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RESEARCH ARTICLE

Experience in diverting and containing lava flow by barriers constructed from in situ material during the 2021 Geldingardalir volcanic eruption

Fjóla G. Sigtryggsdóttir[1] · Hörn Hrafnsdóttir[2] · Jón Haukur Steingrímsson[3] · Ari Guðmundsson[2]

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Abstract
The 2021 Geldingadalir eruption in the Mt Fagradalsfjall Volcanic System within the Reykjanes Peninsula volcanic zone was the first eruption on the peninsula in about 800 years. Prior to the eruption, increased earthquake activity and signs of magma intrusion indicated a volcanic threat to populated areas and important infrastructures. Preliminary design principles were developed for protection works comprising lava barriers, earthen diversion barriers, or dams, respectively, for diversion or delaying lava flow. During the 2021 event, three dams were constructed from in situ earth material, along with a 300-m-long diversion barrier, accompanied by a short 35-m diversion barrier. The barriers constructed reflected the site conditions, available material, and equipment. The article describes the dam construction and the experience in securing the construction site, as well as diverting, containing, and delaying lava flow by the different barriers, for potentially reducing/delaying downstream effects. The importance of considering the lava type in the design of lava barriers is highlighted. ʻAʻā lava thickened considerably behind a barrier with influx of fresh lava under chilled outer crust, while sheets of pāhoehoe lava accumulated and eventually overtopped or bypassed it. Generally, pāhoehoe lava creeping slowly over barriers did not cause erosion or damage. However, pāhoehoe lava could cause failure on a downstream slope in the case of weak dam tops of loose material. The dams delayed lava flow, one of them by up to 16 days, and the diversion barriers diverted lava effectively. The lessons learned were valuable for constructing lava defences in subsequent eruptions closer to populated areas, starting in 2023.

Keywords Eruption · Earthen barriers · Lava flow control · Pāhoehoe · ʻaʻā · Infrastructure safety

Introduction

The Geldingadalir eruption in the Mt. Fagradalsfjall Volcanic System within the Reykjanes Peninsula (RP) volcanic zone in Iceland (Fig. 1) started on March 19, 2021. The eruption was the first on the RP in 781 years (Sæmundsson et al. 2020). Prior to this, increased earthquake activity and signs of magma intrusion had warned of volcanic eruption (Greenfield et al. 2022; Sigmundsson et al. 2022). These warning signals prompted, on March 10, the Department of Civil Protection and Emergency Management (the Civil Protection) under the National Commissioner of the Icelandic Police to establish a group of engineers and scientists, the Infrastructure Protection Group (IPG). The IPG was assigned the task of evaluating infrastructure protection and potential mitigation measures. This became valuable during the eruption for the construction of barriers to divert or temporarily contain the lava flow. The decision to build the barriers was made by the Civil Protection. The construction sites were unusual, not only due to the proximity to an active crater (vent 5 in Fig. 1) and a lively lava field (Eibl et al. 2023; Lamb et al. 2022; Pedersen et al. 2022) but also due to the high tourist traffic (Barsotti et al. 2023; Langridge & Michaud 2023).

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✉ Fjóla G. Sigtryggsdóttir
fjola.g.sigtryggsdottir@ntnu.no

[1] Department of Civil and Environmental Engineering, Faculty of Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

[2] Verkís, Reykjavík, Iceland

[3] Efla, Reykjavík, Iceland

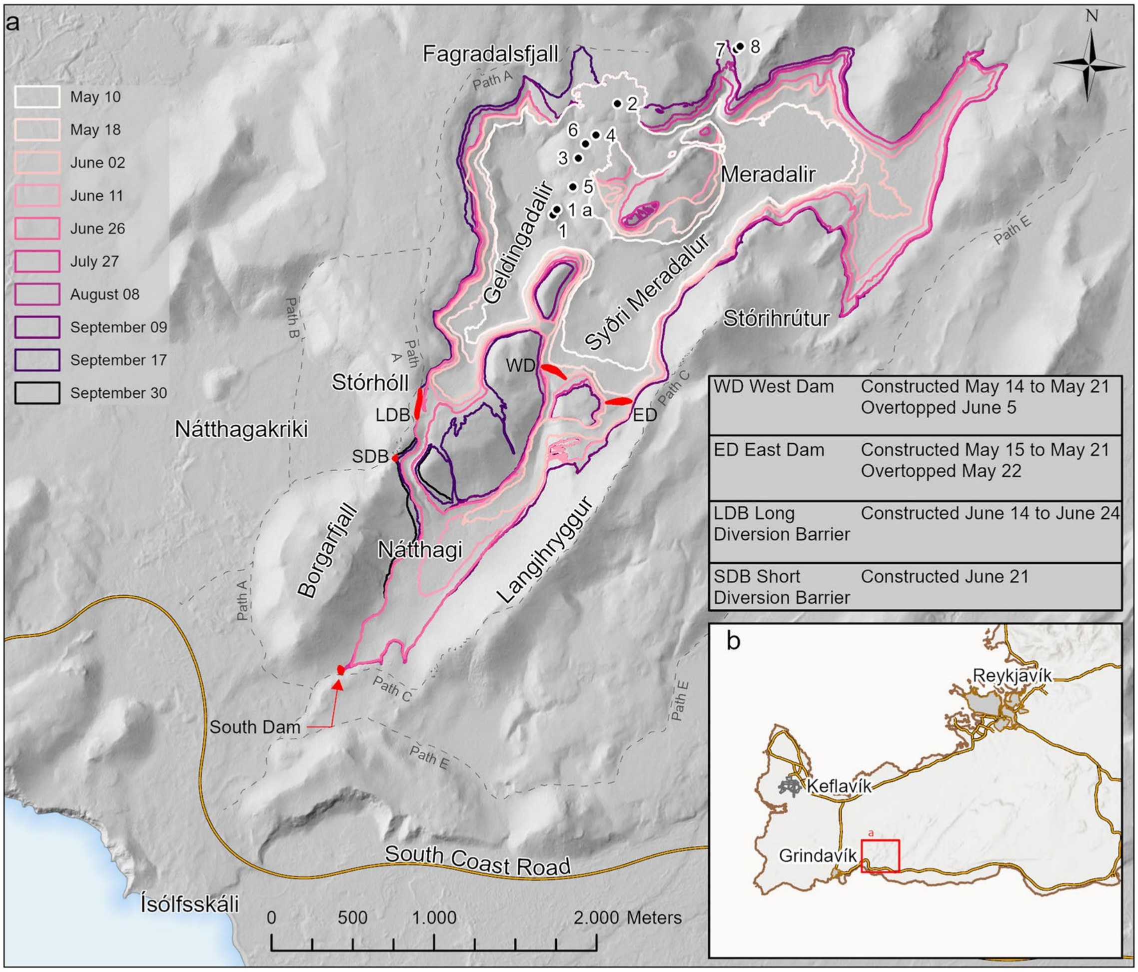


Fig. 1 Map of the lava field and location on the Reykjanes Peninsula. (**a**) The new lava field extent of the 2021 Geldingadalir eruption, from ten surveys in the period May 10 to September 30, and overview of dams and diversion barriers constructed to protect infrastructure, such as the South Coast Road. The vents of the 2021 eruption are labelled 1 to 6. Hiking trails are labelled Path A, Path B etc. (**b**) Map of the Reykjanes Peninsula. The red box indicates the area displayed in (**a**). Data source: The base map is based on data from the National Land Survey of Iceland (www.lmi.is), the IcelandDEM. The lava outlines are from the Icelandic Institute of Natural History (also available at www.lmi.is)

Lessons from past lava mitigation measures

Prior to the 2021 eruption, a literature review of past lava flow mitigation measures was initiated. The attention was on barriers to divert or contain lava, while past lava flow mitigations also include cooling of lava (Williams et al. 1997), aerial bombing of lava flows (Lockwood & Torgerson 1980), lava diversion channels (Colombrita 1984), and interventions at lava skylights aimed at redirecting the lava flow by blasting opening in lava channel levees as well as plugging lava tunnels with large concrete blocks and more (Barberi et al. 1993).

The case histories studied on barriers subjected to lava flow originated from Hawaii (Macdonald 1958, 1962), Italy (Barberi et al. 1993, 2003; Colombrita 1984), and Iceland (Jónsson 1992). Reports on proposed barriers such as this by Moore (1982) were also reviewed. In these case histories, the word “barrier” is normally used regardless of the function of the defence; however, Jónsson (1992) uses the word “dike” for a barrier built for diversion. Macdonald (1962) uses the word “wall” as well as “barrier”. In the present paper, the word “barrier” will be used as a general term, not specifying the function of the structure. The word “dam” will be used if the intended function of the barrier is to contain and delay lava flow, while the term “diversion barrier” is used when the barrier is to divert the lava flow. Additionally, the word “heap” will be used for the barriers created when a bulldozer pushes material into an elongated heap of earth or rubble.

