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Traffic Light System Design and Implementation for Geothermal Stimulation in Helsinki, Finland

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ABSTRACT

St1 Deep Heat is developing a geothermal doublet to deliver deep geothermal heat to local district heat networks. As part of the project, a first well was drilled to a depth of 6.5 km west of Helsinki, Finland, and was stimulated in June to July 2018 to improve rock permeability in contact with the well. Given that the stimulation took place in a densely populated area with multiple sensitive receptors, a seismic Traffic Light System (TLS) was required before the start of well stimulation. The TLS thresholds were established in a probabilistic way to account for uncertainties in the available data. The thresholds were based on a combination of the surface expression of induced seismicity and associated magnitudes, so that false alarms related to surface expression not due to an induced seismic event could be avoided. The final TLS thresholds included a peak ground velocity (PGV) of 1 mm/s associated with a ML $\geq$ 1 event to trigger an Amber alert, and a PGV of 7.5 mm/s associated with a ML $\geq$ 2.1 event to trigger a Red alert. Specific thresholds based on PGV and peak ground acceleration (PGA) were gathered for sensitive receptors and related to earthquake magnitudes in a probabilistic way. The thresholds were then revisited after the well stimulation, making use of the acquired data, using the same methodology.

1. INTRODUCTION

As one of the northernmost countries on the planet, Finland has one of the largest demand for heat per habitant in Europe (e.g., Pezzuto et al., 2015). The total demand for district heating in Finland was 36.6 TWh in 2016 and 2017 (Kaukolämpö, 2018) and about 80% of that demand was met through the burning of fossil fuels or wood, i.e., CO_2 emitting resources. As part of its vision to gradually replace fossil energy with renewable solutions, the Finnish company St1 created the company St1 Deep Heat Oy (St1 DH), which is investigating the option of developing geothermal energy in Scandinavia to supply deep geothermal heat to local district heat network.

The first project by St1 DH is currently being developed in the Otaniemi neighborhood of the city of Espoo, Finland, less than 10km from the center of Helsinki (Figure 1). As part of the project, a 6.1 km deep well, OTN-3, was drilled as a geothermal injector. This well was drilled to the stimulation depth of 6.1 km, completed in May 2018. OTN-3 was then stimulated for seven weeks, starting in June 2018, to improve the rock permeability in contact with the well (Kwiatek et al., 2019).

The City of Espoo's buildings department required that a seismic 'Traffic Light System' (TLS) be developed and approved before granting permission for St1 DH to perform well stimulation activities. The Institute of Seismology at the University of Helsinki (ISUH) was appointed by the City of Espoo to provide consultation on the St1 DH proposed TLS and associated monitoring network.

In this paper, we present the design and implementation of the traffic light system in place during the stimulation of the well OTN-3, as well as the performance of the TLS. We indicate how the TLS can be modified for future well stimulations in the area, using the same method originally used to design the TLS while using the data obtained during the stimulation of the well OTN-3.

Figure 1: St1 Deep Heat Otaniemi site location.

2. TLS DESIGN

2.1 TLS Description

The TLS to be designed aimed at reducing the induced-seismicity hazard, in order to regulate and mitigate the risk of adverse public response and the risk to the built environment. The TLS comprised three thresholds, associated with Green, Amber and Red induced events:

- **Green** conditions allowed for stimulation activities to proceed as planned. During **Green** conditions, TLS activities included network monitoring and confirmation that monitoring stations were operational and transmitting data;
- **Amber** conditions indicated that a TLS exceedance had occurred, which triggered notification, documentation, and evaluation of whether any mitigation of seismic risk was required. While the trigger level for an **Amber** event might result in surface vibrations which would be felt in the vicinity of the event, no cosmetic or structural impacts on the built environment were expected;
- **Red** conditions indicated that a TLS exceedance had occurred. This triggered an immediate stop of stimulation activities with a well bleed-off option, a notification of the earthquake event, and confirmation that activities had stopped. In addition, the event and necessary mitigation measures had to be documented. Stimulation activities following a **Red** event might only proceed with the approval of local authorities. Similar to the Amber threshold, the Red threshold corresponded to a level of shaking where no cosmetic or structural impacts were expected

In addition to the specific TLS thresholds, the full TLS included detailed communication plan, or communication tree, including communication delays, parties to be informed and template of information to be communicated, in case of an Amber or Red alert, as well as actions and mitigation measures following an Amber event or a Red event.

