Mitigating volcanic hazards on the Reykjanes Peninsula

Lava flows and protection of infrastructure, the Grindavík saga

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Summary

Geological evidence shows that volcanic activity on the Reykjanes peninsula follows a periodical pattern with several decades of dormant periods intercepted by shorter volcanic episodes. In 2021 the first eruption in approximately 780 years happened, marking the onset of a new active period. The greatest activity has been near the town of Grindavík and the geothermal area in Svartsengi. To protect the town and power production installations a vast network of lava deflection barriers has been constructed to protect these locations. The barriers extend over 12 km with a fill volume in the range of 2,4 million m^3. Since November 2023 lava flow from a series of five eruptions have successfully been deflected. Over 10 km of roads have been laid out on fresh lava fields only few days old and a network of central heating hot-water pipes, cold-water pipes and power lines have been successfully restored under very demanding conditions. This paper aims to tell the story of the eruptions and measures undertaken to either protect or reinstate the vital infrastructure, rather than to provide a full scientific account of the situation at hand. As of August 2024, the event is still ongoing, the next eruption is to be expected and the future remains uncertain for the population.

Introduction

Iceland is situated on the Mid-Atlantic ridge that forms the divide between the North American and Eurasian continental plates. The ridge is a divergent plate boundary where the two continents spread apart by roughly 2 cm per year. As the continents drift apart magma flows to the surface feeding a belt of volcanic systems stretching diagonally across the island. Iceland also hosts an additional uplift by a mantle plume that coincides with the divergent plate boundary and forces it into a slight bend. The oldest rock formations are about 15 million years old on the west and the east coasts. The youngest rocks follow the active volcanic belt coming ashore on the Reykjanes peninsula, crossing the central highland to the northeast coast where it connects the Jan Mayen ridge via system of transform faults.

Iceland is in a way an infant with very active geology and associated earthquakes and volcanic eruptions, as well as other natural hazards such as landslides, avalanches, floods, storms, and recently, a variety of climate-change induced hazards. Since 2021 a total of 8 volcanic eruptions have occurred on the Reykjanes peninsula affecting greatly the population, especially in the town of Grindavík.

Reykjanes peninsula

The Reykjanes peninsula is a direct continuation of the Mid-Atlantic ridge. Series of volcanic systems lie along the peninsula in an echelon pattern under a 40-45° angle to the main rift axis. That angle is partly caused by the curvature of the Mid-Atlantic plate divide through the island and is a combination of a rift zone and a transform fault, essentially a leaking transform zone. It is a matter of an opinion how many volcanic systems are to be defined as individual systems along the peninsula and how well they are connected. For the current paper the systems are regarded to be six in total. The volcanic systems appear to follow a periodical behaviour showing active periods of roughly 400–500 years and intersected with substantially longer dormant periods of 600–800 years (Sæmundsson et al., 2013 & 2020). For the past three volcanic cycles at least four of these systems have been active, while the remaining two behave more sporadically. The latest active period on Reykjanes peninsula was from AD ~800–1240, and for the system closest to Grindavík from 1210 - 1240. Large portion of the peninsula are covered by lava formations that have been produced over the last 14,500 years, or since after the glacial retreat.

Inhabitants of the Reykjanes peninsula are ~30,000, with the majority living in several towns on the northwestern part of the peninsula. Grindavík is the only major settlement in the southwestern part with ~3,600 inhabitants prior to the evacuation of 2023 and is the second most valuable fishing harbour in Iceland. The area also hosts the Keflavík international airport and the well-known Blue lagoon geothermal spa. Two major power plants are located on the peninsula utilizing geothermal power and producing electricity and supplying hot water for central heating for the region, one of them in Svartsengi close to Grindavík.

Reykjanes awakening

After 780 years of volcanic quiescence on the Reykjanes peninsula, an episode of seismic and later volcanic unrest started in December 2019 that is currently ongoing. Most of the activity has been concentrated around the mountain Fagradalsfjall and Svartsengi geothermal field. Historically there has been a debate on whether those are to be regarded as two separate volcanic systems or not. The seismic unrest started near Svartsengi 4 km north of Grindavík and later moved towards Fagradalsfjall where the first eruption occurred in 2021 (Sigmundsson et al., 2022). This first eruption went on for over six months with rather moderate or small magma flow of 7–15 m^3/s and became a major tourist attraction. Petrographical analysis showed that the magma originated from a substantial depth of 10–15 km (Halldórsson et al., 2022), while the seismicity around Svartsengi was related to an accumulation in a potential magma reservoir at shallower depths, or some 5 km.

After 14 months of earthquake swarms associated with magma intrusions, possibly at shallow depth and with the general knowledge of the periodical volcanic behaviour of the Reykjanes peninsula, the Department of Civil Protection and Emergency Management of the National Commissioner of the Icelandic Police (NCIP) (hereafter referred to as the Icelandic Civil Defence) put together a team of engineers and scientists to map out vital infrastructure that might be threatened or affected by potential eruption and to portray the possible mitigation methods. The work started in February 2021 with immediate analysis of previous eruption sites, extends of older lava flows, potential lava volume, flow rate and general behaviour of the lavas. Narrowing down the most likely eruption sites, series of lava-flow simulations were carried out by several different methods and a ground plan laid out for barrier system that could compensate a selection of scenarios. The constructability, availability of material and suitable machinery had to be analysed to assess realistic mitigation actions with regards to large uncertainty and most likely a very restricted time frame.