Lava flow is gravity-driven and thus influenced by topographical features (Hinton et al. 2019; Rumpf et al. 2018; Saville et al. 2022). On flat ground, the lava flow tends to spread out and accumulate, while lava flowing downhill under the influence of gravity will follow lows in the landscape along the steepest descent paths (Kauahikaua 2007). Simulations of measures to control lava flows, numerically (Fujita et al. 2009) as well as in the laboratory (Dietterich et al. 2015), demonstrate that barriers can successfully change the direction of a lava flow, particularly when placed obliquely to the lava flow. The results from the numerical simulation by Fujita et al. (2009) of the 1986 Izu-Oshima eruption also indicate that a barrier can successfully change the path of the lava flow, and is more effective when aligned nearly parallel to the flow direction at a point where the topography is not very steep. Still, a sufficient slope of the land surface is needed for a successful diversion, as Macdonald (1962) emphasizes. Also, the literature review of case histories revealed that the diversion of lava flow has been successful on a steep downhill slope, such as in Etna, Italy, as described by Colombrita (1984), Barberi et al. (2003), and Scifoni et al. (2010), while Macdonald (1958) reports on flat terrain not being favourable for lava diversion in relation to the 1955 Kilauea eruption, Hawaii. Furthermore, dams have been used to contain and/or delay the flow of lava, with some success, such as in Etna, Italy (Barberi et al. 1993) and the Westman Island, Iceland (Jónsson 1992). However, as the eruptions continued, the dams were either overtopped (Barberi et al. 1993) or breached by the lava (Jónsson 1992; Macdonald 1962). Some of the historical cases (Jónsson 1992; Macdonald 1958, 1962) report of the thickening of lava behind barriers. Macdonald (1962) reports of pāhoehoe lava flow margins standing 1 to 3 m above the crest of a barrier, while Jónsson (1992) describes ʻaʻā lava margins standing up to 25 m above the crest. The design of barriers requires the definition of loads. Scifoni et al. (2010) present loads on a gabion barrier containing lava flow. They provide expressions for the lava pressure and define the forces resisting this, i.e. the barrier's weight and friction against the foundation.

The 2021 eruption

At the onset of the 2021 eruption, lava flow was not considered to pose an imminent threat for populated areas or important infrastructure. The closest populated area, Grindavík, is located 8.5 to 10 km to the southwest of the eruption site (Fig. 1b). Important infrastructure nearby included a road, the South Coast Road (Suðurstrandavegur) (Fig. 1), about 3.5 to 4.5 km to the south of the eruption site, as well as buried fibre cables mostly aligned along the road. Additionally, a house (Ísólfsskáli in Fig. 1) was located about 4.6 km south of the eruption site, and a geothermal power plant as well as a popular bathing resort about 8 km to the west.

As the eruption continued, basaltic lava discharged into adjacent valleys, switching from one valley to another as described by Pedersen et al. (2022). Figure 1 shows the lava expansion with outlines of the lava field at specific dates. The eruption was characterized by multiple vents (labelled 1 to 6 in Fig. 1) with phases of stable activity and episodic activity. The mean bulk effusion rate was 9.4 ± 0.2 m^3/s from March 19 to the end of the eruption September 18, 2021 (Pedersen et al. 2022). The eruption produced a spectrum of lava textural types, including pāhoehoe and ʻaʻā lavas (see Fig. 2) as well as hybrid types (Bindeman et al. 2022). Throughout the eruption, lava flow was simulated with MrLavaLoba (de' Michieli Vitturi and Tarquini 2018) as reported by Pedersen et al. (2023) and by the use of HEC-RAS (Gudmundsson et al. 2021). By the end of the eruption, the bulk volume of the entire lava flow field (Fig. 1) was estimated as 150×10^6 m^3 (Pedersen et al. 2022).

The first concerns for infrastructure safety were raised when the lava flowed out of Geldingadalir Valley (April 16) into the Syðri Meradalir Valley (SM Valley), with a direct flow path through Nátthagi Valley and towards the South

Fig. 2 Pāhoehoe and ʻaʻā lava fronts in the SM Valley on May 8, 2021

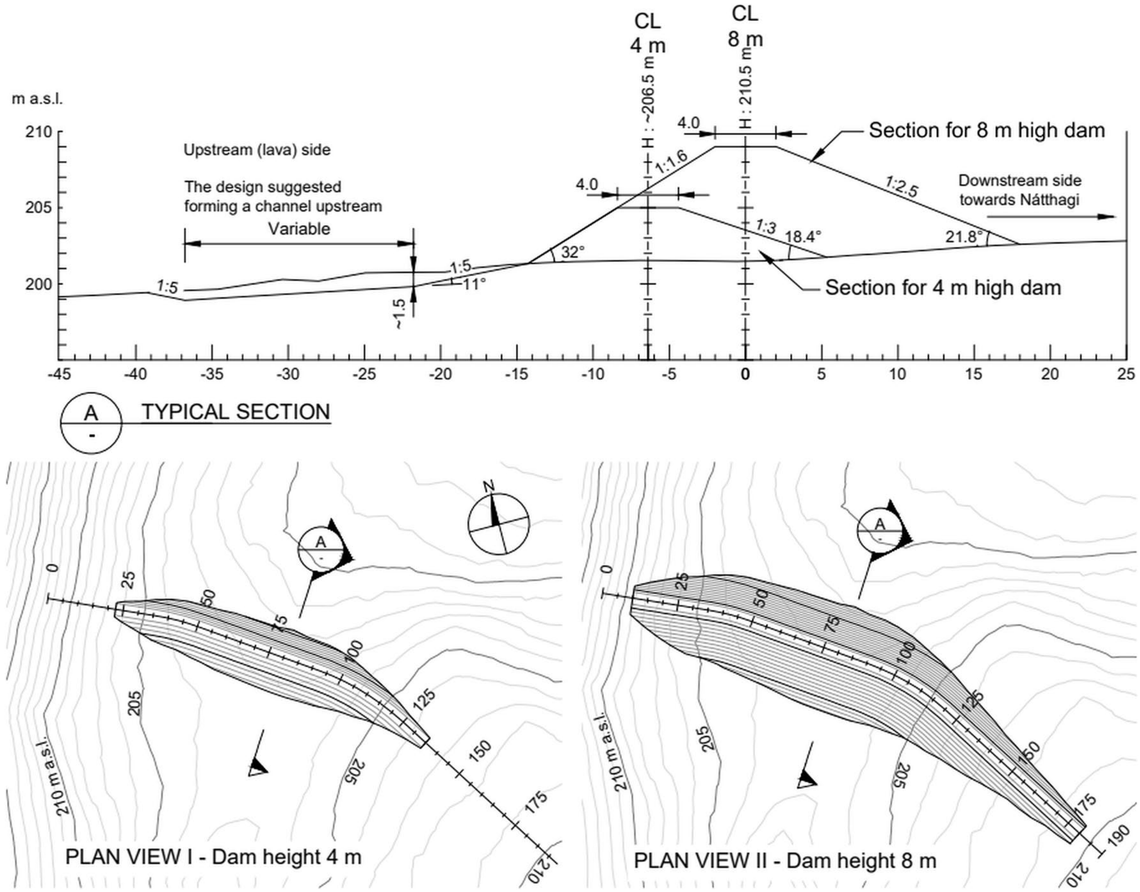


Fig. 3 The geometry the West Dam in the SM Valley, according to the preliminary guidelines. Typical cross section (A) and plan layouts for 4 m high (Plan view I-Phase I) and 8 m high (Plan view II-Phase II). Data source: The base map is based on data from the National Land Survey of Iceland (www.lmi.is), the IcelandDEM

Coast Road (Fig. 1). It was desirable to keep the road open for as long as possible, and preparations to delay the lava flow with barriers were initiated. Sites for two dams, called the East Dam and the West Dam, were selected at the mouth of the SM Valley, above Nátthagi (Fig. 1). Drawings were made (Fig. 3) for two construction phases, with 4 m and 8 m high dams for phases I and II, respectively.

The construction of the dams started on May 13. The construction and lava flow incidents are described later. The East Dam was overtopped on May 22, and the West Dam on June 5. The resulting lava flow headed to Nátthagi. This prompted the third dam, the South Dam in Fig. 1, to be built in Nátthagi to protect the South Coast Road. The South Dam was partly planned as a research object with instruments such as load cells, height scales, and reference points monitored with cameras to record lava thickness over time. However, the South Dam was not subjected to lava flow during the eruption.

