and their relevance for EWS, and (iii) to identify main challenges and actions needed towards achieving future advances in EWS.

[1] UNEP, 2012

[2] financed by the ETH Competence Centre for Environment and Sustainability CCES

1. Overview on existing Early Warning Systems

A sustainable risk management approach is preventive and includes reliable and cost-efficient risk mitigation measures. During the last decades, EWS have been applied as quick feasible, cost efficient measures with a low environmental impact. Although the technical development has advanced rapidly, most of the active EWS are installed as prototypes. Active systems and state-of-the-art technology installed for gravitative mass movement processes are summarized in a recent publication[3]. The United Nations Environment Programme[4] provided a worldwide overview of EWS systems for all kinds of natural hazard processes. In Austria, an overview of EWS for snow avalanche and landslide processes was published in 2008[5]. A recent overview of operational EWS in Europe was assembled for the EU FP7 project SafeLand[6].

Switzerland is a country that is prone to damage caused by RMM processes due to its alpine geography. The first automatic EWS for snow avalanches was operated in Mahnkinn in 1937 to detect spontaneous snow avalanches above an endangered rail road automatically. Today, EWS are operated in a diversity of designs for various natural hazard processes. More than fifty of these were identified and analyzed within the project ReWarn (a collaboration between SLF and Swiss Federal Office for Civil Protection FOCP) to derive a classification for various forms of EWS. The study revealed that EWS can be classified into: i) alarm, ii) warning and iii) forecasting systems. (Pure monitoring systems, on the other hand, do not actively issue warning information, and are, accordingly, not considered as EWS.)

i) *Alarm systems* detect dynamic process parameters of an already ongoing hazard event and thus offer a minor lead time. Detection of debris flow and flooding, in torrents such as at the Illgraben in Canton Valais, can be achieved by an alarm being triggered in downstream locations when a predefined threshold is exceeded. Due to the short lead time (seconds to minutes), the alarm must be released automatically e.g. in the form of red flashing lights accompanied by sirens. In Switzerland, numerous alarm systems for RMM are being installed to detect processes that appear spontaneously: snow avalanches, glacier lake outburst floods, rock fall and debris flows.

ii) *Warning systems* monitor changes in the most significant variable dispositions (for example: the saturation degree of soils, availability of loose debris material) and potential triggering events, before the main event occurs. The warning information is initiated by predefined thresholds, which offer an extended lead time, whereas the final decision is made by experts. In Switzerland, warning systems are usually locally operated systems that allow processes that occur frequently to be determined: rock falls and slow landslides (for example measuring the slope deformation in Preonzo, canton of Ticino).

---

[3] Bell et al., 2010
[4] UNEP, 2012
[5] Schmidt et al., 2008
[6] Michoud et al., 2013

iii) *Forecasting systems* are also used to monitor changes in the variable disposition and triggering events. But, in contrast to warning systems, the warning information is generated in the form of a bulletin from specialist departments. This means that various measurements and model prediction tools are included to forecast the risk of gravity driven mass movements. For example, the WSL Institute for Snow and Avalanche Research SLF runs a snow avalanche forecasting system and publishes a daily bulletin to predict the degree of avalanche danger for the next day on a regional scale and at five levels.

Independent of the category of an EWS, it must fulfill the following criteria:

- Easy to implement: Limited complexity of the technical system, as well as a thorough instruction of the responsible people (often laypersons) is essential.
- Comprehensible and manageable: Thresholds (e.g. precipitation amount or runoff levels) have to be evident and comprehensible for those in charge of issuing warnings.
- Redundancy: The EWS may not depend on single sensors and transmission lines, but be based on a range of different installations (and complementary parameters, if possible).
- Precision: The critical property defining the risk level must be measured with sufficient precision.
- Autonomy (electricity and data transfer): The system must need minimal maintenance and be functional in remote regions.
- Robustness: The instruments must be able to resist cold and wet conditions, and to some extent mechanical perturbation.
- Affordable price: The costs of acquisition and operation have to be in balance with the expected risk reduction.

