Deliverable D1.4
Rockfall and landslide warning system on the Rauma Line

Project acronym:	GoSAFE RAIL
Starting date:	01/10/2016
Duration (in months):	36
Call (part) identifier:	H2020-S2R-OC-CCA-04-2015
Grant agreement no:	730817
Due date of deliverable:	April 2018
Actual submission date:	14-05-2018
Responsible/Author:	Yme Asgeir Kvistedal - YK
Dissemination level:	PU
Status:	Issued

Reviewed: NGI and ROD-IS

Document history		
Revision	*Date*	*Description*
0.1	13.04	First draft
0.2	19.04	Internal revision by NGI
0.3	11.05	External revision by ROD-IS
1.0	14.05	First issue

Report contributors		
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Table of Contents

1. Executive Summary

A prototype rockfall and landslide warning system has been installed at a high frequent rockfall site on the Rauma line, north-western Norway. The system is based on a wireless microseismic sensor network, and uses a combination of geophones and magnetometers to identify vibrations in the railway line, generated upon impact of falling rocks or landslide debris. The aim of the system is to identify when events with potential to generate obstructions or damage to the track has occurred, and to issue an automatic warning to the driver of the next passing train of the potential hazard.

A set of algorithms to identify the different types of events generating vibrations in a railway line has been implemented. The ability to identify rockfalls were tested on an abandoned track section, using a sledgehammer to simulate impact. During these tests the system automatically identified all impacts sufficiently strong to generate a shockwaves in track. Detection of landslides is based on an algorithm previously used for detection of avalanches, having a proven track record. Identification of trains and rolling-stock is achieved using magnetometers, and has so far had an absolute success rate on site.

At the time of writing the prototype has been in operation for a little more than four months, and during this period there has not been any naturally occurring rockfalls or landslides. An extended testing period is needed before making a final conclusion on the reliability and applicability of the technology as a warning system. The technology is reliable, has low maintenance requirement and is easy to install onsite without interfering with normal traffic.

2. Abbreviations and acronyms

Abbreviation / Acronyms	Description
Geohazard	Naturally occurring dangerous phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.
Risk	The combination of the consequences of an event or hazard and the associated likelihood of its occurrence.
NGI	Norwegian Geotechnical Institute
BaneNor	Norwegian National Rail Administration
Rensken	The GoSafeRail landslide and rockfall warning system test site.
GSM-R	Global System for Mobile Communications – Railway
CTC	Centralized Traffic Control
ERTMS	European Rail Traffic Management System

3. Background

The present document constitutes the Deliverable D1.4 “Rockfall and landslide warning system on the Rauma Line” in the framework of the WA 3.1, task 1.2 of CCA 04-2015.

4. Objective/Aim

This document has been prepared to provide documentation on a prototype system for object detection on railways, developed as part of the GoSafeRail project.

5. Introduction

Geohazards such as landslides, rockfalls and avalanches pose significant risk to railways in many countries. This is especially true with older infrastructure, built at a time when available mitigation measures were limited. At some locations geographical challenges and cost constraints left no choice but to build railways through areas with known geohazards. As many of these lines still follow the same routes as when first built, the associated hazards persist today. In the future climate change is also expected to alter the geohazard risk at given locations, as more rain is likely to trigger more landslides, while less snow will result in fewer avalanches (Aunaas, 2016). Physical mitigation measures such as barrier walls and rockfall nets are successfully used to improve railway safety. Geohazard risk mapping has however shown that when the situation is significantly complex these measures become costly and difficult to dimension (Sandersen, 2016). Moving the line and building tunnels are in many cases the only permanent physical alternative.

Figure 1: On the 9th of June 1926 a major landslide hit the Rauma line by Verma station. The landslide crossed the line twice, on both sides of the horseshoe turn in "Vendetunellen"

Monitoring and warning systems are cost-efficient alternatives when permanent mitigation measures become difficult. These systems often need to cover sections of several kilometres and should be able to detect all foreseeable geohazard events. In addition they need to work during all weather and seasonal conditions, and should ideally be easy to install and maintain. Slide detector fences have been used as a warning system for avalanches and rockfalls for many years. These are relatively simple systems where a close circuit is broken when a wire in the fence is cut upon impact. The problem with these installations is that they require personnel to enter a potentially hazardous area to repair a broken fence, before regular operation can continue. Many of these systems are thus left inactive. Pilot vehicles are sometimes used to check a line ahead of a passing train. This will reduce the overall capacity on the line and could unless fully automated become costly to deploy on a large scale. In the future drones are expected to become an alternative to pilot vehicles. This technology is however also subject to limitations, as most geohazard events are associated with severe weather conditions and limited visibility, making flying and visual inspection challenging. In more recent years different technologies have been used to detect track obstructions. Cameras and radars can automatically monitor track sections for objects that could pose risk to trains. Although efficient, these technologies are limited by line of sight and mostly applicable on hotspots such as stations and crossings. Geophones and fibreoptic cables have been used to detect possible obstructions through vibrations in the tracks. NGI installed the first prototype rock and ice fall detection system based on an array of geophones in 2004 (R. Cleave, 2009). This system used a standard seismic data acquisition unit and custom developed software for classification of events. The installation contained 24 geophones, mounted with 25 meter spacing alongside an exposed section of the Nordland line in northern Norway. The system was operational over a five year period, before eventually discontinued due to maintenance issues. Canadian railways also operate a few similar systems produced by Weir-Jones (Nedilko, 2016). Optical methods can be used to detect and locate vibrations and deformations along a fibre-optic cable. This method has been applied along roads and pipelines, and proposed as a solution for object detection on railways (Maloney, 2004). Both fibre-optic detection and wired geophone arrays require cables alongside the track, and are thus cumbersome to install and maintain. Analogue geophone cables are also subject to electrical interference and signal loss, limiting the possible length of a single system (R. Cleave, 2009).