The challenges specific to this specific TLS design were the following:

- Owing to the low levels of seismicity in Finland, there was very little seismic data available for the calibration and design of the TLS;
- The stimulation took place in a large urban area, which meant a large and densely populated area with multiple sensitive receptors and high levels of vibration noise (especially from construction blasting), which posed a risk of false alerts; and
- The population was reportedly very sensitive to earthquakes, bearing the risk of bad public perception, which has been known to shut off geothermal projects in the past (e.g., Giardini, 2009; Diehl et al., 2017).

2.2 TLS Thresholds

The strategy to build the TLS was based on thresholds related to acceptable ground motion levels (peak ground velocity, PGV), on one hand, and on probabilities to reach these thresholds, on the other hand. From the point of view of having the TLS approved by a regulator, basing it on acceptable levels of ground motion at the surface rather than event magnitude at depth facilitated the discussions.

General PGV thresholds were developed in accordance with Finnish Building Code (RIL 253-2010), British Standards on surface vibrations (BS 7385-2:1993, BS 6472-1:2008) and various publications illustrating the relationship between PGV and impacts on human perception and the built environment (e.g., Westaway et al., 2014; Bommer, 2017).

The PGV thresholds were related to event magnitudes using the empirical ground motion prediction equation (GMPE) in PGV by Douglas et al. (2013) and by adapting a GMPE in peak ground acceleration (PGA) provided by ISUH (Ader et al., 2019b).

In order to avoid false alerts or missed alerts, the TLS thresholds were defined in terms of magnitude-only thresholds and a combination of PGV-magnitude thresholds. The full details on the rationale to compute the TLS thresholds is given in Ader et al. (2019b) and the obtained TLS thresholds used during the stimulation of the well OTN-3 are summarized in Figure 2.