The eruptions at Fagradalsfjall were located well away from any infrastructure and the non-violent behaviour of the first eruption provided a unique opportunity for Icelanders and tourists to witness a relatively small and confined eruption. Although not causing immediate threat to infrastructure, the vast number of visitors caused serious strain on the Icelandic emergency response system as thousands flocked towards the volcano in all weathers. The eruption also provided an opportunity to study the lava flows and to calibrate lava-flow modelling by real-time event. Furthermore, a series of trial barriers were constructed that gave immensely valuable experience for the upcoming events in 2023.

The first eruption at Fagradalsfjall lasted for 6 months. In 2022 and 2023 similar but smaller and shorter eruptions followed. Those required a significant response due to massive tourist interest and widespread moss fires that followed the 2023 eruption.

Increased activity near Svartsengi and Grindavík

On October 24th, 2023, yet another major earthquake swarm started north of Grindavík, with the centre slightly NW of the power plant area in Svartsengi and the Blue Lagoon resort. This area was quite active prior to the volcanic eruption in Fagradalsfjall in 2021, but as events unfolded near Fagradalsfjall in 2021-2023 the Svartsengi area showed much lesser activity. Simultaneously fixed GPS stations showed increased horizontal and vertical displacements indicating ground inflation that were confirmed by InSar satellite data. These events were soon interpreted by the Icelandic Meteorological Office (IMO) and other scientific parties as a magma intrusion that progressed with continuous surface inflation and varying seismicity. On November 10th the seismicity increased significantly along with extensive surface fracturing, subsidence and horizontal displacement in the town of Grindavík. An evacuation was implemented that afternoon although many of the inhabitants of Grindavík had by this time already left town due to the constant unrest. The town has been formally evacuated ever since (in August 2024). In few households the inhabitants have chosen to stay in Grindavík and some workplaces, mainly around the harbour, are still in function.

It has been suggested that these events on November 10th were caused by a major dyke intrusion, extending over 15 km in length and at depth between 1 and 5 km (Sigmundsson et al., 2024). The dyke intrusion caused widespread tectonic displacement in Grindavík, at least ~6-7 fault zones intersect the town, some with a vertical displacement of 1,0 m and horizontal displacement of 1,2 m. A network of open fractures cut through the town, destroying tens of houses, streets and affecting all vital utilities.

During the following weeks following November 10th a continuous surface inflation associated with varying seismic activity was monitored through a vast network of fixed GPS stations that have been in operation on the Reykjanes peninsula. On December 18th, the first of many subsequent eruptions along the Sundhnjúkar crater row began.

Drawing from the earlier preparation work in 2021 and the intensity of the uplift rate and a series of three very recent eruptions in Fagradalsfjall, construction work on lava deflection barriers was commenced on November 10th, the very same day as the major rupturing event in Grindavík. The first and foremost priority was to secure, if possible, the power plant location at Svartsengi which is essentially the only source of geothermal extraction for central heating for the towns spread out on the Reykjanes peninsula. The power plant is set up with geothermal turbines as well with 75 MW electrical generation along with 150 MW of geothermal water. The spill water from the power plant is furthermore the main geothermal water source for the Blue Lagoon geothermal resort situated few hundred meters away. Both installations are sitting in a topographical depression or shallow basin surrounded by lavas formed during the last two volcanic episodes on the peninsula. The magnitude and hastiness of this construction exceeded all conventional constructional and planning laws, requiring a special bill to be passed through the Parliament with great urgency in the days before.