This report describes a wireless geophone-based rockfall and landslide detection system, developed as part of GoSafeRail. The prototype installation consist of 12 sensor units, mounted with 30 meter spacing, below a high-frequent rockfall site at the Rauma line in the north-west of Norway. Each sensor unit contains one geophone and magnetometer, a processing unit with radio transmitter and is self-contained with power from batteries and miniature solar cells. Pre-assembled in the laboratory, all sensor units were installed during only four hours in the field on the 28th of November 2017. Maintenance is equally simple, as a single unit can be replaced in a few minutes by local railway staff. The system can be extended for several kilometres and is only limited by bandwidth to a maximum of 1000 sensor units for a single gateway. The estimated cost per kilometre is small compared to all other mitigation measures and warning system technologies.

Figure 2: The GoSafeRail testsite for rockfall and landslide detection cover a 330 meter long section of the Rauma line. The cliff directly above the line is named "Rensken", implying that considerable effort was made to clear the area of loose rocks when the line was built. Observations indicate that there are rockfalls annually on the site.

6. Rauma Line

The Rauma line is a 114 km long railway running between the towns of Dombås and Åndalsnes. It is a branch of the Dovre line connecting the cities of Oslo and Trondheim, and the only port connection on the north-western shore in the Norwegian rail network. While the Dovre line is electrified, the Rauma line is operated on diesel. The line is equipped with GSM-R, but lacks centralized traffic control (CTC). It is scheduled for upgrade to ERTMS by 2030. In 2018 there are four regular passenger services per day and a single daily freight train in both directions. During summer there are additional tourist services through the scenic valley of Romsdalen, between Åndalsnes and Bjorli.

Figure 3: Kylling Bridge with a single type 93 passenger service between Dombås and Åndalsnes. The bridge is part of the second horseshoe turn at Verma.

The Rauma Line was constructed between 1912 and 1924, and opened in parts from Dombås to Bjorli in 1921, and forward to Åndalsnes in 1924. The line was originally intended as the first stage of connection to the city of Ålesund, but this extension was never realized. Without major exceptions the line follows the same track today as when built. Between Bjorli (575 m asl) and Åndalsnes (4 m asl) the line descends through the valley of Romsdalen. By Verma the line makes a double horseshoe turn to account for the steepest part of the decline. Coming from Bjorli the track follows an elevated line in mountainside to the 1396 m long Stavem tunnel. This tunnel is normally referred to as "Vendetunellen" as it encloses the first horseshoe. Onwards from the tunnel the line backtracks down the same mountainside to Verma station. After passing the station the line enters the 480 m Kylling Tunnel before crossing the river Rauma on the landmark Kylling Bridge. This tunnel and bridge form the second horseshoe, enabling the line to continue onwards to Åndalsnes on the other side of the valley. NGI performed a geohazard risk mapping of the entire Rauma line in 2016 (Sandersen, 2016). In this report it was shown that approximately 8 kilometres of the line, at both sides of the valley around Verma, is exposed to a complex variety of landslides, avalanches and rockfalls. The length of the section, combined with the complexity of geohazards and the slope of the mountainside, makes protective measures with walls or nets expensive and difficult to design. A monitoring and warning system was therefore considered the most cost efficient solution for this section of the line. The report also identified a set of hotspots, with a 330 meter long rockfall site called "Rensken", as one of the most exposed. The GoSafeRail prototype rockfall and landslide detection and warning system is installed at this location.