Natural hazard experts responsible for the management of RMM risks in canton Bern have gathered extensive experience with EWS and they are extremely positive about their value and potential. Nevertheless, they have to make sure that the specific technical components of such systems always fit with the respective intervention measures. They have also experienced that a technical design is of low value without having implemented a clear distribution of responsibilities and organizational tasks in being able to provide effective management of emergencies.

A further concern for these experts is the abundance of important information required to provide a more complete risk assessment. But more measurements and data do not necessarily make the risk management easier. Often, it is not the amount of data, but the understanding of the processes and the complex relationships between measured quantity and risk of rapid mass movement that limits the success of an EWS.

2. Shortcomings and limitations of current EWS

In spite of the continuous development of EWS worldwide, and the comprehensive experience obtained by operators and those responsible for managing them, we still face inherent shortcomings and limitations of current EWS:

1) *Current EWS are too closely focused on simple thresholds*

The regional emergency management is often carried out by a layperson. Accordingly, the measured values used to define warning levels to initiate protective activity must be rather simple. Thresholds (e.g. of measured precipitation sums) for the release of RMMs cannot be defined universally, but must be adapted to local conditions. The definition of local thresholds and corresponding warning levels is an iterative process that requires a long-term record of events. Newly-installed EWS or EWS set up to protect against only rare events do not provide a sufficient basis for defining plausible thresholds. In addition, thresholds can change over time, e.g. as critical geotechnical properties are changing (e.g. permafrost) or as a consequence of previous events (e.g. slope erosion or raised saturation degree in the ground after a wet winter).

2) *The observations used in current EWS are often not representative*

In many cases, the available measurements (e.g. rain fall data) used for the early warning of RMM are too far away from the critical area and therefore not representative. For example, recent work[7] has illustrated the importance of the sensor position in the field towards the system performance. Inclusion of additional sources of information (e.g. from private weather services or hydropower companies) could partly reduce this problem.

3) *Current EWS typically measure simple proxies of RMMs rather than the critical slope properties*

Sensors typically measure environmental variables that affect the trigger process (e.g. rainfall, precipitation), but not the critical slope properties controlling the initiation of triggering (suction or pore water pressure, soil water content and saturation profiles, depth and stratigraphy of the snow cover). Depending on distributions of water pressures in the ground, soil water contents and snow cover, slope failure may occur in response to a large variety of precipitation intensity and duration and the occurrence of RMMs resembles a random spare ('point') pattern, without any direct link to the measured precipitation structure. Accordingly, the monitoring of precipitation may induce considerable uncertainty for the warning procedure.

4) *Current EWS are typically geared to the actual RMM process and only rarely to precursors*

If an EWS is geared to the actual release of a RMM, the lead time is typically too short to be used as warning level and to initiate protective measures. Triggering failure will usually be

[7] Sättele et al., 2013

preceded by development of local strains along the eventual shear zones, which may occur gradually or as specific events. So far, the relationship between these 'precursor events' and the time and size of mass release is poorly understood. The observation of the onset of precursors is an unsolved problem from a technical point of view; it is unclear 'what' should be measured and what would be the appropriate technique.

5) *Current EWS do not account for uncertainty in an appropriate way*

Uncertainties are inherent to all EWS and their management. Accounting for uncertainty represents one of the main challenges of EWS. Uncertainties are related to the prediction/recognition of the triggering as well as to the transition of the mass, and thus directly affect success or failure of warning and effective risk reduction (avoidance of loss of life or damage). Unfortunately, uncertainty estimates (e.g. ensemble forecasts that give representative samples of the possible future states) are often missing or only weakly represented in current EWS. Furthermore, uncertainties are difficult to communicate to authorities and to the population that potentially may be affected. Past studies have shown that false alarms are less problematic if people have a better understanding of how the EWS functions and what the thresholds are.