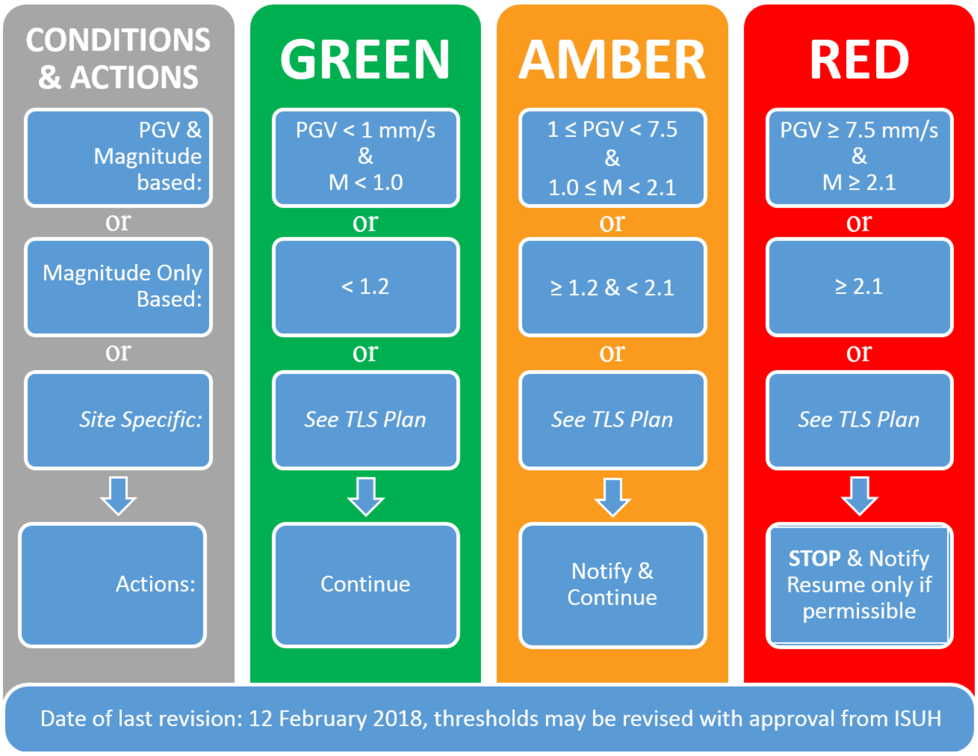

Figure 2: Summary of the TLS thresholds used for the stimulation of the well OTN-3

3. TLS IMPLEMENTATION

The implementation of the TLS is described in great details in Ader et al (2019b) and we here summarize the main aspects of the implementation.

3.1 TLS Monitoring Networks

The TLS for the stimulation in Finland relied on the input of two seismic monitoring networks (Figure 3): a 12-station borehole network composed of seismometers installed in boreholes between 300 m and 1,150 m depth (the Satellite Network) and a 14-station surface network composed of geophones placed at strategic surface locations, such as nearby critical infrastructure sites (the Surface Network).

An observation well, OTN-2, was drilled about ten meters away from OTN-3 to a depth of 3.3 km and instrumented with a 12-level string of 3-component seismometers, at depths from 2,200 m to 2,630 m. The satellite network and this vertical array were used to locate the source of seismic events and estimate their other source parameters, such as time and magnitude. The surface network measured the amplitude of the surface expression of seismic events. The installation and maintenance of the satellite network was performed by *Advanced Seismic Instrumentation & Research (ASIR)*, while the localization of the seismic events and computation of source parameters in near-real time was undertaken by *fastloc GmbH*. The surface network was installed and maintained by the local company *Kalliotekniikka Consulting Engineers Oy*.