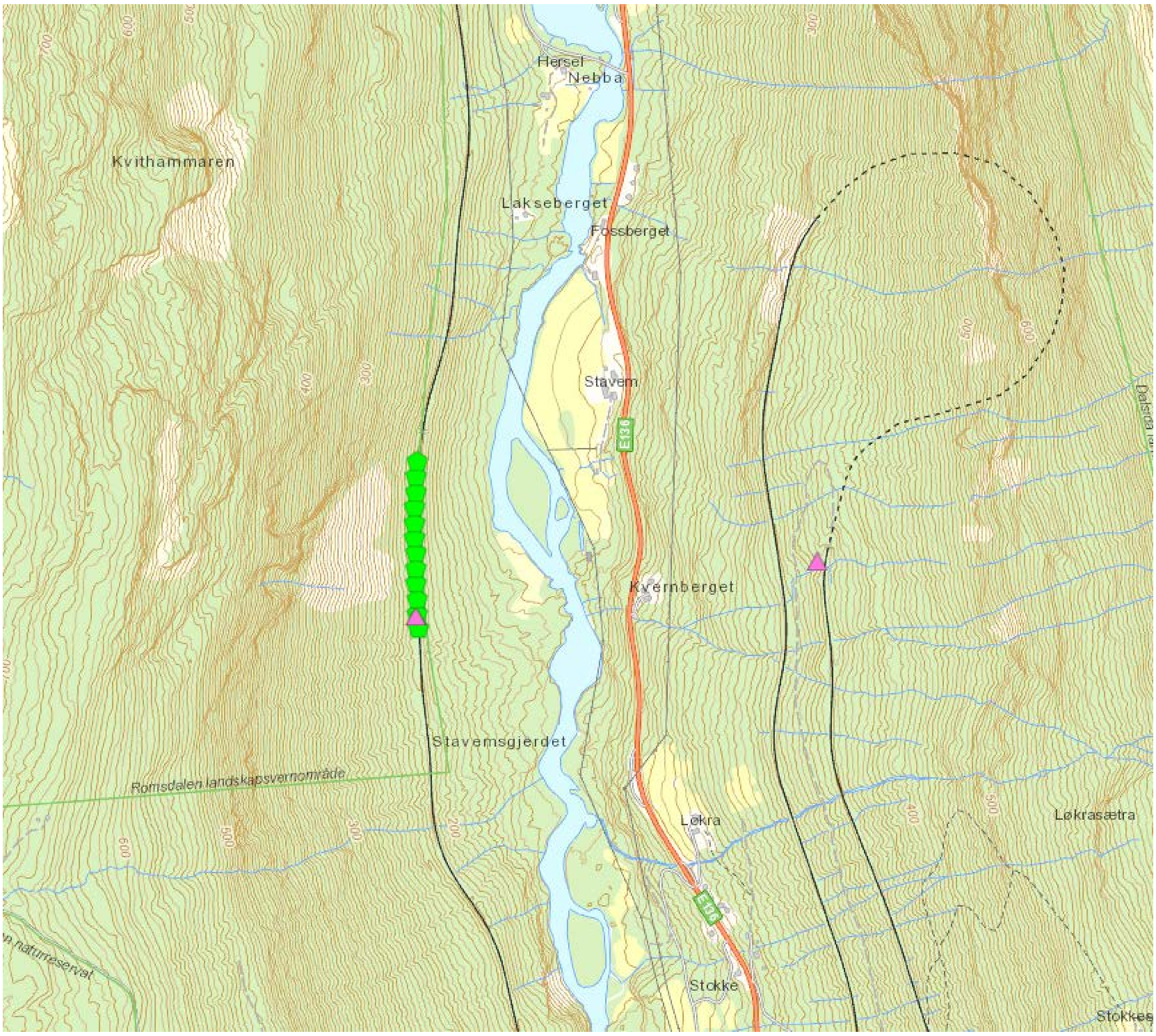

Figure 4: The GoSafeRail test site is located in Romsdalen, directly opposite from "Vendetunellen". The two pink triangles mark the positions of the two electronic cabinets, containing the gateway and the trackside relay radio. The twelve green hexagons mark the positions of the sensor units.

Figure 5: The line below Rensken. Several rocks and boulders can be observed partially covered by the snow beside the track. The photo was taken on the 27th of November 2017 during the installation of the sensor units.

7. Detection and warning system - hardware

The detection and warning system installed at Rensken detects rockfalls and landslides indirectly through vibrations in the railway embankment generated upon impact. 12 sensor units were installed with 30 meter separation between the kilometre marks 421,955 and 422,285. Each sensor unit contains a SM4-8Hz geophone and a ZMY20M permalloy magnetometer. The magnetometer is of the same type used in carpark detectors and its primary function is to verify vibration events triggered by passing trains. Both sensors are connected to a data acquisition and communication unit based on an ARM Cortex-M3 microcontroller. The unit is an assembly containing the EFM32 Giant Gecko microcontroller starter kit from Silicon Labs, a SmartmeshIP radio module from Linear Technology and a custom developed PCB with analogue signal conditioning and energy harvesting.