3. Current innovations in the research of rapid mass movements

In cutting-edge research, a fundamental change is ongoing in assessing the risk of imminent release of rapid mass movements. New models and observation techniques are currently being developed that can be combined into an integral system that makes use of various complementary information.

3.1 Sophisticated use of precipitation patterns

Accurate and timely knowledge of precipitation is a key for warning about impending RMM. The inherent problem with measuring and predicting precipitation is its large variability over a wide range of spatial and temporal scales. This variability needs to be properly taken into account in EWS. Traditional ways of monitoring precipitation using 1 or 2 rain gauges over an entire catchment is far from optimal because rain gauges have a very limited spatial representativeness. Weather radars can provide precipitation estimates that are more representative over larger areas, but their resolution is often too coarse to be directly used in EWS. New stochastic disaggregation techniques[8] are currently being developed that allow rain rate fields collected by radar or simulated by numerical weather prediction models to be downscaled, while preserving their main statistical properties (e.g., distribution, intermittency and structure). Because it is stochastic, the proposed method can be used to generate large numbers of different outcomes for a single input field. These scenarios can then be applied to landscape models and used to determine the most vulnerable areas for a particular rain event. It can also be used to derive new thresholds for EWS and help to identify critical rainfall patterns that could trigger rapid mass movements.

3.2 Detection of precursors

Before a destabilized soil or snow mass is released, local damage and the gradual formation of a slip zone will deliver precursor events. The progressive character of slip plane formation comprises many small scale mechanical failure events, such as destruction of bonds and/or mobilization of friction between grains, redistribution of internal stresses, or rupture of elements (biological fibers, cemented grain contacts, plant roots, ice crystals).

Local mechanical failure events cause release of energy that propagates through the porous medium as an elastic wave that can be measured as an Acoustic Emission (AE). Because of the small size/scale of precursor failure events, signals are generated at a high frequency. Tests with natural soils revealed characteristic frequency ranges between 1 kHz and 100 kHz for acoustic emissions associated with failure[9]. The range extends towards 1000 kHz for failure in permafrost specimens[10]. Providing the ability to detect single failure events down to the grain scale, acoustic emissions present a mechanical microscope for in-situ monitoring of progressive slope failure. Direct shear tests with different synthetic and natural granular

[8] Schleiss and Berne, 2012
[9] Michlmayr et al., 2012
[10] Yamamoto and Springman, 2014

media corroborated a coherent link between shear plane formation, micro-mechanical failure events, and synchronously observed acoustic emissions[11]. Theoretical considerations based on granular material dynamics and wave propagation concepts allow the acoustic signature to be modelled and provide potential to interpret measured AE with respect to the material failure mode.

On the practical side, an ongoing study by the WSL Institute for Snow and Avalanche Research SLF at a field site above Davos aims to measure acoustic precursory patterns prior to avalanche release. Snow slab avalanches are released as the result of crack formation and propagation in a buried weak snowpack layer. Recent laboratory fracture experiments with snow samples containing a weak snow layer confirmed that acoustic signals originate from within the weak layer[12]. The failure of a weak snow layer resembles a progressive transition into a critical state[13] that is manifested by typical power-law statistics. Such power-law behavior was also observed in snow samples and it was revealed that the distribution of the AE signals changed before, during, and after fracture. During the winter of 2012-2013, two AE sensors were deployed to monitor continuously in an avalanche start zone, and preliminary results are encouraging.