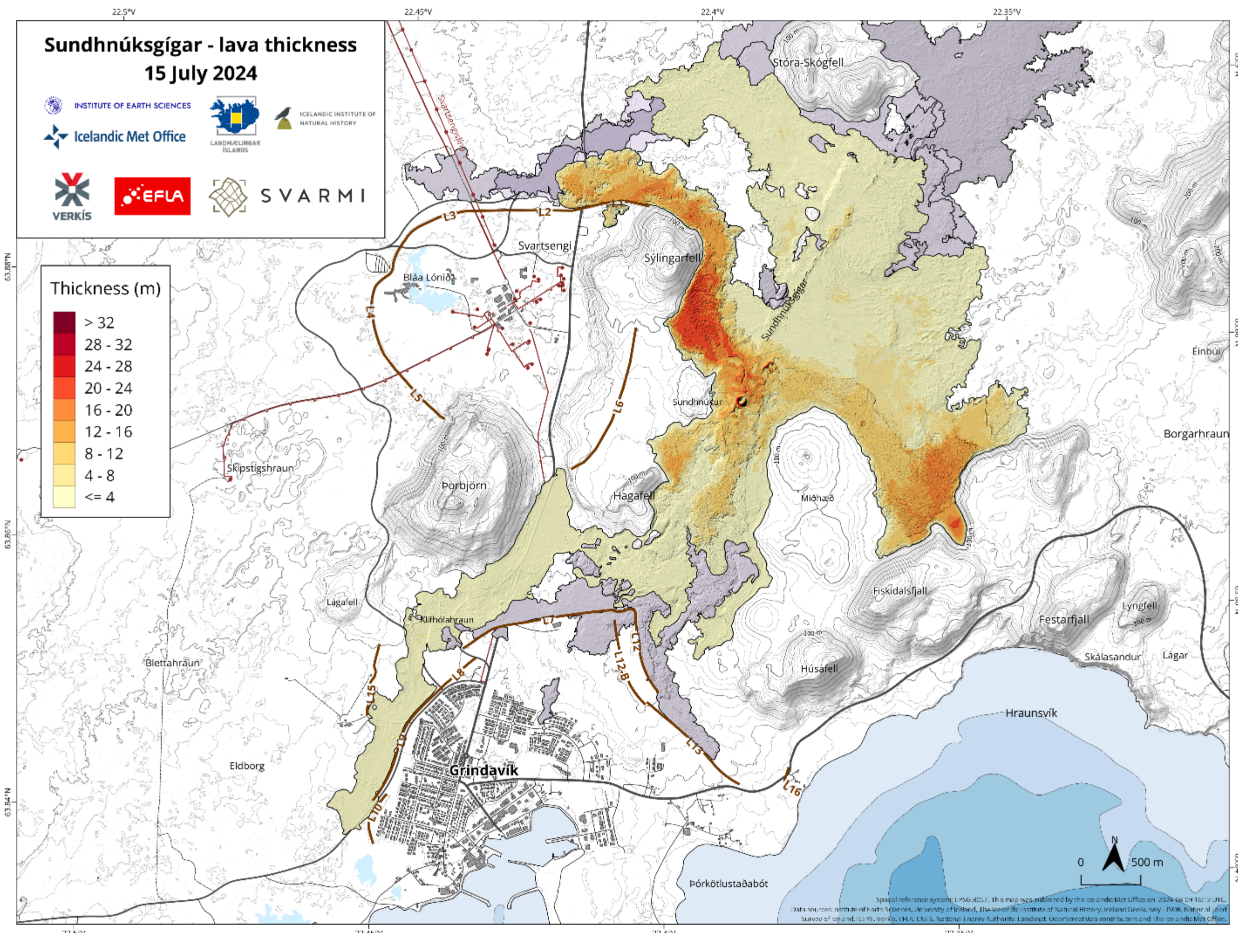

Figure 1. Overview of Svartsengi and Grindavík, status of lava flows in July 2024.

The Svartsengi barrier system

As the focal point of uplift and earthquakes coincided with the power plant location it was not known if the mitigation plans had to consider both previous eruption sites located at Eldvörp and Sundhnjúkar crater rows west and east of the Svartsengi basin, respectively, or each one of them individually. The Eldvörp site was active with at least three eruptions in the Middle Ages from 1210-1240 and the Sundhnjúkar crater row that produced vast lava fields surrounding the town of Grindavík and the power plant site was active some 2,400 years ago.

It became quite evident that the Svartsengi basin had to be defended by series of deflecting barriers covering an almost circular envelope around the basin. As both literature study, lava flow modelling and work on the trial barriers in 2021 had shown, the plan had to be to convey or deflect the lava flow to a lower topographical level where it could spread out and accumulate without affecting the heart of the power plant. By doing so it had to be accepted that other important utilities as roads, power lines, hot-water and cold-water pipes would potentially be overrun by new lava. The barriers around the Svartsengi basin, named L1-L6 extended over 5.5 km with varying height from 8-13 m above the surrounding ground level, see figure 1. Estimated volumes for initial design involved some 600,000 m^3 of earth to be piled up. The "lava" side of the barriers were formed with a slope of 1:1.5 (vertical:horizontal), with a top width of 4 m and an "air" side (leeward) of 1:2. Later this basic form was modified as many barriers were elevated or adjusted to suit the ever changing topography.

The first phase of the construction involved immediate barriers that are crudely piled up to provide a first line of defence along the entire barrier system. The fill material was sourced by large bulldozers from the older lava formation immediately along the "outside" of the barrier line and hauled in from a gravel mine some 15 km away by regular lorries. The initial bulldozed fill extended generally some 3–5 m above the intact ground elevation providing a base for the top fill to be hauled in by dump trucks and placed by large excavators shaping the barriers. The first line of defences was largely completed on December 18th, apart from several gaps or passes in the system where the barriers crossed major roads and utility paths.

December 18th eruption - 2023

This first major eruption on the evening of December 18th proved to be quite dramatic in the opening phase compared to the previous eruptions at Fagradalsfjall. In a matter of minutes, a 4-km-long eruptive fissure opened. The crater line extended from Stóra-Skógfell in the north and towards Hagafell in the south, crossing the tectonic plate boundary but following the same orientation as the Sundhnjúkar crater row which was active 2,400 years ago. In the first few hours the outermost ends receded quite fast and after the first day the lava flow was confined only to centre part of the crater row slightly north of the old Sundhnjúkar main crater. The immediate response was to close the road passes on the barriers closest to the eruption, which was achieved within few hours. But as the first night went off with receding magma outflow it became evident that a direct contact with the barriers or some vital infrastructure was not imminent. On December 21st the eruption ceased with new lava covering an area of 3,5 km^2. Estimated lava volume was 20 million m^3, which is rather small in relation to older lava formations in the vicinity. After an evident ground deflation at Svartsengi during the eruption a distinct uplift was noted immediately, concurring with continued inflation in the magma domain resting underneath Svartsengi, indicating that these events were potentially only the beginning of a larger and more persisting event.