The signals from both sensors are amplified by 40dB with an INA122 instrumentation amplifier, and low pass filtered using a first order RC filter to avoid aliasing, before sampled with one of the EFM32's analogue inputs. The EFM32 has a 12 bit AD converter, but using oversampling enables aliasing free acquisition with 16 bit resolution. The amplified geophone signal is also connected to one of the EFM32's analogue comparator inputs. Using the comparator makes it possible to "listen" for vibrations while maintaining a low power sleep mode of the microcontroller. Once the geophone signal reaches a predefined threshold the comparator will generate an interrupt, initiating acquisition and real-time processing (as described below) of data streams from both sensors. The power supply to both magnetometer and instrument amplifiers are controlled directly by the EFM32, making it possible to minimize consumption by turning off the magnetometer when there is vibrations detected.

The sensor unit communicates using a wireless sensor network with mesh configuration. The SmartmeshIP technology uses the 2.4 GHz band and has relatively low transmitting power. The range limitation is overcome by deploying relay nodes and careful selection of antennas. The main advantages of the technology is low power consumption, instantaneous two way communication and a reliable communication protocol. The possibility to use the synchronized network time for time-stamping of datasets also replace the need for GPS antennas. The EFM32 is programmed to sample datastreams at 425 sample per second, but inaccuracies and temperature dependence of the crystal oscillator account for variations of as much as +/-3%. When acquiring a dataset we query the network time at both the beginning and end of the measurement sequence, and use this information to determine both time and the actual sampling rate for each individual recording. Each sensor unit is powered by a single lithium-ion battery, and the average power consumption is less than 2 mW. Battery capacity is dimensioned for continuous operation throughout the arctic winter, with sensor units fully covered by snow and ice. Miniature solar panels recharge the batteries during summer months, ensuring virtually maintenance free operation within the battery lifetime. To limit unnecessary battery strain the energy harvesting circuit is configured to avoid excessive recharging cycles and charging during sub-zero temperatures.

Figure 6: One of the sensor units installed on site. The enclosure encapsulates the sensors, data aqusition unit, radio module, antenna and battery. The only external components are the miniature solar panel visible on the lid, and a debug connector (not visible on the image). The sensor units are self-contained with no external cables.

Both sensors, data acquisition unit, radio antenna and battery are mounted inside a custom designed enclosure. The solar panel is mounted on top of the lid, and a debug connector is installed for easy maintenance and software upgrades. The geophone is glued to the inside of the enclosure baseplate, giving optimal mechanical coupling to the tracks, while all electronics are mounted with rubber gaskets minimizing strain from train-induced vibrations. The enclosures are constructed in a rugged plastic material (POM) and fastened directly to the sleepers with concrete-penetrating steel screws.

The sensor enclosures are installed mid-track. In order to avoid interference with snow moving and maintenance operations, the enclosures were designed to extrude as little as possible, while still giving room for a small vertical dipole antenna inside. The top of the enclosures extends 85 mm up from the sleepers, giving more than 100 mm headspace to the top of the rails. The footprint measures 80x220 mm.

The system is designed so that the sensor units will form a series of radio-links along the rail. In addition to producing its own data, the sensor units will forwards messages from neighbouring units, forming a chain of radio-links down the track. In theory this system could be extended over very long distances, but at some point there will be limitations due to bandwidth. During the 2018 winter all sensor units were fully submerged by snow and ice between the rails. The snow cover proved to limit the range of single radio-links to such an extent that four temporary radio units had to be install alongside the track. These radios serve as additional relay station, forwarding messages received directly from the sensor units.

The gateway, containing the master radio and a 3G cellular modem, is the only part of the system requiring grid power. This is installed in a cabinet next to "Vendetunellen", on the opposite side of the valley. A stable 800 meter long radio-link, between the gateway and a dedicated relay radio trackside at Rensken, is achieved by using directional yagi antennas on both ends. The gateway is equipped with a small 24V UPS and an output relay for possible light signal warnings to the train operators.

Figure 7: The cabinet containing the gateway is installed on the wall of a building by the entrance to "Vendetunellen". The gateway is the only system component requiring grid power, and this location was chosen as it is the only Railway owned installation within radio distance from the test site, with available power. The larger cabinet on the opposite wall is a GSM-R installation, enabling possible future integration of the system with existing railway telecommunication.

Figure 8: A second electronics cabinet is installed next to the line at the test site. This contains two relay radio units with directional yagi antennas. One antenna is directed towards the gateway on the opposite side of the valley, while the other is pointing towards the sensor units in the track. For optimal protection during snow moving, both antennas are mounted inside the enclosure.

8. Processing and detection - software

The rockfall and landslide warning system has a software suite called RMAD (real-time microcosmic avalanche detection) containing four individual components. The EFM32 microcontrollers have a software/firmware that interfaces with the hardware, stores sensor data to local memory and extracts statistical information in real-time from the data streams. Information from the sensor units are transmitted via the wireless sensor network to the system gateway, and forwarded through the mobile telecommunication network to a backend application running on a NGI server. The backend application is used to remotely configure the sensor units, download saved datasets and evaluate events based on statistical information received simultaneously from multiple sensor units. All information collected in the field by sensor units, relay stations and modem are saved. The most relevant data is loaded into a Vista Data Vision database and made available online through the associated web interface. Vista Data Vision is also used to issue email warnings on events. Finally, Matlab is used for post processing, visualisation, development of detection algorithms and quality assessment of recorded datasets.