During the first weeks of June, the lava continued flowing into the surrounding valleys. The pileup of lava in Geldingardalir Valley raised concerns for potential lava flow down to Nátthagakriki (see simulation of the lava flow by Pedersen et al. (2023)), as this could eventually reach Grindavík in the case of a prolonged eruption. Proposals for lava diversion were presented on June 14 and the construction started the same day. Two diversion barriers were constructed (Fig. 1), the Long Diversion Barrier along the ridge of the hill Stórhóll and the Short Diversion Barrier crossing a hiking trail in the saddle between Stórhóll Hill and Borgarfjall Mountain. The trail had been constructed for tourists visiting the eruption site. The construction and lava flow incidents are described later.

Hence, by the end of the eruption, three dams and two diversion barriers had been constructed (Fig. 1). It is important to note that while the diversion barriers along with the East Dam and West Dam were considered experimental, these measures were unfortunately not planned and carried out as a research project. Thus, data was not collected to the detail needed for scientific analysis, such as the lava flow advance rate towards the dams, piling of lava with time against the barriers, measurements of lava pressure, and placement and properties of different materials in the barriers. Still, the work and the experiences reported in the present study bring forth important lessons. These became of value for constructing lava defences for the town of Grindavík (Fig. 1) and a nearby geothermal power plant prior to and during a series of volcanic eruptions, the Sundhnúkur Fires, starting in December 18, 2023 (Troll et al. 2024).

In the following, the defences built during the 2021 eruption are described, and the construction methods, construction process, lava flow incidents, and lava interaction with the barriers are reviewed along with lessons learned.

Collaboration, design, construction, and monitoring methods

This section shortly outlines collaboration, highlights the main points from the design guidelines, and describes the construction equipment, material, and methods employed as well as monitoring with webcams and drone surveys.

Collaboration and decision-making

The IPG held regular online meetings during the eruption, which could be convened at short notice. The communication with the Civil Protection was through the project manager. By the time it was decided to build the barriers, available construction time was already limited as the lava field was growing rapidly. This, among other things, resulted in that decisions and changes at the construction sites, that needed to be taken quickly, were made by the site engineer.

Design guidelines

Lessons from past historical cases were incorporated into preliminary guidelines that were also based on relevant national civil design standards. The design guidelines assumed a dam subjected to an ʻaʻā like lava front, as this was considered to represent the highest load on a barrier. It was recognized that a barrier planned for diversion might, depending on the direction of the lava flow, take on the function of a dam, particularly on flat terrain. Equally, a barrier planned as a dam might also divert lava.

The design drawing, Fig. 3, of the West Dam, also applied for the East Dam. The drawing proposed the minimum cross-section from the preliminary guidelines in the case of limited construction material at the site. The minimum cross-section was intended to provide sufficient resistance against lava pressure from its weight. Still, the guidelines recommended a wider crest and cross-section to enable two-way traffic of construction equipment on the dam, as well as to be able to increase the dam height faster, if needed. Colombrita (1984) recommended, for example, a wide cross-section for these reasons. In Fig. 3, the dam is placed with its foundation inclined upward towards the downstream, requiring a larger force or pressure from the lava to cause sliding of the dam body compared to a dam placed on near horizontal foundation.

The guidelines recommended compaction of the material for denser structure (increased weight), and incorporated recommendation by Macdonald (1962) for a gentle downstream slope to reduce potential erosion during lava overflow. The guidelines also included Macdonald's (1962) advice to form a channel along a barrier upstream (Fig. 3), thereby enhancing lava diversion by creating a path free of obstacles that could otherwise disturb the lava flow. Moore (1982) similarly recommended to create the most favourable lava flow conditions with a deep and wide channel on the flow-ward side of diversion barriers.

Construction equipment and supervision

The construction equipment employed comprised two bulldozers (CAT D9R and CAT D10T), one excavator (Volvo EC250EL), and one vibratory roller (Hamm H13 ix). The bulldozers were used to push soil material in place while the excavator was used to dig, replace, and handle the material. The purpose of a vibratory roller is to compact soil material to increase both density and stability, in the absence of the roller, the bulldozers were used to compact the soil as possible. Not all the equipment was available throughout the construction of the dams and diversion barriers. For example, one bulldozer (CAT D9R) and one excavator (Volvo EC250EL) were available for the construction of the diversion barriers.

The construction work was carried out by a local contractor under the supervision of a site engineer. Altogether, five engineers took shifts at the different construction sites, usually only one on each shift.

Construction material

Overburden comprising aeolian soil and well-graded volcanic gravel sand was the main building material for the West and East Dams. Organic topsoil was taken aside as much as possible; however, it found its way into the dams. Pillow lava ripped at the site was a source for additional material when the overburden was depleted.

Overburden (aeolian soil and well-graded volcanic gravel sand) was plentiful at the Short Diversion Barrier site, however sparse at the Long Diversion Barrier site. Available overburden was used in the north and uppermost end of the Long Diversion Barrier, whereas much of the fill in the lower part of the diversion barrier comprised coarse material of ripped basaltic rock/rubble.

Soil samples were taken, both in situ and as placed, and tested in the laboratory for material properties such as unit weight, moisture content, and grain size distribution. The unit weight of samples taken from the overburden material placed in the East and West dams was respectively 19.4 kN/m^3 (1978 kg/m^3) and 17.2 kN/m^3 (1753 kg/m^3) (average of three samples). However, the results are only indicative as the material and the compaction varied within the dams. The material properties of the ripped basaltic rock and pillow lava were not tested, but Icelandic pillow lava generally has density in the range of 17–21 kN/m^3 (1733–2140 kg/m^3).

Construction methods

A standard procedure to temporarily secure a construction site involved using bulldozer to push overburden (same type of material used in the dams) into elongated heaps against the advancing lava front. The method was also employed in emergency situations when lava flowed towards the construction sites.

The construction methods were adapted to the conditions and available material at each barrier site. The construction was fast and relatively easy at sites where available volume of overburden was abundant. Generally, the bulldozer pushed the material directly up the barrier slope and the excavator, located on top of the barrier, generally placed the fill, and formed the top part. The excavator and the bulldozer drove back and forth over each layer of fill, providing compaction of the material, as much as possible with this equipment.

Initially, it was intended to employ material on the lava side of all the proposed barrier sites, considering availability of construction material as well as that construction scars in this area upstream the barriers would most likely eventually be covered by lava. Simultaneously, a channel for the lava flow would be formed (Fig. 3). However, in all cases, the lava fronts had advanced too close to the dam/diversion barrier sites when the construction started, resulting in most of the material having to be taken from the downstream. On the positive side was a safer work environment for the construction workers when working from the downstream, i.e. further away from the lava front as opposed to working from the upstream, i.e. between the dam and the lava field.

Monitoring

During the construction of the barriers, 3D drone surveys were carried out to track changes in the geometry of the dams and the progression of the lava. The time interval between surveys ranged from 1 to 3 days for the dams, and weeks to months for the diversion barriers. Hence, for the East and West dams and associated emergency heaps, drone survey data is available once per day on May 18, 21, and 22, while for the Long and Short Diversion Barriers, surveys were similarly carried out June 26 and September 17 and 24. Additionally, measurements of the whole lava field on certain dates, as shown on Fig. 1, are available from the National Land Survey of Iceland (Umbrotasjá, n.d.).

The drone surveys of the dams were carried out by Svarmi Ltd using DJI M300 drone equipped with DJI Zenmuse P1 full-frame camera with 45 MP sensor, while Efla Ltd surveyed the diversion barriers. Photogrammetry was used to create the 3D models in the software Agisoft Metashape for the dams and Trimble UASMaster for the diversion barriers. The accuracy of the 3D models is about 0.06 to 0.09 m vertically for the dam site, while for the diversion barriers site, it is reported as 0.12 m vertically. Horizontal accuracy is higher, or about 0.07 m. The Civil Protection and the Icelandic Meteorological Office (IMO) installed a network of webcams to monitor the eruption site. Images from the IMO webcams were uploaded to a dedicated website with restricted access, while the images from the webcams operated by the Civil Protection were sent via FTP to a server and copied to a website available to the public. Barnie et al. (2023) describe the networks and the webcams in detail. A webcam operated by IMO was installed at the west end of the West Dam on June 2. The camera successfully captured a still image every minute of the lava overtopping on June 5 until the camera was itself buried under lava. Furthermore, IMO operated one webcam installed at the west end of the Long Diversion Barrier that captured still images about every 10 min of the lava flow towards the diversion barrier on September 15, but every 5 min on September 17. Additionally, two cameras operated by the Civil Protection overlooked the construction site of the Long Diversion Barrier, from more than about 0.6 km, and captured a still image every 10 min.

A camera was neither installed at the East Dam nor the Short Diversion Barrier, although this was requested. Conversely, the South Dam was extensively instrumented as previously mentioned, but lava had not reached the dam when the eruption ended.