3.3 New models and insights for triggering of mass movements

Precipitation affects the 'load' acting on hillslope elements and, in the case of landslides, it also will affect the shear strength mobilized, which contributes to the stabilizing forces. As prerequisite to model landslide triggering, the change of hydro-mechanical material properties with increasing water content must be understood. Modern concepts of unsaturated soil mechanics are included in constitutive models and numerical simulation tools have been developed to take into account the transition of the soils from a partially to a fully water-saturated state[14]. Numerical and field experiments revealed that not only the local state and strength of a soil element in a slope (as for example expressed in a local factor of safety) controls the initiation of mass release, but the spatial patterns at larger scale, including macro-permeability and the local hydrogeology. In a field study on triggering a shallow landslide by intense sprinkling[15], it was shown that not only the local build-up of positive pore pressures, but the establishment of persisting high water saturations and exfiltration from the bedrock eventually combined to trigger a landslide, whereas zones in which drainage into the bedrock prevented the water table from rising, remained stable. This observation is a first indication that the interconnection of various hillslope elements must be taken into account to model the triggering of mass release successfully. An additional challenge for physically-based landslide triggering models is the abrupt transition of steady saturation patterns to a mass release without additional 'measurable' indication of changes in the system. New landslide triggering models based on a concept denoted as self-

[11] Yamamoto, 2013
[12] Reiweger et al., 2011
[13] Johansen and Sornette, 2000
[14] Nuth, 2009
[15] Springman et al., 2009; 2012

organized criticality were developed to simulate abrupt mass release as progressive failure of interconnected soil columns[16]. During intense rainfall events, 'weak columns and connections' break and a rapid chain reaction culminating in mass release may be initiated. The weakening and local failure of soil was modelled explicitly to capture precursor statistics that change with imminence of mass release and comprise information that could be used in an EWS.

3.4 Innovations in monitoring slope movement and debris flows

Prediction of the triggering of debris flows remains a significant challenge, however, because it is rarely possible logistically or financially to install instruments at all possible failure locations. Broadband seismic networks, most commonly for earthquake or other geological research, have also recently been used to document several landslides and the transformation of one of these landslides into a debris flow[17]. We expect that this technology will be improved through the elaboration of seismic triggering thresholds and by cataloging seismic properties of various types of landslides, thereby eventually making it possible to automate the detection of landslides and debris flows for early warning.

Recent advances in portable ground-based radar interferometry[18] using a new tripod-mounted radar instrument have reduced the amount of time necessary to determine the spatial distribution of movement of a hillslope by accounting for the influence of atmospheric disturbances on the radar signal, thereby increasing the usefulness of ground-based radar interferometry for early warning. For example, for a landslide with an estimated volume of 500'000 m^3 at the Illgraben catchment (Canton VS, Switzerland) it was possible to measure rates of hillslope movement of 3 mm per day. The radar interferometer can measure from several locations to permit construction of 3D movement vectors of landslides. Preliminary results from the nearby Meretschibach, another well-known debris-flow prone catchment, indicate that this technique is also likely to be suitable for creep rates of hillslopes with a large heterogeneity of surface movement.

[16] Lehmann and Or, 2012; von Ruette et al., 2013
[17] Burtin et al., 2014, In Press
[18] Caduff et al., 2014

4. Main challenges

The transition from current well-established, but limited, EWS to future innovative EWS implies a number of challenges both to scientists developing the scientific basis, and to the natural hazard experts putting such EWS in place, and operating them. We are convinced that overcoming the following challenges will be most important in order to make significant advances towards effective next-generation EWS:

Obtaining **accurate and spatially high-resolved precipitation information** in real-time and at a reasonable cost represents a great challenge, especially in Switzerland where the complex terrain significantly hinders the visibility of weather radars. Disaggregating these radar data to represent the intermittency and heterogeneity of the rainfall fields will also be a challenging task that, today, is difficult to automatize fully. This requires extensive further investigations.

A fundamental **advance in the availability and use of information** about the **soil, snow and bedrock** will be the key for enabling numerical models to be used in operational EWS. At present, Switzerland still lacks a soil hydrological map that could be used to derive soil hydraulic properties. The spatial exploration of soil properties relevant for slope instabilities, as well as of the snow cover, requires substantial further development of non-invasive geophysical methods. Such information at the scale of slopes will become essential to translate precipitation fields into maps of water saturation, loads and soil/snow strengths for slope stability models. To ensure reliability of such derived soil-water fields, spatial measurements of water content and water pressure will have to be assimilated. This, on its part, will require considerable innovations in the development of (wireless) sensors and remote-sensing based methods.