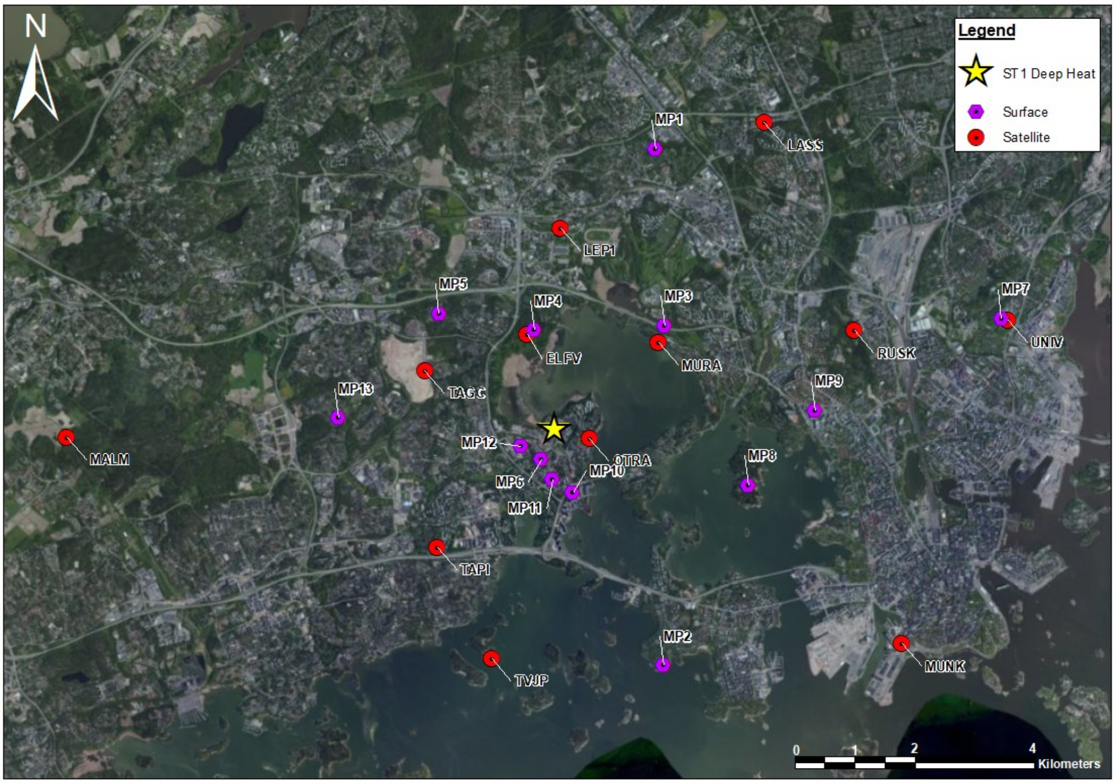

Figure 3: Location map of the monitoring networks used for the TLS

3.2 Procedures for the TLS Alerts

In order to implement the TLS alert actions, an on-site 24h-a-day presence was required, and St1 DH hired four so-called TLS managers, who worked 12-hour shifts during stimulation. The TLS managers underwent training before the start of the stimulation activities and a user manual was put together to assist them through their task.

The main role of the TLS manager was to monitor seismicity and to give the alert in case of a TLS exceedance. A communication tree was designed to ensure that the different parties were alerted and provided with the right information in due time. The TLS manager had to ensure that the different parties were alerted by phone within 20 minutes of the event and by email within 30 minutes of the event. A more comprehensive report on the event and possible mitigation measures taken by St1 DH was sent out within four days of the event. In order to minimize further the risk of false alert, an automated alert was also sent to all members of the operating team through the Pushover app, when an event of magnitude greater than 1 was detected within the TLS volume, within five minutes of the event. This procedure ensured that the TLS manager had initiated the TLS procedure and that the event magnitude and location was being manually checked if needed.

3.3 Stimulation of the Well OTN-3

The stimulation of well OTN-3 started on 4 June 2018 and ended on 22 July 2018. A total volume of 18,160 m^3 of drinking quality water were injected through five stages, inducing 1,357 $M_L \geq 0$ events. The injection rate was generally set at 400 l/min or 600 l/min and was increased to about 800 l/min for a couple of hours during stage 2. The start times of each stage, net injected volumes, max injection pressures, mean depth and number of events are detailed in Table 1.

A total of 36 alerts were triggered during the stimulation, which were all Amber alerts; the largest magnitude recorded was ML = 1.9. No Red event occurred during stimulation. Three of the 36 Amber alerts happened after the end of the stimulation activities and the latest Amber was a ML 1.21 event, which occurred about 30 hours after the end of stimulation.

Only six of the Amber events resulted in surface motion with PGV >1 mm/s, i.e., the PGV Amber threshold (Figure 4). The lowest magnitude event generating a PGV > 1 mm/s was a ML 1.55 event, which caused a maximum PGV of 1.19 mm/s. The greatest PGV recorded during stimulation was 2.99 mm/s during the ML 1.87 event.

Figure 4 shows that events started to trigger Amber alerts at magnitudes lower than the ones required to exceed the Amber PGV threshold of 1 mm/s. This suggests that the magnitudes associated to the PGV thresholds, established with very limited local seismic data, were slightly conservative, but reasonable.

Table 1: Details of the five stimulation stages.