Towards Grindavík – January 2024

Work on the Svartsengi barriers continued towards the Christmas holidays. By that time no decision had been made about the protection of the town of Grindavík. Preparation work with lava-flow simulation and layout design for Grindavík continued along with the barrier construction at Svartsengi. The first plans involved a U-shaped envelope around the town, close to 6.5 km long with a fill-volume of close to 1 million m^3.

With ongoing inflation in the magma domain and the December eruption situated close to the town an order was given to commence construction of the first Grindavík barrier named L7 on January 2nd, 2024, at the northern border of the town. By that time the uplift at Svartsengi had reached similar levels as for December 18th eruption. The barrier started at the watershed northeast of the town and extended 1.7 km diagonally towards southwest crossing the main road to Grindavík. All major utilities as central heating, cold water, power cables and communications followed the same road, resulting in an 150 m open gap in the barrier where it crossed the road. The barrier layout aimed to lead the potential lava flow under moderate gradient towards west, where the road would later be moved to allow for the road to swing by the tip of the barrier through an overlap with next barrier, L8 and a topographical threshold heading towards the town.

An old gravel pit resting under the south slopes of Hagafell had been put in use by this time allowing for much shorter hauling distance and greater fill capacity. With the continued pressure increase in the magma domain a great urgency was put on the work and by the first week of January an immediate first crude barrier line was in place. The northeastern part was substantially higher than the immediate plan called for as the bulldozers could pile up that part easily, whereas fill material to the middle and westernmost part of the barrier had to be hauled in.

The road and pipe crossing called for some special measures as the hot water main to Grindavík was a surface pipe. Since the preceding summer a new hot-water main and cold-water main had been under construction. Both pipes were planned as underground pipes in the same trench, to replace the older surface pipe and a fragile cold-water pipe. As the situation unfolded in October–November 2023, work on the pipes was abandoned due to safety concerns by the privately owned utility company. Work on the pipes was again well underway, the cold-water main had been put in use, while the new hot-water main lay still in the open ditch with only the final touches remaining before the trench could be closed. That was the situation north of Grindavík in the second week of the new year.

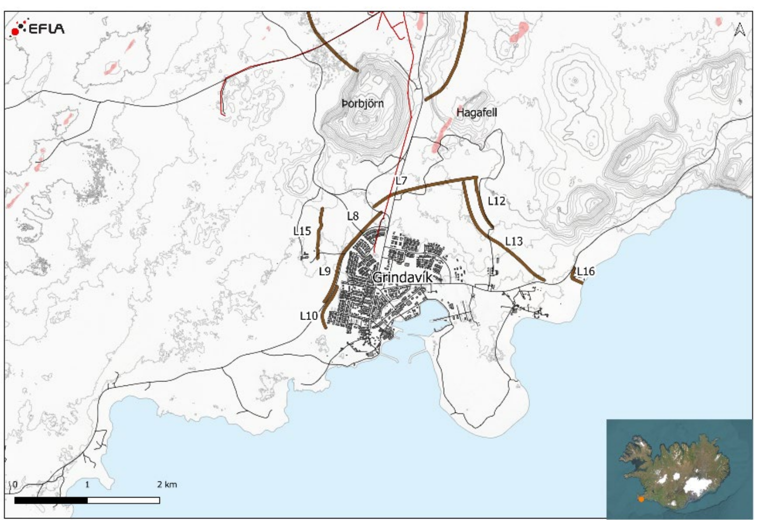

Figure2. The Grindavík barrier system, old volcanic craters shown with red polygons.

January 14th eruption

On Sunday morning January 14th the second eruption started, preceded by early warning signs by increased seismicity, tectonic displacement and increased surface fracturing in Grindavík. This time the eruptive vents were located south of Hagafell on a fissure system slightly east to the fissure system associated with the crater row active in December. The new crater row extended through the L7 barrier southward, with one of the main vents located directly in the barrier. As the barrier defined a flow path with sufficient gradient, most of the lava followed the barrier to the west instead of taking the otherwise more direct path towards the town.