Once geophone activity is detected by the comparator, the EFM32 immediately wakes up from deep sleep and initiates recording of a dataset. The first steps are to power on the magnetometer and instrumentation amplifiers, configure the AD converter and query the network time. This process normally requires less than 20 milliseconds before all analogue electronics are warmed up and ready for acquisition. For every 400 samples the EFM32 calculates the mean, standard deviation, max and min of both geophone and magnetometer data. If the standard deviation is above a predefined threshold a radio package is sent to the backend. The length of a dataset is also determined by the standard deviation, and acquisition will continue while these values are above the threshold. All acquired data is saved locally to the EFM32 flash. This memory is configured as a ring buffer, and it is always the oldest datasets that are overwritten once the memory is filled up. When there are no longer any significant vibrations detected, the EFM32 will automatically stop recording. Before returning to deep sleep the magnetometer and instrument amplifier are turned off, the network time quarried a second time, and a radio packet containing information about the recorded dataset (timestamps, number of samples and actual sampling rate) transmitted to the backend.

During an event the backend receive data from all sensor units that are activated by the vibrations. Depending on the vibration magnitude and range, all twelve, a subset or only a single unit may activate. As each unit is activated by its own geophone signal, data acquisition is asynchronous between sensor units. Network communication may also cause uneven transmission delays and packages being received in different order than transmitted. As all data packages are timestamped by the sensor units, it is still possible to evaluate events with statistical information from multiple sensor units in close to real-time.

The first backend processing stage is to identify whether detected vibrations are triggered by a passing train. A simple criteria stating that at least three sensor units need to simultaneously measure activity on both geophones and magnetometers, has had a 100% success rate on train detection. The threshold values are tuned based on data from confirmed passages, and set to values ensuring that all rolling stock comply (passenger and freight trains, maintenance vehicles and tractors). The data acquired during a train passage could easily be used to calculate train position, velocity and direction, type of train as well as number of carriages, but this has not been within the scope of this study. The time and duration of each passage is entered into the database, but apart from lifting rockfall and landslide warnings after the first passage, they are otherwise ignored.

All events that are not trains are evaluated with specific criteria for the landslides and the rockfalls. To classify landslides a similar criteria has been implemented as previously used for monitoring of avalanches. At least three neighbouring sensor units has to simultaneously detect significant continuous vibrations over a given period of time. While the criteria of detection from multiple sensor units efficiently exclude most events caused by external environmental sources, this algorithm is prone to false positives from earthquakes and construction blasts if incorrectly tuned. These type of events are, however, rare in Romsdalen and will, until proven a problem, be handled by limiting the consequence.

A single rockfall on the track will create vibrations with different acoustic signature than landslides and avalanches, and cannot be detected with the landslide algorithm above. In the extreme case a single rock could fall tens of meters through the air, hitting the track in a single impact, before bouncing further down the slope and into the river below. Such a high velocity impact will generate a shockwave in the track, progressing in both directions from the point of impact. The algorithm for detecting a rockfall is implemented with a criteria that the shockwave needs to be detected by sensors on both sides of the impact, and that the measured amplitude must decrease with increasing distance between impact and sensor. In addition, none of the activated sensors are allowed to report higher standard deviation values during the first second prior to, or after, the impact. This algorithm has proven reliable in detecting shockwaves from sledgehammer tests (described below), as long as the impact is sufficiently strong to activate at least three sensor units. Potential criteria for minimum amplitude and number of sensor units detecting the shockwave, will likely need to be evaluated based on data from actual events.

Figure 9: A single rockfall will generate a shockwave in the track, propagating in both directions from the point of impact. This acoustic signature is distinguishable from most other events, when the shockwave is strong enough to be detected by several sensors on both sides.

When an event is registered, its duration and number of sensors are entered into the database, together with a set of flags indicating if the event is a train, landslide, rockfall or unclassified. If a landslide or rockfall is detected an email waring is issued, containing a request for the next train passage to be conducted at reduced speed. If the registered event has created an obstruction or damage to the track, the driver will be able to stop the train and avoid an accident. If the event was a rockfall that stopped by the side of the track, without creating damage, the train will be able to pass unhindered with minimal delay. Responding to warnings with speed reduction also increase the tolerance to eventual false positives, compared to a scenario where operations are halted until the event is manually verified. Once the next train has successfully passed the site a new email will be issued stating that the previous warning has been lifted. Email warnings on landslides and rockfalls will be sent to the project group and the train operator at Dombås station. Upon occurance of an event it will be the operator's task to instruct the train driver to reduce the speed. Once ERTMS is implemented, these warnings could be sent directly to the train driver, bypassing traffic control.