The eruption site was additionally monitored by different video webcams operated by the media with direct streaming and included one located on Langihryggur that occasionally overlooked the construction site of the West and East dams, but from about 0.7 km. The webcam on Langihryggur was operated by Ríkisútvarið (RÚV), the Icelandic National Broadcasting Service (RÚV, n.d.). Finally, tourists visiting the eruption also provided valuable information by uploading photos and videos on the internet.

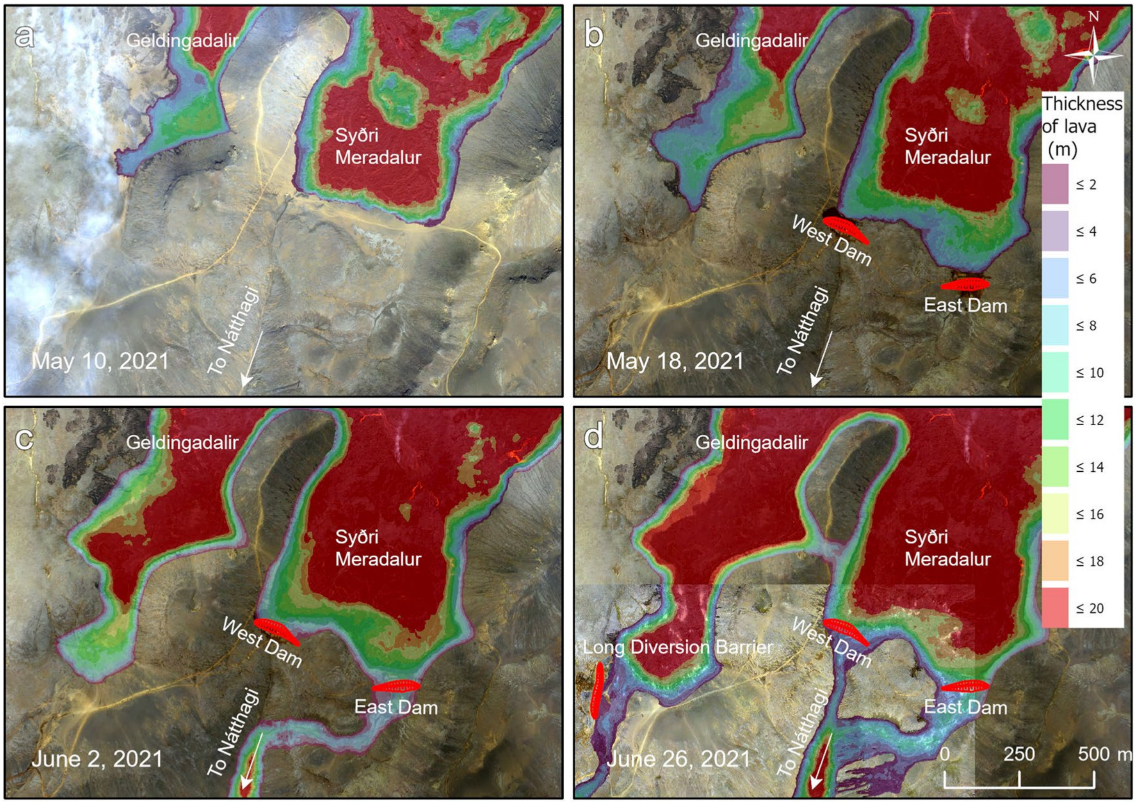


Fig. 4 Status of the lava flow and thickness, and construction of barriers. (**a**) May 10, 2021. (**b**) May 18, 2021. (**c**) June 2, 2021 and (**d**) June 26, 2021. The West Dam and East Dam (constructed from May 13 to 21, 2021) and the Long Diversion Barrier (constructed from June 15 to 24, 2021) are sketched as per the design proposals. Data source: The base map is based on data from the National Land Survey of Iceland (www.lmi.is), the IcelandDEM. The lava surfaces are from the Icelandic Institute of Natural History

Construction process and lava flow incidents

This section describes the construction of the dams and diversion barriers and the interaction with lava during the construction. Figure 4 shows the expansion of the lava field and lava thickness in the area of the dams and the Long Diversion Barrier on four different dates. Figure 4a shows the status on May 10, 3 days before construction started.

All the dams and diversion barriers were subjected to pāhoehoe lava flows, while some of the heaps were also subjected to ‘a‘ā lava fronts. The viscosity of the lava flows was not measured as part of the present study, but the pāhoehoe lava flows referred to below were visually deemed of low viscosity which agrees with the report of Soldati et al. (2024) on measured viscosity at different locations during the eruption. The speed of the lava flow referred to below is similarly based only on visual observations. The lava flow is described verbally, such as with “slow” or “fast” lava, with rough estimates of the velocity provided in parentheses.

The construction of the West and East dams is intertwined as focus shifted between the dams, mainly due to lava flowing into the dam site and the limited availability of construction equipment. The timeline in Fig. 5 provides an overview of the construction and lava incidents at the dam sites, as well as of the available equipment. Furthermore, available equipment and the shifts of four different site engineers (E1 to E4) during the dam construction are presented in Fig. 5. In the following, the construction of the two dams is described separately, followed by a description of the construction of the diversion barriers.

The West Dam

On May 13, the site for the West Dam was temporarily secured as the bulldozer pushed overburden into elongated heaps, 2 to 3 m high, against the ‘a‘ā lava front. The construction of the West Dam started the following day, May 14 (Fig. 5). By the early afternoon of May 15, the first phase (Phase I in Fig. 3) was completed, with the crest elevation reaching 205 m a.s.l., resulting in about 4-m high dam with about 7 m wide crest, seen in Fig. 6b and c from the May 18 drone survey.

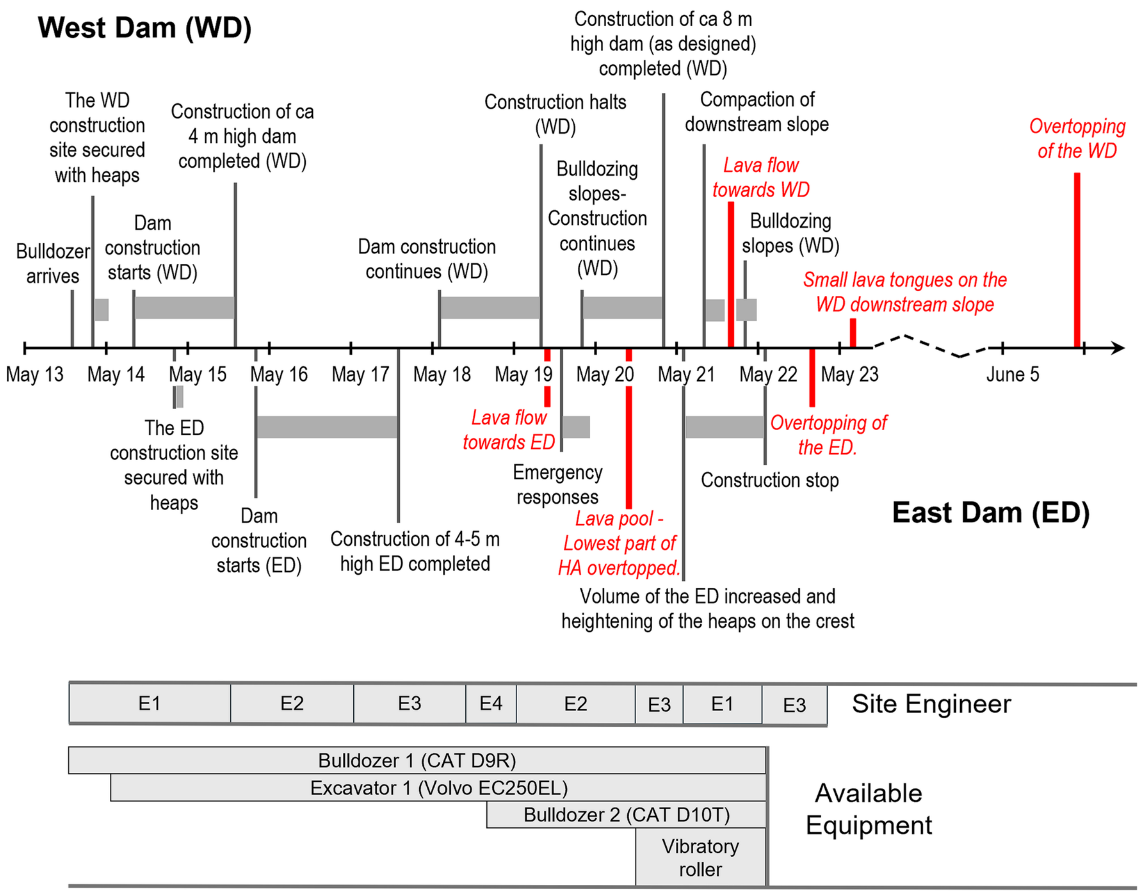


Fig. 5 Timeline for construction of the West Dam and East Dam, along with lava flows occurrences, availability of the different construction equipment and different site engineers on duty

By May 18, the decision was made to proceed to the second phase (Phase II shown in Fig. 3) and construct up to 8 m high dam. Accordingly, construction resumed at the West Dam site. The status of the lava field on May 18 can be seen in Fig. 6 and in Fig. 4b.