As the eruption started on a Sunday morning the construction team had a rare day off. The construction machinery stood parked on top of the barrier few hundred meters away from the craters, including all the heaviest bulldozers and excavators, which are the most vital components of the machine park. The lava flow was rather moderate compared to what would later be seen in this series of events and the main lava front moved only with a speed of brisk hiking pace. The contractors were obviously eager to get in and save their machines, but the Regional Command Centre situated outside the area and with a limited view of the situation denied that request. After a prolonged communication between the construction site supervision and the Regional Command Centre, and helicopter fly-over to assess the situation the Regional Command Centre granted a permission to save the equipment and start to fill in the gap over the main road, that would otherwise provide an open path for the lava into the town. Work on closing the road gap started immediately with all available machines operating in a confined area with great haste. The final buckets were being shovelled as the lava front reached the road. Again, drawing from the work on the trial barriers in 2021 when work on actively steering the lava front along the main deflecting barrier near Stórhóll gave important lessons in working around the hot moving lava. Soon afterwards the surface hot water pipe broke, but as the pumps had been turned off, there were no steam explosions. To save the cold-water pipes, fire hydrants in the town were opened to allow the water flowing along the pipe to cool off the skin and hopefully save the pipe. Work in the road pass was abandoned when the lava front passed by on the request of the Regional Command Centre, leaving the hastily piled up fill, substantially lower than the remainder of the barrier. As combined result of the lava front interaction with the hot-water pipe and significantly lower fill over the road a minor overflow occurred that could otherwise be most likely be avoided.

During the eruption a small eruptive vent opened inside the town border producing a small lava field that engulfed one house and set two other houses on fire. It has been suggested that the lava travelling laterally along open surface fissures at shallow depth and emerging to the surface only hundred meters from the northernmost houses in Grindavík.

As the day and next night went on, emphasis was put on to pile up an immediate barrier along the northwestern and western border of the town along a road following the outskirts of the town. After some 12 hours the flow rate declined and on the following morning the lava front had come to a rest. The eruption continued, gradually decreasing and on January 16th the eruption was over.

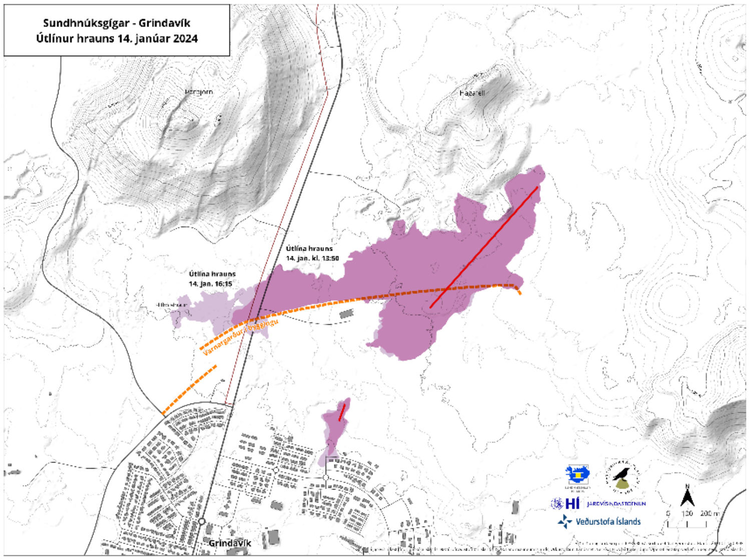

Figure 3. The January lava

January eruption aftermath

This short-lived eruption caused a significant havoc although being rather small in all comparison, covering only 0.7 km^2 and with volume of 2.8 million m^3. The main road to Grindavík was covered by new lava, the town was without central heating and in three days after the eruption the power cables submerged by lava gave away. The cold-water pipe was conveying water, but the minor lava overflow overran the control station for the water distribution destroying it completely. One week later an overhead transmission line had been erected. The new hot-water pipe was connected, and conveying water, but without pressure buildup caused by leaking heat expanders. Few days after the eruption, work on extracting the cold-water supply from underneath the lava started. There were some successes as the pipe conveyed water, but some damages had occurred. In the end an old asbestos pipe lying on the ground underneath the lava was used as a conduit after being cooled down and new pipe fitted through. Work on trying to repair the leaking hot-water pipe was abandoned and a section of older steel pipe was brought in and placed over the surface of the new lava.

The latter half of January entered with rather strange mood for the people on site. The town had now been completely evacuated by the State Police Commissioner under a special clause in the Civil Protection laws, following a fatal accident in the town and a great uncertainty on the status of fault systems and possible hidden fractures og bedrock weaknesses that could potentially collapse and open without warning. There was also uncertainty regarding the continuation of the barrier construction work, if further action to prevent lava from flowing into Grindavík were to be justified and approved by the government. In the meantime, work on completing the Svartsengi system continued along with repair work. Preparations for barriers along the eastern part of the town were made along with plans for elevating the L7 barrier that took on the January lava flow. That involved installing construction roads and loosening materials from the gravel pit by Hagafell.

On February 4th an order was given for continued barrier work with elevation of L7 north of Grindavík and adjusted barrier along the eastern part of the town, named L12 and L13. The eastern barriers followed slightly diagonally and partly through the watershed formed by an 8,500 years old Hópsnes lava formation. The easternmost tip of L7 was cut off to allow the northern tip of L12 to connect into the eastern boundary of the January lava and facilitate a natural pathway for future lava flows that would likely follow the outskirts of the January lava.