At the time of writing BaneNor has been offered a service to receive email warnings upon event occurence, directly to the train operator, and is working on developing procedures on how to handle these. Until that time all warnings are only issued to the project group at NGI and BaneNor.

9. Data examples from Rensken

An example of data recorded during a single train passage is shown in Figure 10 and Figure 11. The x axis shows time in seconds, and the y axis represents distance along the rails. Each of the 12 charts contains the time series recorded by a single sensor unit. Figure 10 illustrates vibrations measured with the geophones, and Figure 11 illustrates the changes in magnetic field, measured as the train passes directly over the magnetometers. The data example is recorded during a passage of a dual carriage passenger train, similar to the one shown in figure 2, traveling downhill from Dombås to Åndalsnes at approximately 100 km/h.

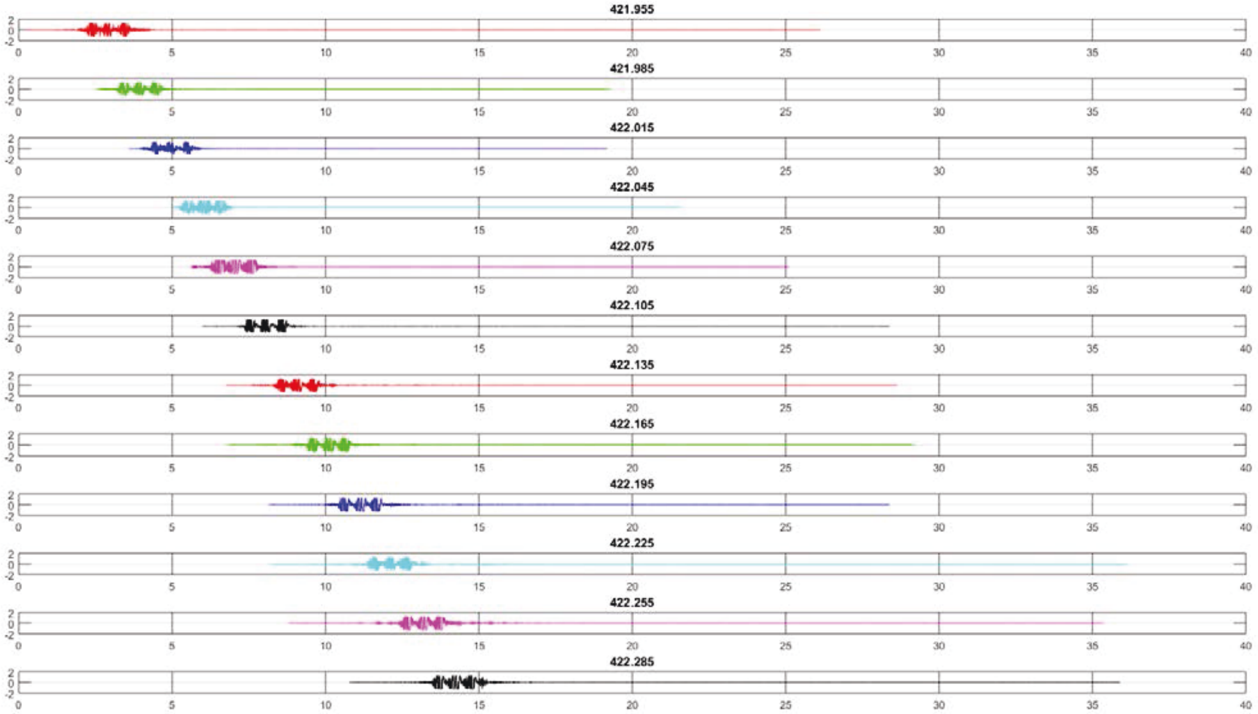

Figure 10. Vibrations generated by a passenger train. The x-axis is time in seconds and each horizontal line represent data from a single sensor unit.