Early in the afternoon of May 19, the construction at the West Dam site halted as equipment was moved to the East Dam site in response to an approaching lava flow. In the evening, the site engineer decided to temporarily increase the height of the West Dam by bulldozing the downstream slope to form heaps at the crest. This action was taken in anticipation of potential lava flows towards the West Dam overnight.

On May 20, the construction of the West Dam continued. The first task was to even out the heaps formed by the bulldozing the previous evening. The West Dam was completed by the end of the day (May 20) with a 7-m-wide dam crest at an elevation of 208.5 to 209 m a.s.l. The completed dam is shown in Fig. 7a (from May 21).

On May 21, a vibratory roller was at the West Dam site, compacting the downstream slope. As the roller was working, pāhoehoe lava broke out of an existing ‘a‘ā lava toe (Fig. 7a) flowing very slowly (at a speed less than 0.3 m/s) towards and along the dam. However, a new breakout opened from the existing lava field and headed towards the dam’s east end with faster flowing (at a speed less than 1 m/s) pāhoehoe lava. The lava spread out between the older lava and the dam in about an hour (Fig. 7b). The lava flowed along the dam towards the west, past the boundary of the existing lava field and turned towards the north (Fig. 7b). Thus, the West Dam acted first as a diversion barrier and then as a dam as the lava accumulated and filled the available space or storage between the dam and the margin of the older lava field upstream. The lava storage reached a maximum thickness of about 6 m (Fig. 6c). The lava flow also attracted the attention of tourists, who used the dam as a platform for a better view of the lava flow.

The site engineer again instructed emergency responses on the West Dam with bulldozing of the downstream dam slope resulting in heaps on the dam crest (Fig. 7b). Thereby the volume of the dam body was reduced for the purpose of heightening the dam with the heaps. The dam height reached about 209 to 210 m a.s.l. and the crest comprised of uneven tops of loose earth material (Fig. 6b).

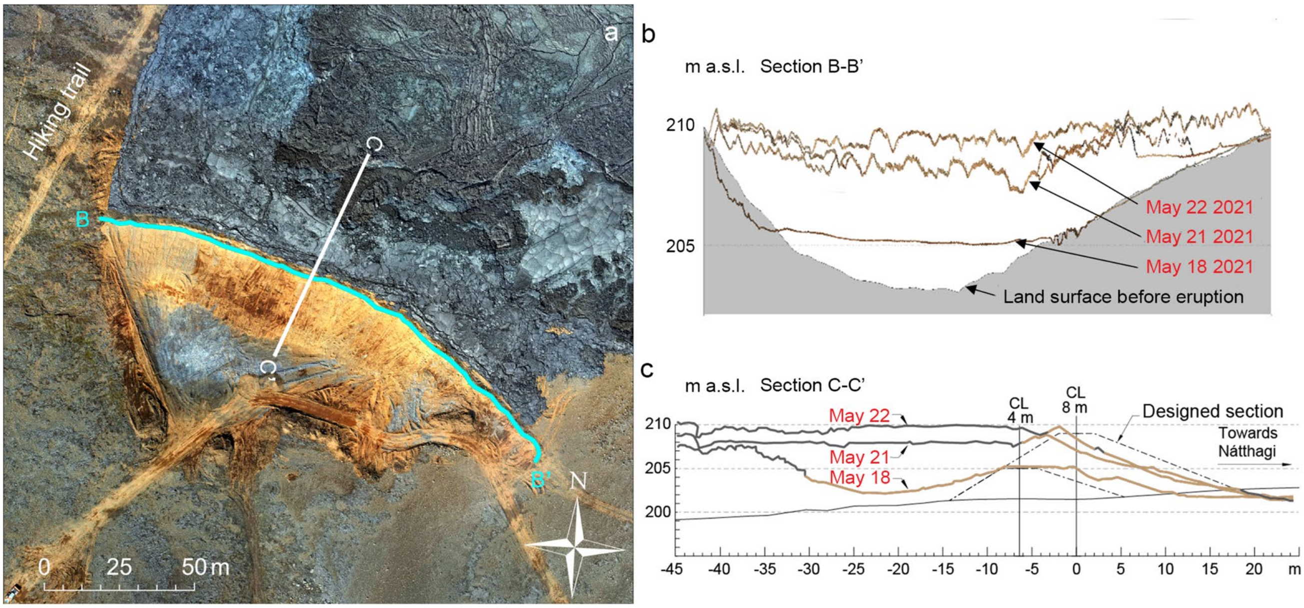


Fig. 6 The West Dam. (**a**) Plan view (picture from May 22). (**b**) Longitudinal section B-B' (along the cyan line on the plan view) as measured by drone survey on May 18, 21, and 22, 2021. (**c**) Cross section C-C' as measured by drone survey on May 18, 21, and 22, 2021, along with the designed cross section. The black measurement lines represent the surface of the lava, while brownish lines represent the dam's and soil surface. For the May 18 measurement, the brownish line also outlines the heap and the channel between the heap and the dam. The May 18 outline of the downstream slope of the elongated heap upstream the dam meets the outline of the lava 30.5 m upstream the centreline (CL) of the designed dam crest (CL 8 m). The May 21 dam outlines show a status during the bulldozing activities on that day, while the May 22 dam outlines present the final bulldozed dam section as completed in the evening of May 21. Data source: The base map is based on data from the National Land Survey of Iceland (www.lmi.is), the IcelandDEM. Data for the lava and the dam: Drone surveys by Svarmi

The downstream slope of the dam after the bulldozing was about 45° (1H:1V) for the uppermost 2 to 3 m (for the emergency heaps on the top) and about 22-30° (1.7-2.5H:1V) on the slope below. The inclination of the upstream slope was about 26–33° (1.5–2H:1V). However, when the dam height was increased, an extension was required towards the abutments. This extension towards the east was provided with elongated heap of loose material, however, ending abruptly at the easternmost end (see Fig. 7c).

The lava piled up against the West Dam on May 21 reached an elevation of about 208 m a.s.l. (Fig. 6c), leaving a freeboard of 2 m to the bulldozed top of the dam (Fig. 6c). The freeboard reduced during the night and into the morning of May 22 as lava slowly continued to pile up. On May 22, the lava surface had reached the elevation of the bulldozed top of the West Dam (Fig. 6c); however, it sloped down towards the dam about to the designed crest elevation (209 m a.s.l.). This resulted in a shallow trough or trench (depth < 1 m) within the lava surface along the dam, where the lava met the dam (Fig. 6c).

Construction work on the West Dam ceased after the emergency reactions on May 21, except for some finishing work at the West Dam site. Thus, the final dam body did not adhere to the design guidelines.

In the early hours of May 23, lava slowly flowed towards the West Dam from the east (RÚV, n.d.). Two small tongues of pāhoehoe lava crept through lows in the uneven surface of the heaps forming the top of the West Dam and solidified on the downstream slope (Fig. 7c). The next lava flow towards the West Dam occurred on June 5 when pāhoehoe lava flowed on top of the solidified crust of the existing lava field and passed over the east end of the West Dam at about 10:20 AM. The overtopping process captured by IMO's webcam is shown in Fig. 8. Within an hour, a lava channel had formed over the east end of the dam. However, more lava approached the dam west of the lava channel. The first small lava tongues (closest to the lava channel) started to creep very slowly (at a speed less than 0.1 m/s) over lows in the heaps at around 13:25 PM. Such lava tongues continued to creep slowly over the dam, always first through lows between the heaps, and fully covering the whole dam at about 20:00 PM. Only the westernmost heaps had not been covered by the end of the day.