	Start time	Net injected volume (m^3)	Max injection pressure (bars)	Mean depth (m)	Number of events		
					$M_L > 0$	$M_L > 1$	$M_L > 1.2$
Stage 1	4 Jun 2018 16:30	3,783	890	6056	173	5	3
Stage 2	16 Jun 2018 14:50	4,023	900	5973	280	11	6
Stage 3	23 Jun 2018 23:00	1,537	850	5884	131	8	4
Stage 4	1 Jul 2018 07:30	4,411	860	5771	361	14	9
Stage 5	12 Jul 2018 13:00	4,406	870	5625	412	18	14
TOTAL	**22 Jul 2018 19:00**	**18,160**	-	-	1,357	56	**36**

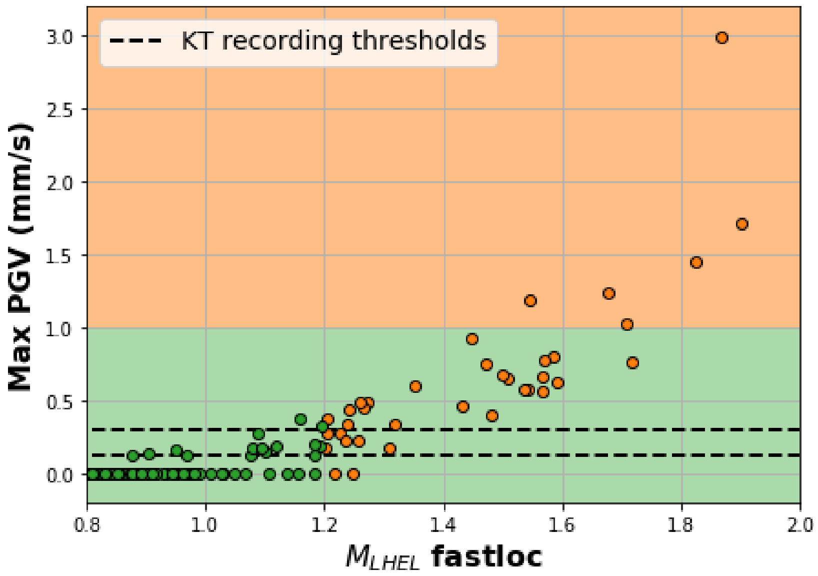

Figure 4: Maximum PGV recorded for $M_L \geq 0.8$ events during stimulation. The dashed lines show the 0.13 mm/s and 0.3 mm/s thresholds of recording at the surface stations.

4. TLS REVISION

4.1 Recorded Peak Ground Velocities

Ground motions were recorded at several stations from the surface network for events of magnitudes ranging from M_L 0.9 to 1.9. Examples of PGVs recorded by the Surface stations are plotted in Figure 5 for M_L 1.2, 1.5, 1.7 and 1.9 events and overlaid on the predictions from the different GMPEs used in the TLS design: the empirical GMPE by Douglas (2013) and the GMPE computed from the GMPE in PGA provided by ISUH (referred to as Fin17 in Figure 5 and hereafter).

The median predictions of both GMPEs usually seem to underestimate the measured PGVs: the measured PGVs systematically plot above the median prediction line of the GMPEs. From the point of view of the TLS design, the uncertainties on both GMPEs used were large, so that the 1-σ uncertainty intervals contain some of the measured PGVs, while the 2-σ uncertainty intervals include all of the measured PGVs for both GMPEs. In other words, the uncertainties on the GMPEs used in the TLS design were large enough to cover the uncertainty on the median value on the measured PGVs (epistemic uncertainty), in addition to the spread of the measured PGVs around their median value (aleatory variability). However, the GMPE should predict the median expected PGV and the measured PGVs should fall equally above and below the predicted PGV.

As detailed in Ader et al. (2019a), once the stimulation of the well OTN-3 was completed, a site-specific GMPEs was developed using the data available by adjusting the GMPE Fin17 (Figure 6). This updated GMPE could then be used to design new TLS thresholds.