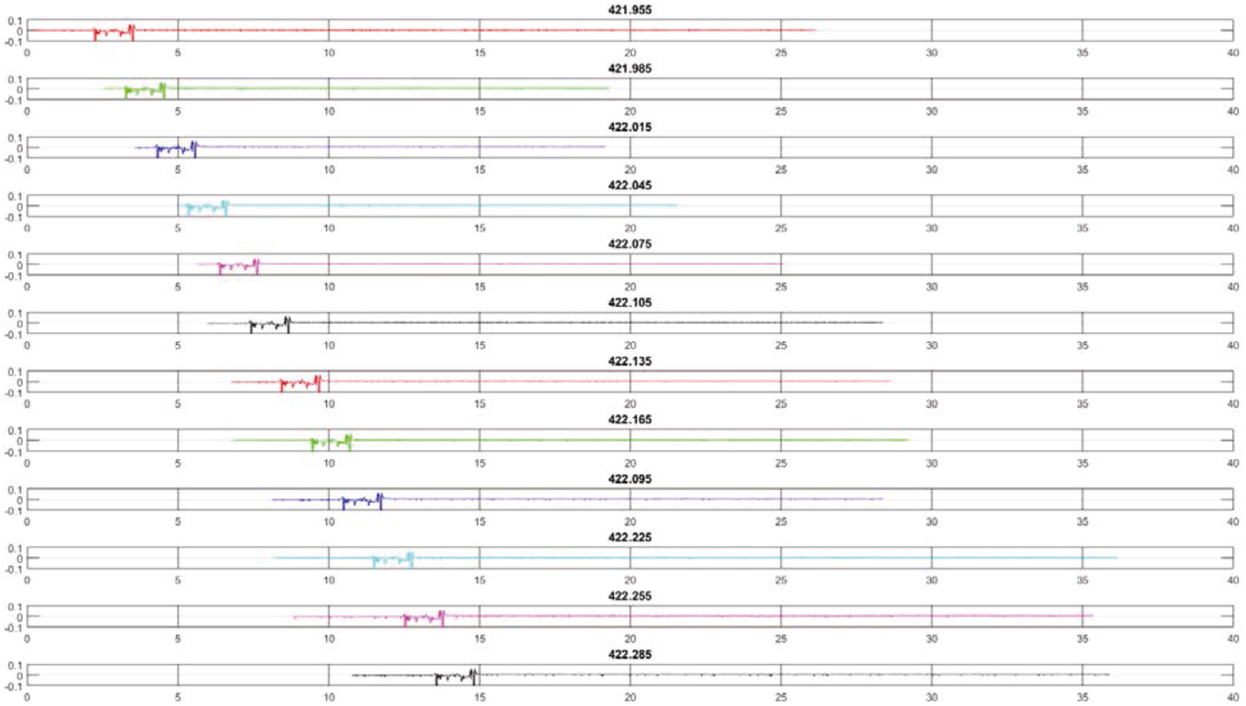

Figure 11: A passing train creates a local disturbance to the earth magnetic field. The magnetometers are used to verify passages of rolling stock, in order to simplify the analysis of vibration data. The illustrated magnetometer data is from the same passage as the vibrations in the figure above.

10. Rockfall simulation tests

In order to test detection of rockfalls a series of experiments were conducted on an abandoned track. This section was once part of the Main line northbound from Oslo, and is of similar quality to the Rauma line. In these tests four geophones were mounted directly on the sleepers using expansion bolts. Each of these geophones were hooked up to individual data acquisition units, similar to the ones installed on the Rauma line, and the data were acquired using a laptop and USB radio module. In order to generate the same type of shockwave expected from a rockfall, a sledgehammer and a 10 kg rock was used simulate a sequence of impacts to different components of the track (sleepers, rail, ballast). An example of data recorded during a single impact is shown in Figure 12. 26 individual tests were performed and the algorithm developed to detect rockfalls identified all of the events that were powerful enough to register on at least three sensors. Similar types of tests will be performed at the Rensken test site as soon as the snow and ice has melted.

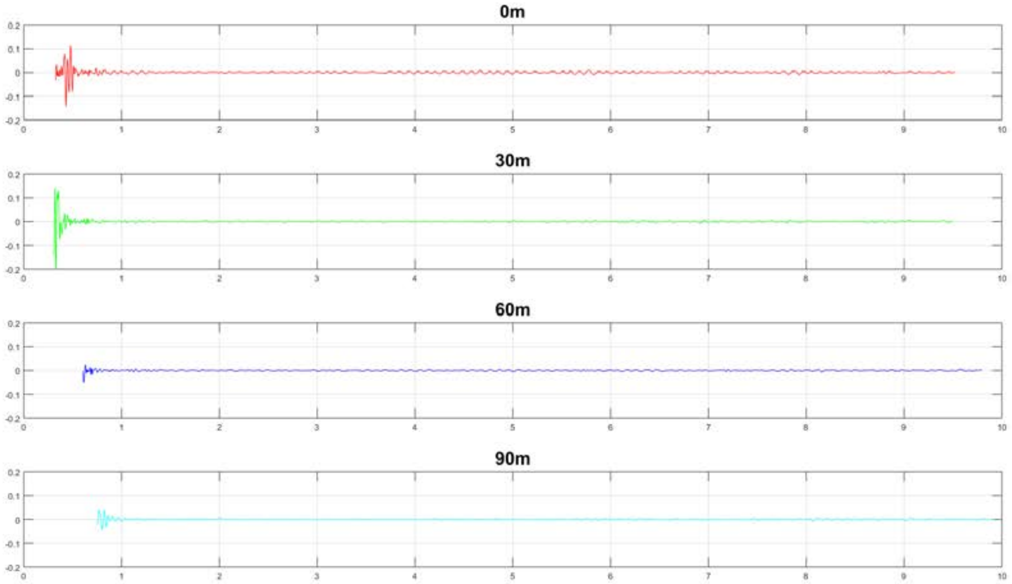

Figure 12: Data example from rockfall simulation tests. A sledgehammer impact directly on a sleeper at approximately 20 m generated a shockwave progressing in both directions along the track. The signal was first registered on the closest sensor at 30 m. The other three sensors registered the same impact slightly later, with a delay proportional to the distance between the impact and the sensor. The amplitude of the signals also decreases the further away from the impact the sensor is located.