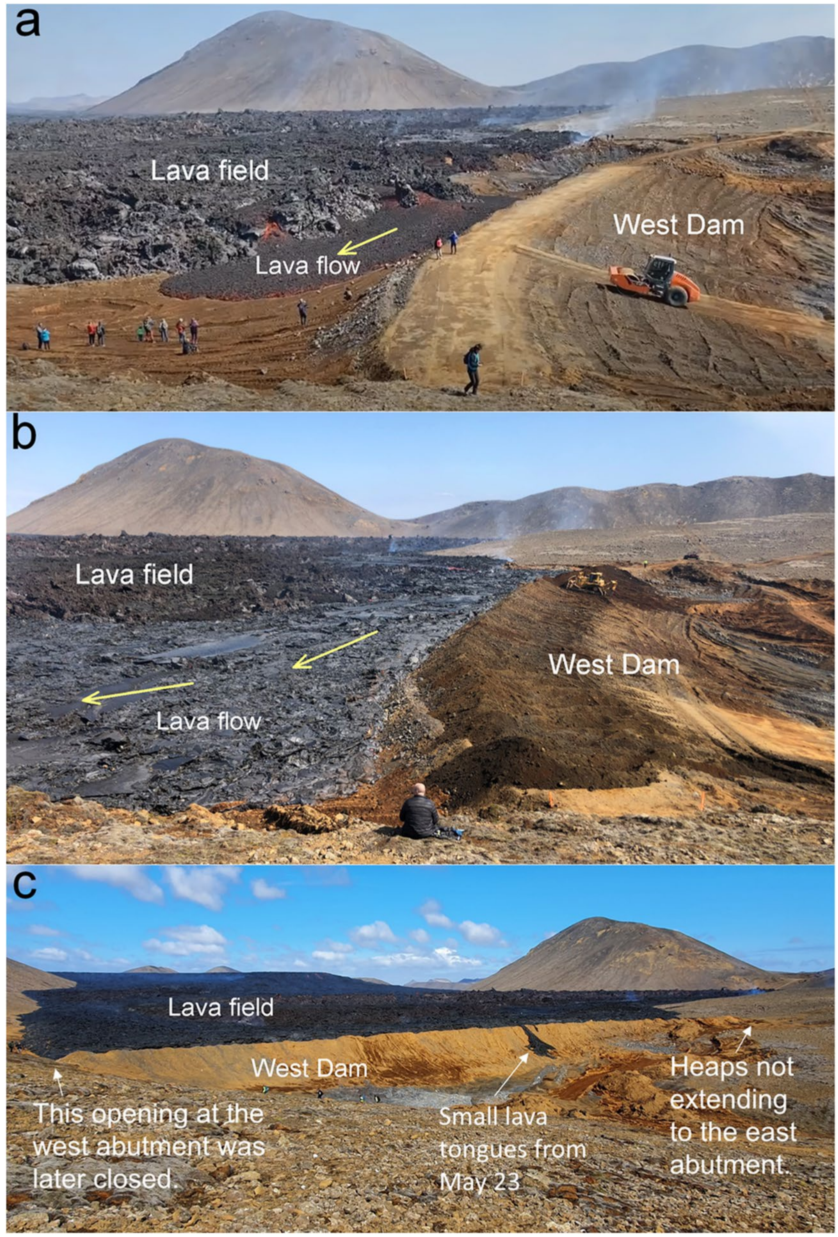


Fig. 7 Lava flows towards the West Dam on May 21 and resulting changes in the dam's geometry. (**a**) Lava flow on May 21. The West Dam completed with a 7-m-wide crest and a vibrating roller compacts the downstream slope (yellow arrow indicates the main lava flow direction other than spreading in the area between the dam and lava field) (view towards east) (courtesy of Bernd Kliebhan, snapshot from YouTube video https://www.youtube.com/watch?v=KvfDkDEXEhk). (**b**) View towards east on May 21. Bulldozing to form heaps at the dam crest after the main lava flow (yellow arrow indicates the main lava flow direction other than spreading). (**c**) View towards northeast on May 25. The heaps do not fully extend to the abutments and a lava tongue has crawled over the dam on May 23

The East Dam

In the afternoon of May 14, the site for the East Dam was temporarily secured with 1.5 to 2 m high heaps against the existing ‘a‘ā lava front. The construction of the East Dam started in the afternoon of May 15, and continued without distractions through May 16 and 17 (Fig. 5).

In the evening of May 17, a 4- to 5-m high dam had been built (with a 7 m wide crest at about 205 m a.s.l.), as presented in Fig. 9b and c with the May 18 drone survey. As previously mentioned, by May 18, the decision was made to proceed to the second phase and start at the West Dam site.

Early in the afternoon of May 19, pāhoehoe lava broke out from the existing lava field and approached the East Dam, flowing along the easternmost boundary of the existing lava. The construction equipment left the West Dam site in response to this as previously mentioned. An attempt was made to delay the lava with emergency heaps against the flow about 40 m north of the dam's eastern end. However, the lava overtopped the heaps about an hour later (Fig. 10a). A pathway was cleared along and between the existing lava front and the East Dam, and heap HA formed (labelled in Fig. 10d). The pāhoehoe lava, heading towards the dam at an angle of about 45°, turned and flowed slowly (at a

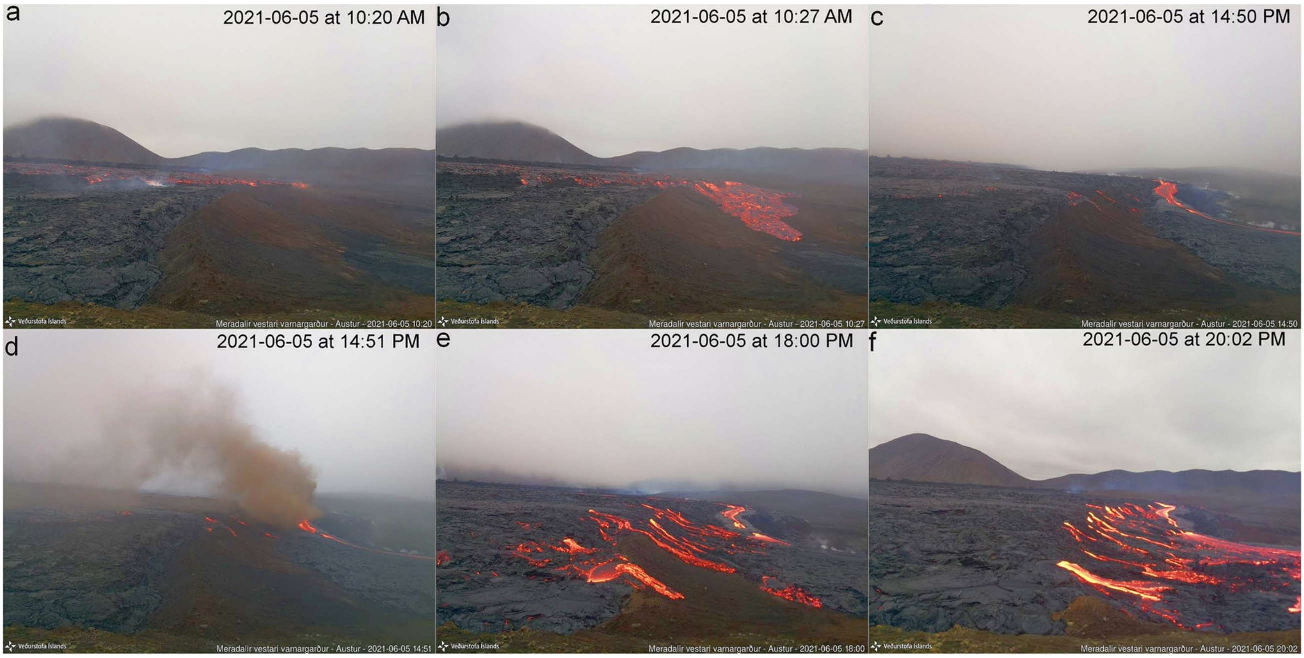


Fig. 8 Overtopping of the West Dam on June 5 recorded (with still image for every minute) by a camera operated by IMO located west of the dam and looking towards southeast. Time and description of each image is as follows: (**a**) at 10:20 AM, pāhoehoe lava flowing on the surface of solidified crust of the lava field reaches the east end of the dam; (**b**) at 10:27 AM, lava flow down the slope of the easternmost end of the dam; (**c**) the lava channel that formed within an hour is seen here at 14:50 PM, lava has started to creep slowly through lows in the bulldozed heap forming the dam's crest; (**d**) at 14:51 PM soil dust plumes rise from under the lava flow; (**e**) at 18:00 PM the lava has overtopped most of the dam; (**f**) at 20:02 PM the lava has fully covered the dam, except the westernmost heap (Photocredit: Webcam/The Icelandic Met Office)

speed of about 0.3 m/s) along the pathway (Fig. 10a). Thus, the East Dam along with heap HA functioned as a diversion barrier as the lava flowed along the dam towards west. Emergency heaps were also formed on the crest of the East Dam by pushing material up the slope onto the dam's crest (Fig. 10a), thereby increasing the dam height by about 2 m. Elevation of the heaps forming the crest (Fig. 10b, c) was just below 207 m a.s.l. The crest of the East Dam, defined by the heaps, was uneven and made of loose material, while material in the lower part of the dam was compacted below about elevation 206 m a.s.l.