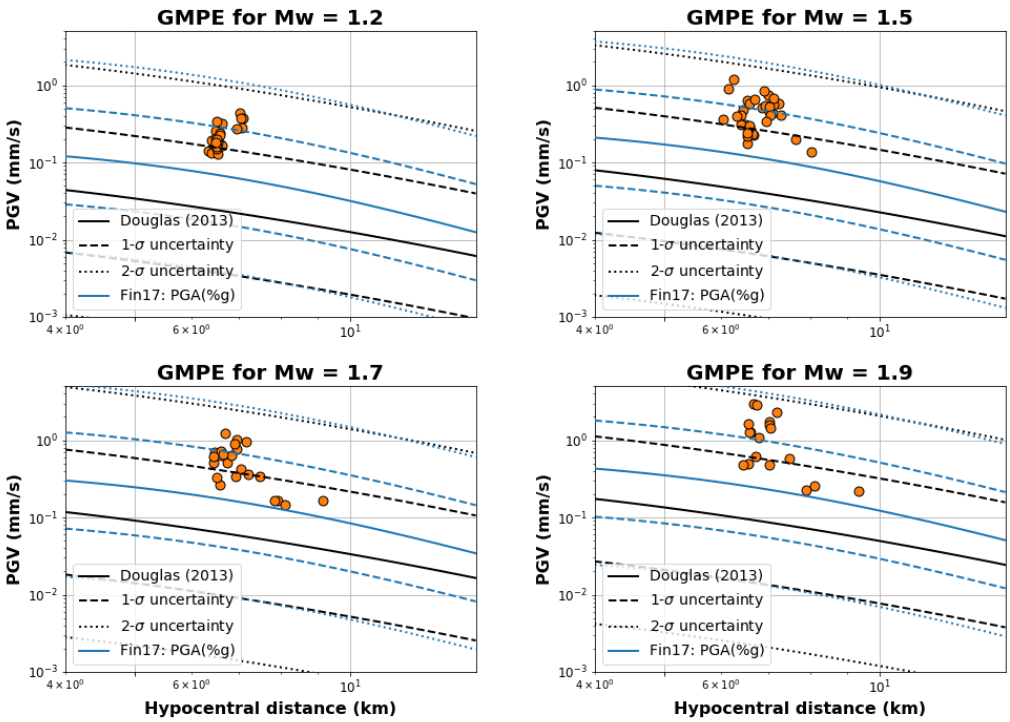

Figure 5: PGV recorded for M_L 1.2, 1.5, 1.7 and 1.9 events. The recorded PGVs are compared to the predictions of the different GMPEs used for the design of the TLS thresholds.