Figure 13: Simulated rock fall tests on an abandoned rail section. The geophones were mounted directly on the sleepers and a sledgehammer was used to generate shockwaves in the tracks.

Figure 14: One of the authors in a "makeshift office", verifying data quality during the experiments.

11. Discussions

At the time of writing the rockfall and landslide warning system has been undergoing testing for a little more than four months. Throughout this time all sensor units have been fully submerged in snow and ice. This has affected the quality of the testing in two different ways:

Firstly, the range of a radio link is strongly influenced by how high above the ground the antennas are mounted. As the sensor units are mounted directly on the ground, the corresponding radio links were anticipated to become relatively short. As the addition of snow in-between the rails has made it difficult to achieve stable radio links between sensor units, we had to add extra undesired complexity by installing additional relay radios along the track. We have in parallel tested a solution with different types of antennas we believe will mitigate the issue next winter. As snow will only be an issue in a few specific countries, we believe it is important to observe the system behaviour once the snow has melted before implementing this onsite.

Secondly, the snow cover also shields the sensor enclosures form diurnal influences. Once the snow melts we are anticipating the geophones to respond to local vibrations triggered by wind and rainfall. This will add significant noise to the measurements, and could potentially generate signals triggering false positives. A revision of the detection algorithms is therefore likely needed already during the 2018 summer. The performance of the system has so far been promising, but an extended testing period of at least a few more months will be required before we can conclude on the systems applicability as a reliable warning system.

The Rauma line is neither equipped with CTC nor ERTMS, and is at large operated with the same technology as implemented when the line was built. There is a single operator located at Dombås station responsible for controlling traffic on the line using a switchboard. If the rockfall and landslide detection system is to become a successfully applied warning system, it is considered important to implement a warning scheme well integrated with the daily operations of the line. After discussions with BaneNor the favoured solution will be an additional yellow warning light installed in the switchboard. The colour indicates reduced speed and a note could potentially be added, stating that additional information about the event is sent on email.

As a temporary conclusion on the project, the technology appears promising and has potential for usage as a warning system for rockfalls and landslides. The technology is reliable, has low maintenance requirement and is easy to install onsite without interfering with traffic. An extended testing period is, however, required in order to obtain enough data to adequately qualify the system.

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Kontroll- og referanseside/
Review and reference page

Dokumentinformasjon/*Document information*		
Dokumenttittel/*Document title* Deliverable D 1.4. Rockfall and landslide warning system on the Rauma Line		**Dokumentnr./*Document no.*** 20160760-01-R / H2020-S2R-OC-CCA-04-2015
Dokumenttype/*Type of document* Rapport / Report	**Oppdragsgiver/*Client*** EU H2020	**Dato/*Date*** 2018-05-14
Rettigheter til dokumentet iht kontrakt/ *Proprietary rights to the document according to contract* NGI		**Rev.nr.&dato/*Rev.no.&date*** 1 / 2018-05-14
Distribusjon/*Distribution* ÅPEN: Skal tilgjengeliggjøres i åpent arkiv (BRAGE) / OPEN: To be published in open archives (BRAGE)		
Emneord/*Keywords* Rockfall, Landslide, Early-warning system, Railroads, Raumabanen, Rensken		

Stedfesting/*Geographical information*	
Land, fylke/*Country* Møre of Romsdal	**Havområde/*Offshore area***
Kommune/*Municipality* Rauma	**Feltnavn/*Field name***
Sted/*Location* Verma	**Sted/*Location***
Kartblad/*Map*	**Felt, blokknr./*Field, Block No.***
UTM-koordinater/*UTM-coordinates* **Zone: East: North:**	**Koordinater/*Coordinates*** **Projection, datum: East: North:**

Dokumentkontroll/*Document control*
Kvalitetssikring i henhold til/*Quality assurance according to NS-EN ISO9001*

Rev/ *Rev.*	**Revisjonsgrunnlag/*Reason for revision***	**Egenkontroll av/ *Self review by:***	**Sidemanns-kontroll av/ *Colleague review by:***	**Uavhengig kontroll av/ *Independent review by:***	**Tverrfaglig kontroll av/ *Interdisciplinary review by:***
1	Original document	2018-05-14 YK	2018-04-19 AOL	2018-05-11 Lorcan Connolly	*Select control date* Type your name
		YK 14/5	AOL 14/5-18		

Dokument godkjent for utsendelse/ *Document approved for release*	**Dato/*Date*** 14 May 2018	**Prosjektleder/*Project Manager*** Yme Asgeir Kvistedal

P:\2016\07\20160760\Leveransedokumenter\Rapport\Review and reference page.docx