The pāhoehoe lava flow on May 19 impounded the area upstream of the East Dam to around elevation 205 m a.s.l., i.e. approximately the crest elevation of the dam as it was before the emergency bulldozing. When the East Dam height was increased, an extension towards the west abutment was required. This extension, provided with heaps, is marked HA, HB, and HC on Fig. 10d (HB and HC are also marked in Fig. 9a). Due to the rush of the emergency response, the layout of the heaps was not optimal. Furthermore, the top elevation of both heaps HA and HB was lower than the top of the heaps forming the crest of the dam. The lava flow continued into the morning of May 20, until about 6 AM (RÚV, n.d.).

Pāhoehoe lava flowed towards the East Dam again at noon on May 20. The lava broke out at the ‘a‘ā lava front upstream the dam, formed a lava pool on solidified lava surface, and then broke out at the lava front lying against the dam (Fig. 10d). The lava reached up to an elevation close to 207 m a.s.l. as measured on May 21 (Fig. 9c). Furthermore, the lava overtopped the lowest part of heap HA formed the previous day (Fig. 10e). The lava against the dam was about 7 m thick (Fig. 9c) after the May 19 and May 20 incidents.

On May 21, work on the East Dam continued. Material was pushed up the downstream dam slope, heightening the heaps of loose material at the crest as well as increasing the volume of the dam (Fig. 9c). The elevation of the top of these heaps was at around 209 m a s.l., resulting in a freeboard of about 2 m from the lava surface (Fig. 9c). The downstream slope of the dam was about 45° or 1 horizontal (H):1 vertical (V) for the uppermost 2 to 3 m (the emergency heaps on the top) and about 30° (1.7 H:1V) on the slope below. The inclination of the upstream slopes was between 25 and 34° (1.5-2H:1V). In addition to increasing the dam height, actions were initiated to increase the height of the heaps HB and HC.

Construction work on the East Dam was discontinued after the emergency reactions on May 21. Thus, the final

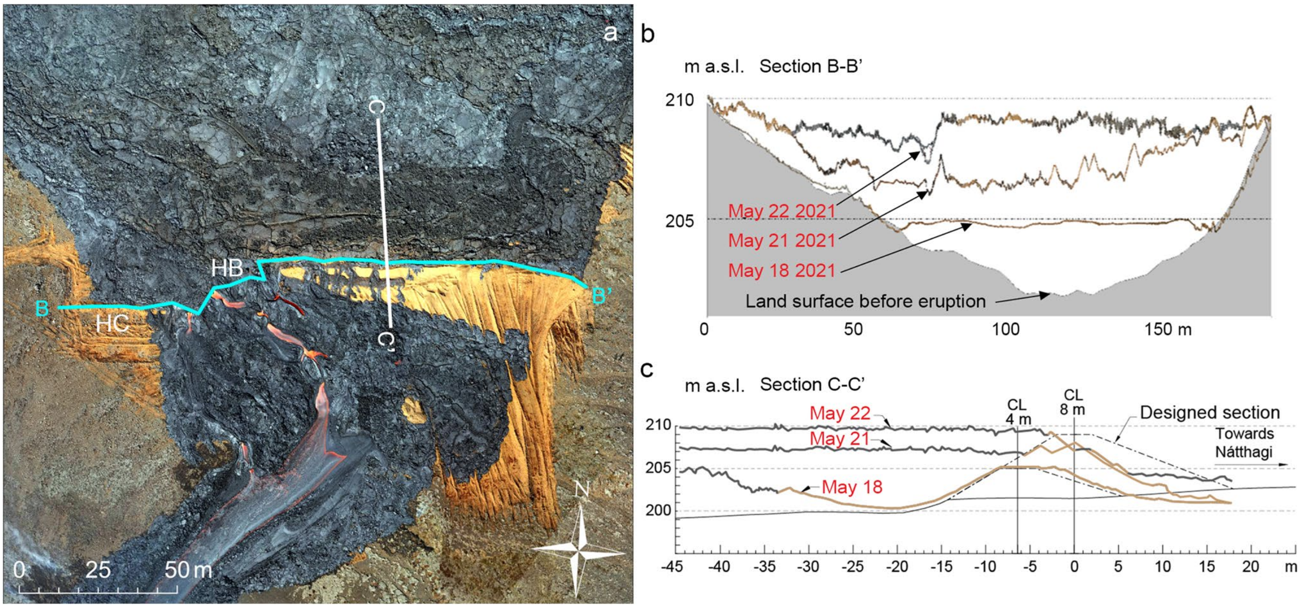


Fig. 9 The East Dam. (**a**) Plan view (picture from May 22, 2021). (**b**) Longitudinal section B-B' (along the cyan line on the plan view) as measured by drone survey on May 18, 21, and 22, 2021. (**c**) Cross section C-C' as measured by drone survey on May 18, 21, and 22, 2021, along with the designed cross section. The black measurement lines represent the surface of the lava, while brownish lines represent the dam's and soil surface. For the May 18 measurement, the brownish line also outlines the heap and the channel between the heap and the dam. The outline of the downstream slope of the elongated heap upstream the dam on May 18, starts ca 32 m upstream the centerline of the designed dam crest (CL 8 m). The outline of the lava for the May 18 measurements starts ca 33.5 m upstream the same centerline and extends further upstream. The May 21 measurement shows that the lava has piled against the upstream slope to about elevation 207, while on May 22 the lava rises to 1 m above the highest top of the heap forming the dam crest, and lava spilling through the heap B flows along the downstream slope (the black line ca 6 m downstream the centerline of the designed dam crest (CL 8 m)). The May 21 dam outlines show a status during the construction activities on that day, while the May 22 dam outlines present the final bulldozed dam section as completed in the evening of May 21. Data source: The base map is based on data from the National Land Survey of Iceland (www.lmi.is), the IcelandDEM. Data for the lava and the dam: Drone surveys by Svarmi

dam body was not as recommended by the design guidelines, but with loose, uneven crest of heaps. Furthermore, the action initiated on May 21 to increase the height of the heap HB and HC was interrupted due to lava flows at the West Dam site and the heaps remained a weak part in the defences towards the downstream (see May 22 measurements of the dam in Fig. 9b, c).

On May 22, pāhoehoe lava flow approached the East Dam again and this time lava overtopped the dam (Fig. 9a, Fig. 11). The lowest sections of heaps HB and HC (Fig. 10e) were overtopped first, as well as the westernmost end of the East Dam and lows in the uneven top of the dam. The overtopping is discussed later. The lava overtopping continued the following days. The status and thickness of the lava field on June 2 is shown in Fig. 4c.

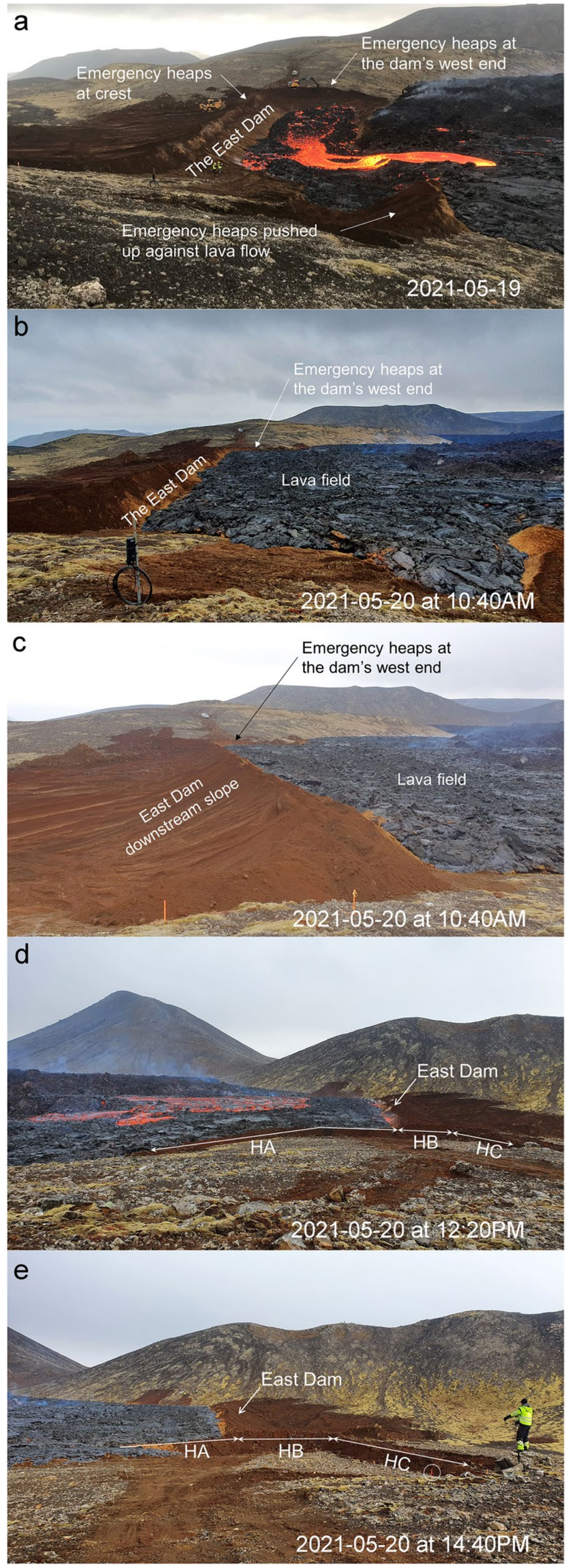
The diversion barriers

The construction site above Nátthagakriki was on a popular route for tourists visiting the eruption site; thus, hundreds of tourists were passing through every day. The construction of the Long Diversion Barrier on Stórhóll Hill above Nátthagakriki started on June 14.