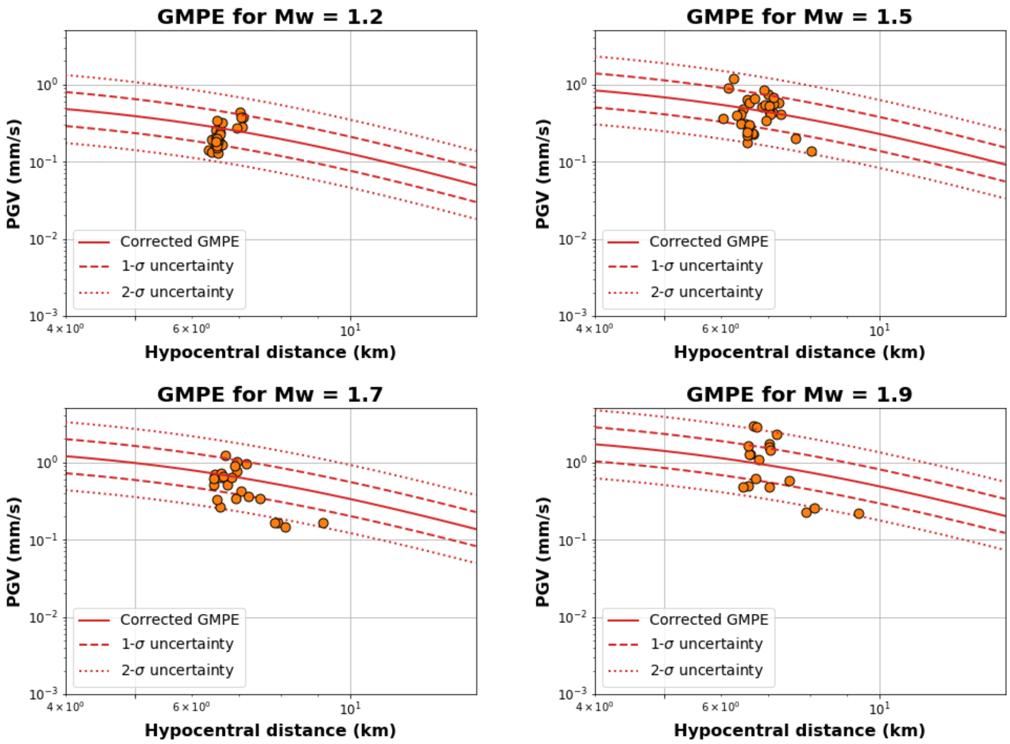

Figure 6: PGV recorded for M_L 1.2, 1.5, 1.7 and 1.9 events, similarly to Figure 5. The recorded PGVs are compared to the predictions of the corrected GMPE (in red).

4.2 Public Perception

During the stimulation, felt induced seismicity could be reported by the local population either to St1 DH or to ISUH. St1 DH received a total of 25 notifications during the seven weeks of stimulation. ISUH also received a total number of 173 notifications from the public, which were logged through their website. The total number of reports recorded by ISUH and St1 DH for each event is plotted as a function of the event magnitude in Figure 7.

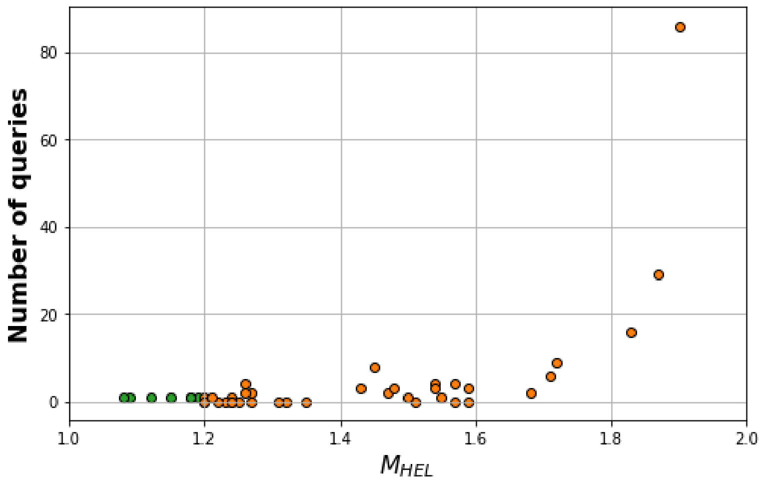

Figure 7: Number of public reports recorded during the stimulation of well OTN-3.

Figure 7 shows that the $M_L > 1.8$ events are the only events for which the total number of reports was greater than ten. The event for which both St1 DH and ISUH received the largest number of public reports was the largest event recorded, i.e., the M_L 1.9 event, which generated 8 reports to St1 DH and 78 reports on the ISUH website.

The reports mentioned that events were usually heard rather than felt and they were compared to distant thunder for magnitudes as low as M_L 0.9. Vibrations were only reported as felt (although very rarely) for events with magnitudes greater than 1.5. The fact that such low magnitude events could be heard is an unexpected feature and is currently under examination.

The $M_L > 1.8$ events have received some press attention, where the content of the reporting was factual and without any apparent negative bias to St1 DH. The press reports also described the events as being heard and sounding like thunder and sometimes observing some window vibrations. The reports indicated that the level of vibrations generated by the events were much too low to create any damage to structures and could not pose a threat.

4.3 Proposed New TLS Thresholds

Based on the new GMPE obtained after the stimulation of OTN-3, it was possible to recalculate new TLS thresholds, following the method used to calculate the initial TLS thresholds (Ader et al., 2019b). The philosophy behind the TLS magnitude thresholds was to tabulate the magnitude thresholds to the probabilities of exceeding the different PGV thresholds and was approved by ISUH.