A further challenge will be to **develop innovative technical systems to measure precursors at affordable cost**. For example, the measurement of acoustic emission (AE) precursors in a field setting is today in a fledgling state. Numerous problems must be solved before AE devices become practical tools. For example, the strong attenuation of the high frequency elastic waves will have to be counteracted. A potential technology to overcome this problem could be fiber-optic AE sensing. Novel data acquisition methods can provide information on elastic waves impinging on a fiber-optic cable with a spatial resolution in the range of a few meters along a distance of several hundred meters. Entire transects of a susceptible hillslope may be monitored with this method, and precursory AE events can be reported from failure-prone sections instantaneously. The feasibility of this technique at field scale will be tested in the near future.

Related to the implementation of future innovative EWS, a main challenge will be to **make the technical system comprehensible and usable by operators.** Typical operators of EWS may have a basic knowledge of the observed processes, but they are probably not scientists or engineers. Automated operation can be dangerous if the person responsible for security can't make a link between an automatically generated value and the process (e.g. warning level red without knowing which values should generate a red level). The processes are normally too hazardous so that the necessary measures can be deduced from an automatically generated value (e.g. a warn level). Therefore, interpretation is essential. But interpretation by locals is only possible if the EWS is not a black box and clear guidance is provided about how the warning level must be interpreted.

Finally, the key-requirement of **redundancy and reliability of the technical system** remains a difficult task, which is also the case for future EWS. Current advances in remote sensing, e.g. by satellite-based radar systems, need to be better integrated into operational systems. Recent work in the Upper Reuss Valley (Switzerland)[19], contracted by the SBB, has shown that such observations could become a useful complement to ground-based measurements. Not least, the added value of numerical models running in a real-time mode (providing ensemble forecasts) for the redundancy and reliability of technical systems needs to be further explored.

[19] Wegmüller et al., 2013

5. How can we get there? Promising avenues towards future EWS

A substantial advance from current to next-generation technical systems for early warning of rapid mass movements will require fundamental investments in basic research, in the dialogue between researchers and EWS operators, as well as in the exploitation and exchange of experiences.

First of all, the basic research related to mechanisms, early detection and prediction of the initiation of rapid mass movements has to be further intensified. The TRAMM project has demonstrated that a substantial advance can only be achieved in an interdisciplinary setting and not through single disciplines. Our experiences suggest that most important will be new insights in how local observations – typically of very small scale – can be used to derive, over a short time and with high certitude, a risk estimation for the scale of slopes and regions. In this respect, innovations in the use of (complex) numerical models as a complement to observation systems will be of great importance.

Second, the knowledge increase at the research institutes has to be followed up and influenced by practitioners much more than in the past. A critical review of new research outcomes by those being in charge of, or operating, EWS will become essential. To this end, the dialogue between practitioners and scientists needs to be strengthened and institutionalized. Establishing a common language will be a non-trivial prerequisite. A regular dialogue between practitioners, engineers and scientists will also help to foster a much better understanding of the real problems and needs of operators.

Gaining real experiences with new (prototype) EWS will be a key to developing confidence and to reduce skepticism of those making decisions and operating them. To this end, it would be necessary to set in place pioneer examples of functioning/existing EWS that both constitute a real case of emergency with institutional need for action and serve as a playground for testing innovations. Such prototype EWS could then be exploited for the training of practitioners and students. A systematic collection of negative experiences from technical failures, wrong interpretations and wrong decisions in emergency measures will help further improving future systems.

Acknowledgement

This document has been developed for the project TRAMM – Triggering of Rapid Mass Movements in Steep Terrain – financed by the ETH Competence Centre of Environment and Sustainability (CCES).

References

Bell, R., Mayer, J., Pohl, J., Greiving, S. and Glade, T. 2010. Integrative Frühwarnsysteme für gravitative Massenbewegungen (ILEWS). Monitoring, Modellierung, Implementierung. Klartext Verlag, Essen, Germany.