Geotechnical issues crossing tectonic fractures

Associated with the January 14th eruption a significant tectonic displacement affected Grindavík. That involved especially the main fissure line which the eruptive vents followed into the town, forming a small graben in the eastern part of the town. The previous displacement associated with the November 10th dyke intrusion formed a 4.5 km wide graben in the western part of the town. Between those grabens is a 200–300 m wide horst formation (De Pascale et al., 2024). Prior to the January eruption measures had been taken to repair some of the most important streets within the town. The most significant faulting system following a known fracture by the name Stamphólsgjá was activated severely during the November event with vertical displacement of 1.2 m, horizontal displacement of up to 1 m and several tens of meter deep. The conventional way in Grindavík and mostly elsewhere in Iceland has been to fill in the fractures after seismic events. As a long-term measure with expected further ground movements that was seen as rather short-lived method. Instead, the most critical crossings were repaired with the aid of geotextiles and reinforced with geonet. After rounding off the bedrock and filling in the bedrock fracture as practicable a layering of reinforcement was placed over the fractures providing a ductile pass way. The main function of the geotextile is to keep the fill material in place and thus providing an arching effect over the fractures. Several of these had been constructed prior to the January displacement and all performed very well providing a safe passage through the town.

Figure 4. Grindavík and the fracture systems, yellow and orange.

February 8th eruption,

At 5:30 on Thursday morning February 8th an intense seismicity started northeast of Sýlingafell along the Sundhnjúkar crater row. About 30 minutes later an eruption started on approximately 3-km-long fissure following similar location as in the December eruption. The lava flow quickly formed a distinctive front towards west and monitoring through web cams and drone surveillance showed the lava front moving quite fast along towards Stóra-Skógfell where it accumulated for a bit before taking a sharp turn towards Svartsengi. The new lava followed a defined channel in a depression formed by the boundaries of two older lava formations. The lava front progressed at a pace of 600–700 m/hr and by 10:17 it had reached the main road to Grindavík, north of Svartsengi. By 12:00 it reached the utility corridor from Svartsengi connecting all towns on the northern part of the peninsula. By 13:30 the lava front reached the maximum extension towards west, then it had travelled some 4.5 km in 6 hours. Simultaneously the eruption receded with lava fountaining confined to three active vents, and the following day, February 9th, the eruption ceased. The February lava covered 4,2 km^2 and with a lava volume of approximately 15 million m^3.

Work on protection measures for the very important hot-water pipe from Svartsengi, which provides geothermal water for central heating for the entire Reykjanes peninsula, started in January. The main pipe was as for Grindavík a surface installation and as such very susceptible to lava flows. As the project stood in February, some 500 m of new Ø700 mm pipe had been laid down in a trench crossing the most obvious depression and potential flow path. Work on the pipe had not been completed and the trench was still open when the eruption began. The construction teams started immediately to cover the pipe with sand and protective gravel fill. As the lava front progressed work on closing the road passages in the barriers also went on. The surface pipe ruptured almost instantly as the lava hit and carried the remainder of the pipe downstream with a great plume of steam rising from the lava. Condition on the new Ø700 mm pipe remained uncertain. Consequently 30,000 inhabitants on the Reykjanes peninsula were without central heating in subzero winter conditions.

The main cold-water supply for Svartsengi power plant is located 3.5 km north of Svartsengi and the pipes follow the same corridor as the hot-water pipes north of Svartsengi. This water supply is essential to operations in Svartsengi as it is the only source of cooling water and after running through heat exchanger it is returned as hot water for central heating, while the remaining brine is discarded. To protect the cold-water pipes under the new lava a continuous flow was maintained to allow proper cooling of the pipes.

A major high voltage overhead transmission line also follows the same corridor, connecting Svartsengi power plant to the main grid. Two of the most exposed transmission towers had been protected by piling up fill material against the towers. To avoid uncontrolled electrical outage the transmission line was shut off temporarily to reduce sagging as the heat flux from the running lava affects the conductors significantly. These measures were essential as by 17:00, when the heat flux had receded, the transmission line was connected again to the main grid without interruption although 6–7 m thick new lava surrounded two towers.

Restoring infrastructure

The largest blow to the infrastructure was the loss of geothermal power supply to the towns on the Reykjanes peninsula, the international airport included. The main road to Grindavík was also cut off resulting in 1-hour-long diversion along the nearest roads. As the lava front slowed, work on a construction road began immediately to connect the work sites on either side of the new lava. It was anticipated that the new Ø700 mm pipe had survived as the pipe had been mostly covered before being overrun with new lava. When the protruding northern end of that pipe was inspected a significant lengthening of the pipe had already occurred buckling the end through the new lava. Geothermal pipes are constructed with heat expanders to facilitate pipe expansion when heated to 80°C. The first alternative was to connect the part of this new pipe, now covered by lava with remains of the older surface pipe. The connection was completed on Friday afternoon, but when water started to run through the pipe the water temperature rose towards 100°C at the north side of the lava, while being pumped in at the other end at 80°C. The flow maintained for few hours until the pipe broke in the evening, rendering hope for a quick repair.