The probabilities of exceedance for the different TLS triggers presented in the original TLS plan (Ader et al., 2019b) were:

- 2% for the scenario where the TLS alert is based on the combination of a PGV exceedance and an associated magnitude; and
- 10% for the scenario where the TLS alert is solely based on magnitude.

Given the improved confidence in ground motion prediction, it is worthwhile simplifying the TLS plan to magnitude only thresholds, as these are more practical to implement.

Table 2 details the numerical values for the 10% exceedance probability at the three PGV thresholds. The values for the corrected site-specific GMPE are indicated in bold, while the values for the GMPEs used in the initial TLS design are recalled for comparison.

Table 2: Magnitudes with a 10% probability to exceed each of the three PGV thresholds, at the epicenter of an event located at 6km depth.

	10% exceedance probability		
	0.3 mm/s	**1 mm/s**	**7.5 mm/s**
Corrected (2018)	**0.8**	**1.5**	**2.6**
Douglas (2013)	*1.2*	*1.8*	*2.8*
ISUH PGA (2017)	*0.9*	*1.6*	*2.7*

Although the corrected GMPE predicts larger median ground motions than the GMPEs used in the design of the TLS, the uncertainties are significantly reduced. Therefore, the approach based on low probabilities of exceedance yields somewhat similar magnitudes. At 10% probability of exceedance, the magnitudes from the site-specific GMPE are slightly smaller (Table 2). This is because the median of the site-specific GMPE is higher and the 10% probability is still too high for the reduction in uncertainty to compensate for it.

Based on the values presented in Figure 4 (maximum PGVs associated to Amber events during OTN-3 stimulation), Figure 7 (public perception of induced events) and Table 2, the TLS thresholds can be updated based on the following results and observations:

- The 10% probabilities of exceedance of the PGV = 1mm/s and PGV = 7.5 mm/s thresholds are respectively $M_L \geq 1.5$ and $M_L = 2.6$;
- Out of ten events with magnitudes between 1.5 and 1.6, only one resulted in a PGV ≥ 1mm/s ($M_L = 1.55$ with $PGV_{max} = 1.2$mm/s);
- No PGV ≥ 1mm/s was ever recorded for events with magnitude $M_L < 1.55$;
- The fact that, except for one M_L 1.55 event, only $M_L \geq 1.68$ events resulted in PGV ≥ 1mm/s during OTN-III stimulation; and
- The fact that only $M_L \geq 1.8$ events resulted in in more than ten public reports during OTN-III stimulation.

Since the thresholds are based on magnitudes, any PGV exceedance should be reported if an alert is triggered, so that the final updated thresholds would be:

- **Amber** threshold: $M_L = 1.6$, while PGV ≥ 1mm/s should be reported; and
- **Red** threshold: $M_L = 2.5$, while PGV ≥ 7.5mm/s should be reported.

CONCLUSIONS AND RECOMMENDATION

The present work aimed to introduce a methodology to design and implement a TLS for geothermal well stimulation, which would be applicable in data-rich and data-poor environments. The present case, located in the Helsinki area in Finland, started as a data-poor environment, where TLS thresholds were established using global GMPEs and diverse published surface vibration data. We have shown that the method was able to provide TLS thresholds in a data-poor environment, which were well adapted to the seismicity measured during stimulation operations.

The stimulation of the well OTN-3 was extremely well instrumented and a lot of data was generated during the operations. The methodology to evaluate the TLS thresholds was then applied in what had become a data-rich environment. The new TLS thresholds established were only slightly higher than the initial thresholds, demonstrating that the initial thresholds delivered by the method were conservative, but in a reasonable range. The new thresholds also appeared in line with the observations gathered during the stimulation of OTN-3, showing that the method is effective in a data-rich environment as well.

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