Burtin, A., Hovius, N., McArdell, B. W., Turowski, J. M. and Vergne, J. 2014. Dynamic links between channel and hillslopes revealed by seismic monitoring, Earth and Planetary Science Letters

Caduff, R., Kos, A., Schlunegger, F., McArdell, B.W. and Wiesmann, A. 2014. Terrestrial Radar Interferometric Measurement of Hillslope Deformation and Atmospheric Disturbances in the Illgraben Debris-Flow Catchment, Switzerland. Geoscience and Remote Sensing Letters, IEEE , 11 (2): 434-438.

Johansen, A. and Sornette, D. 2000. Critical ruptures. European Physical Journal B, 18, 163–181.

Lehmann, P. and Or, D. 2012. Hydromechanical triggering of landslides: From progressive local failures to mass release, Water Resour. Res., 48, W03535, doi:10.1029/2011WR010947.

Michlmayr, G., Cohen, D. and Or, D. 2012. Sources and characteristics of acoustic emissions from mechanically stressed geologic granular media — A review. Earth-Science Reviews 112, 97–114.

Michoud, C., Bazin, S., Blikra, L.H., Derron, M.-H. and Jaboyedoff, M. 2013. Experiences from site-specific landslide early warning systems. Natural Hazards and Earth System Sciences, 13: 2659-2673.

Nuth M. 2009. Constitutive modelling of unsaturated soils with hydro-geomechanical couplings. Ph.D. thesis, Ecole Polytechnique Fédérale de Lausanne, Switzerland.

Reiweger, I., Simioni, S. and Schweizer, J. 2011. Failure of weak snow layers. Geophys. Res. Abstr. 13: EGU2011-14072.

Sättele, M., Bründl, M. and Straub, D. 2013. Bayesian networks to quantify the reliability of a debris flow alarm system. In: Safety, Reliability, Risk and Life-cycle Performance of Structures and Infrastructures - Deodatis et al. (eds). Taylor & Francis Group, London, UK.

Schleiss, M. and Berne A. 2012. Stochastic Space-Time Disaggregation of Rainfall into DSD fields. Journal of Hydrometeorology, 13 (6): 1954-1969.

Springman, S.M., Kienzler, P., Casini, F. and Askarinejad, A. 2009. Landslide triggering experiment in a steep forested slope in Switzerland, Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering, edited by M. Maza et al., doi: 10.3233/978-1-60750-031-5-1698.

Springman, S.M., Askarinejad, A., Casini, F., Friedel, S., Kienzler, P., Teysseire, P. and Thielen, A. 2012. Lessons learnt from field tests in some potentially unstable slopes in Switzerland. Acta Slovenica Geotechnica, 1: 5-29 (ISSN 1854-0171).

United Nations Environment Programme. 2012. Early Warning Systems: A State of the Art Analysis and Future Directions. Division of Early Warning and Assessment (DEWA), United Nations Environment Programme (UNEP), Nairobi, ISBN: 978-92-807-3263-4.

von Ruette, J., Lehmann, P. and Or, D. 2013. Rainfall-triggered shallow landslides at catchment scale - threshold mechanics-based modeling for abruptness and localization, Water Resources Research, 49, (1-20), 10.1002/wrcr.20418.

Wegmüller, U., Strozzi, T., Gruner, U., Gisler, C. and Hauser, M. 2013. Verschiebungsmessungen mittels Satellitenradar im Urner Reusstal oberhalb der Nord-Süd-Verkehrsachse im Zeitraum 1992 – 2010. Swiss Bull. angew. Geol., 18 (2): 139 – 153:

Yamamoto, Y. 2013. Acoustic emission response of soils during direct shear tests. Internal TRAMM report.

Yamamoto, Y. and Springman, S.M. 2014. Axial compression stress path tests on artificial frozen soil samples in a triaxial device at temperatures just below 0°C. Canadian Geotechnical Journal. In review.