In the subzero temperatures it was foreseen that it would only be a matter of 2–3 days before a significant and widespread frost damages would set in as electrical installation in the towns were not capable of running all households by electrical heating. With ~30.000 inhabitants without central heating, widespread actions were taken to safeguard public and private installations against frost damages as plans were drafted on how to reconnect the hot-water connection over the new lava. On Saturday morning, only 48 hours after the eruption started, a suitable Ø500 mm steel pipe material had been located. Welding and auxiliary crews were mobilized to facilitate a 24 hrs operation on two welding platforms. The pipe would be welded into length of two 250 m sections to be moved over the new lava if possible. The lava crossing was very uncertain as by this time there were only 48 hours since the lava crossed the pipe corridor. After careful inspection and drone surveying a small 17 tonne bulldozer started to level the scoriated surface crust. The crust was about 50 cm thick; surface temperature of the lava was ranging from 200–250°C and through cracks in the crust temperatures over 650°C could be measured at 50 cm depth. The lava surface was quite level, thickest at 7 m and gradually thinning towards either side, with this thickness solidification of the lava takes many months up to a year. The surface crust has a certain bearing capacity, but a liquid core remained underneath. Despite the general believe, the levelling went quite smoothly and after only 2 hours on the new lava the bulldozer broke through. Dump trucks waited on the other end ready to place fill material over the levelled crust scoria. Upon completing a "road" connection over the new lava it became certain that the new temporary pipe section could be pulled over the new lava. By Sunday afternoon the new pipe section was installed and connected to the still surviving parts of the main pipe and run up of central heating commenced.

On the main road to Grindavík a 300-m- long section was now covered by new lava. Drone surveying showed that this part of the lava was only 2.5–3.0 m thick, and therefore expected to solidify in few days. Work on levelling the top started on Saturday and on Sunday a useable construction road was in place. Work on the road continued through the next days, by levelling side areas and finalizing surface course for public use. On Wednesday afternoon, only six days after the eruption started, the road was opened for public use.

March 16th eruption

Along with the infrastructure restoration after the February eruption, work on the Grindavík barriers continued. Inflation of the magma domain showed the same tendency as before; therefore, a new eruption was to be expected within few weeks. The priority was to elevate the L7 barrier north of Grindavík and the barriers at the eastern border. On March 2nd a dyke intrusion occurred without eruption and without affecting magma accumulation significantly. Two weeks later, on a Saturday evening the March 16th, a fissure eruption started at a similar location as in December and February. During the first hours the lava flow was estimated to be 1100–1200 m^3/s. After 3–8 hours the lava flow had receded to 100 m^3/s before settling down to 15 m^3/s on the second day, gradually decreasing thereafter. The lava fronts followed similar paths as before, a western lobe running towards Svartsengi, covering the main road to Grindavík again before coming at rest close to the utility corridor. Another and more significant front flowed south towards Grindavík. That front followed previous formation but were directed by the January crater row and then by the recently constructed L12 and L13 barriers away from the town before halting some 400 m from the coastal road east of Grindavík. The main road to Grindavík was restored 5 days later again over the new lava.

After the initial phase the newest lava covered 6 km^2 and expanded only slightly over the next weeks although its volume increased. The eruption continued until May 8th and was the longest eruption this winter with estimated lava volume of 34 million m^3. When the first intense phase was over and the eruption settled into a similar pace as seen during Fagradalsfjall 2021–23 events, the fluid lava started to accumulate in the near vicinity of the craters. The lava accumulated in lava ponds and large open channels with a gradual building up on top of earlier flows. Lower magma flow from the crater does not sustain lava flow over long distance as with reduced effusion the temperate of the running lava is lowered and with more exposure it loses gases resulting in a more viscous mass. After few days of lava accumulation south of the main vent, a thick viscous and slowly moving lava front approached the north corner where barriers L7 and L12 met. This slow flowing mass carried large blocks of solidified lava, up to 5 m in diameter. On average the crust appeared to be in the range of 3–4m thick. As the lava touched the barriers it stood 3 m above the top and rolled like a belt on a bulldozer along the barriers. Blocks touching the barrier came at rest, while there was a continuous movement further out in the main flow, some 15–20 m away from the barrier. The following days the flow continued by filling completely the precious gravel pit under Hagafell. During Easter holidays another change happened as small lava outlets began to squeeze out higher up in the system along with rising of the surface crust. That development continued downward along the system, indicating that the lava was flowing slowly in connected tube system under the crust. During the second week of April the expansion of the lava had reached the L12 barrier and lifted the few weeks old surface lava even higher than already seen, building up a pile of large blocks some 5 m above the barrier. Still only a one minor overflow resulted by squeezing. At the same time the first geotechnical deformation of the barrier occurred, when a large flat block was lifted by the expansion, scraped the inside slope until standing vertical near the top of the barrier pushing the top outwards. This deformation only affected the topmost 1 m of the 4 m wide barrier top with an expanding lava approximately 5 m higher than the barrier, thrusting the now vertical block outwards like a giant bulldozer blade.

May 29th eruption

On Wednesday May 29th the fifth eruption on the Sundhnjúkar crater row started. The initial phase of the eruption was even more intense than the previous ones. Some estimations have been put forward for lava flow up to 1.500-2,000 m^3/s (Icelandic Met Office, 2023-2024). The lava flow followed similar patterns as before since the main vents were close to the December, February, and March eruption sites. The main flow headed towards Grindavík and was led by the older lava formations and barriers along the northern and western border of the town, while less significant fronts flowed towards Svartsengi and east of Grindavík. The lava flow was extremely liquid and fast flowing and reached the maximum length at 5.6 km west of Grindavík in ~4–5 hours. The immediate effect of this initial phase was that all roads connecting Grindavík from north and west were covered by the new lava, leaving only one major road connection functioning towards east.

As for the March eruption this initial phase receded fast and on the second day of the eruption all fronts were standing still, and the lava started to accumulate close to the craters. Eventually on June 8th the lava accumulation northwest of the main crater succumbed, and a viscous slow-moving front developed towards Svartsengi, taking out the Grindavík main road for the third time on this specific location. As the viscous lava front reached its terminal length, signs of inflation within the lava body higher up in the system appeared. During the next two weeks the lava expanded from within via tube system and rose to an elevation 7 m higher than the barrier it lay against. Eventually the lava boundary gave in, and multiple small overflows squeezed over the barrier. Those were kept at bay with active plugging and steering by fill material and with the aid of water cooling. Luckily the eruption ceased soon after or by June 22nd. Even though the crater went quiet, the lava continued to move gradually over the next days, not coming fully to arrest until June 28th.

In July and August 2024 inflation has continued in the Svartsengi magma domain with expected eruption within the first three weeks of August. Compared to the Krafla eruptions in North Iceland from 1975–1984 it appears that the Grindavík fires can possibly be reaching the final stages. That might be a wishful thinking, but as long as magma is accumulating more eruption must be expected. How many and for how long remains uncertain. The infrastructures in Grindavík and Svartsengi are still functioning and holding out and with each event the mitigating measures need to be adjusted accordingly.

Conclusions

The theme of this meeting is “next generation meeting” and the subthemes of sustainable foundation, digitalization, challenges for the future, construction in urban areas and handbooks or guidance. What can we draw from the past months of our operations on the Reykjanes peninsula that may have relevance to some of these subjects.

Digitalization. This project has been realized mostly without traditional drawings when transmitting the design to construction. The lava flow modelling is highly dependent on accurate topographical models. The topographical models have mostly been sourced by drone surveying both photogrammetric and by Lidar scanning. After finding a suitable barrier elevation and form of the barriers, the model is delivered to the contractor’s cloud service where the operators have instant access to new or updated models. This seamless transfer allows for fast adjustments and adaptability that is badly needed in a constantly changing environment. With the ever-changing topography with each eruption the topographical models need to be updated fast and with great accuracy, mainly by drone surveying. During inflation periods of the viscous slow-moving lavas in the March and June eruptions, the drone surveying has also been vital to recognize the slow movements in the lava fields.

Volcano monitoring, eruption prediction and management of response is obviously very reliant on automation, interpretation of vast data quantities, and remote surveillance. However, there is the danger of remoteness associated with this approach as monitoring operators and command centres are at great distance often lacking communication with the ground, that is both ground personnel and the physical ground conditions. As personnel on the ground may be noticing important signs that are not incorporated in the assessments made at distance. Thereby we are at the risk of missing the trust and understanding between parties that is a crucial part of effective teamwork. Increased compartmentalization in the science community and within the response system may also contribute to misunderstanding as different entities are putting their narrow understanding forward that might shadow a more generalized view of the situation at hand.

Challenges for the future and construction in urban areas. In Iceland we already see present and future challenges related to climate change in both rural and some urban areas. with increased frequency and size of eruptions, landslides, and glacier outburst floods, as well as sea-level changes due to retreating glaciers on local and global scales. In addition, we have now a very definitive situation of a new volcanic episode that has started on the Reykjanes peninsula where we have the highest population density. We have large urban areas placed on lava fields that are relatively young. If we were to compare frequency of lavas flows to landslide and avalanches, we would most likely limit or not allow inhabitation on those areas. The great question is how do we move on? Do we need to restrict further urban development within such areas, or are we going to accept the situation as is and rely exclusively on monitoring and mitigation measures as have been carried out for Grindavík and Svartsengi in the past months? It all come down to the value of acceptable risk which is at presently being evaluated. Central heating for the region is obviously too reliant on one source, alternative sources must be incorporated, either by low temperature harnessing or strong connection to the Reykjavík area.

Handbook and guidance. Familiarize yourself with the terrain! Engineering is in many ways based on a trial and error, to be moulded and adapted into practical theories and methods. There are no applicable handbooks on how direct lava flows or to interact with running lava or how to lay roads or other utilities on a fresh lava. In a way we must gain that experience in the field through the sole of our boots and have the courage to pioneer something that would look absolutely ridiculous in the eyes of the general public or safety managers in industrial complexes used to a very controlled work environment. At the same time, we need to study previous historical undertakings and experiences achieved, constantly learning and adapting. In the end, fresh lava is just a material that we need to learn to work with and around.

We also must maintain a strong focus on the task ahead and not loose sights in all the digital and physical noise surrounding us. There is a good chance that Grindavík and Svartsengi can be protected. If we were to compensate for all possible outcomes that have been suggested, the situation would be near unrealistic. We can only cover the most likely scenarios, but those must be done at full steam, any half-hearted attempts are not likely to secure a positive outcome.

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