One bulldozer pushed overburden into heaps attempting to secure the construction site (heaps H1 and H2 on Fig. 12a). The lava had already advanced close to the site when the bulldozing started. During the night and the early morning of June 15, pāhoehoe lava flow towards Nátthagakriki increased and overtopped parts of the heaps. The lava flow reached some 20 m into the planned layout of the Long Diversion Barrier but was hindered in going further towards Nátthagakriki by new earth heap pushed against the lava as seen in Fig. 12b. These actions resulted in a bend in the layout of the diversion barrier, potentially aligning nearly perpendicular to possible lava flows. Therefore, an attempt was later made to soften the bend resulting in the as-built layout in Fig. 13a. This softening of the bend considered that fluid can move more readily along an obstacle (such as a diversion barrier) at low rather than high angles between the flow direction and the obstacle (Dietterich et al. 2015).

The construction of the 300-m Long Diversion Barrier was completed on June 24 (Fig. 13a). The status

Fig. 10 Lava flows towards the East Dam on May 19 and 20, 2021. ▶ (**a**) Emergency reaction on May 19 to lava flow. (**b**) Status upstream (on the lava side) on May 20 at 10:40 AM (view from the east of the dam towards west-southwest). (**c**) Status downstream on May 20 at 10:40 AM (view from the east of the dam towards west-northwest). (**d**) Lava pond upstream and glowing lava breaking out at the lava lying against the dam, on May 20 at 12:20 PM. Emergency heaps pushed up the previous day at the west end of the dam are labelled HA, HB, and HC (view from the west of the dam towards east). (**e**) May 20, 14:40 PM, status after the lava flow. Heap HA was overtopped (view from the west of the dam towards east)



and thickness of the lava field 2 days later are seen in Fig. 4d. The cross-section of the diversion barrier varied greatly along its length. The uppermost approximately 100 m of the diversion barrier (the north end), built from overburden, had a relatively wide crest (ca 5 m), a mild downstream slope of ca 20–22° (ca 2.5H:1V) (the downstream side facing away from the lava), but a steeper slope (29–34° (ca 1.5 to 1.8H:1V)) upstream (facing the lava). Conversely, the rest of the diversion barrier (towards the south) was built from ripped basalt rock, coarse material with relatively large boulders (rubble), placed in a narrow diversion barrier (1 to 1.5 m wide at the crest) with steep slopes (33–45° (ca 1 to 1.5H:1V)) facing the lava as well as on the downstream side (29–34° (ca 1.5 to 1.8 H: 1V)) (see Section A–A' in Fig. 13d). Furthermore, due to the lava incident on June 15, the plan layout was not as originally proposed. The resulting plan layout is shown in Fig. 13a (yellow line) along with the designed centreline (white broken line).

Construction of the Short Diversion Barrier started on June 21 and was mostly completed the same day. The slope on the lava side was steep with an inclination close to the angle of repose of the material. Conversely, the slope was mild on the downstream side (Fig. 13e). The uppermost 1 m or so of the Short Diversion Barrier had a downstream slope of about 35° (ca 1.4H:1V), but below this, a mild slope of about 12°(ca 4.7H:1V). The upstream slope on the side facing the lava flow was steep or about 35° (1.4H:1V). The crest or top was narrow or about 1 m. However, due to the mild downstream slope, the Short Diversion Barrier was quite voluminous.

The construction of the Long Diversion Barrier was only interrupted by the lava incident on June 15. The working conditions on some days were difficult due to gas (SO_2) and airborne soil. The workers had to use gas masks when the gas reached a certain critical level, and the soil in the air made it difficult to see out of the windscreens and caused air filter problems in the machines. Lava flow incidents did not disturb the construction of the Short Diversion Barrier.

In the morning of September 15, pāhoehoe lava broke from the base of the lava field in Geldingardalir Valley and

Fig. 11 Lava overtopping of the East Dam on May 22 (courtesy of Elvar Þór Ólafsson). Soil dust plume rose from under the main lava flow over the dam. (**a**) Seen from the upstream and west of the dam. Heaps HA and HB have been fully overtopped. Only the westernmost end of heap HC is still visible. (**b**) The overtopping seen from the downstream. (**c**) Closer view from the downstream of one of the main lava streams at that time and the thick soil dust plume

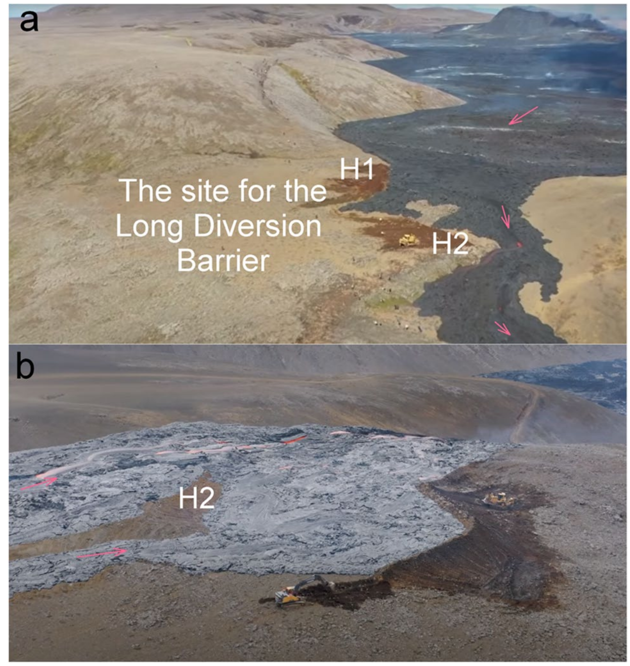


Fig. 12 Securing the construction site of the Long Diversion Barrier. The direction of lava flow is indicated with red arrows. (**a**) On June 14, site material pushed to form heaps (H1 and H2) against the lava stream. The crater is seen in the upper right corner of the figure (view towards north) (courtesy of Gylfi Gylfason, snapshot from a JustIcelandic video https://www.youtube.com/watch?v=kcdYOzKcc8Q). (**b**) On June 15, the bulldozers surround lava flow running along the margin of the existing lava field, passing and running downstream of the heaps H1 and H2 (view towards the South-southeast) (courtesy of Visit Reykjanes, snapshot from their video https://www.youtube.com/watch?v=qPShqWZCYxM)

flowed towards the Long Diversion Barrier (Fig. 14a). The lava flow advanced at an angle of about 20° to the longitudinal direction of the Long Diversion Barrier (Fig. 13) and turned to flow alongside the diversion barrier (Fig. 14b). Thus, the Long Diversion Barrier diverted the lava flow successfully towards Nátthagi (Fig. 14b, c). Comparing Fig. 14a and b, the lava flowed along the entire length of the Long Diversion Barrier within 10 min (from 10:53 to 11:02 AM). However, a time step of 10 min between the still images is insufficient to estimate the exact speed of the flow, and it is likely that the lava traveled the full length in less than 10 min, with a speed exceeding 0.3 m/s.

On September 16, a lava channel started to form. By September 17, the lava channel had developed further (Fig. 14e, f), swaying towards the south approximately 120 m from the Long Diversion Barrier, then running almost alongside the diversion barrier, closest at about 55 m (Fig. 13b). Then, the lava flowed down the mountain slope into Nátthagi Valley, expanding towards the banks on each side as well as towards the Short Diversion Barrier (Fig. 13a, b).

In the evening of September 17, the intensity of the lava flow increased. The flow was fast, or about 1 m/s, where the lava flowed in the lava channel past the Long Diversion Barrier. The lava channel levees were overflowed (Fig. 14g), resulting in lava flowing between the lava channel and the Long Diversion Barrier just before midnight (around 23:30 PM). Again, the Long Diversion Barrier diverted the lava overflow successfully downstream, towards the Short

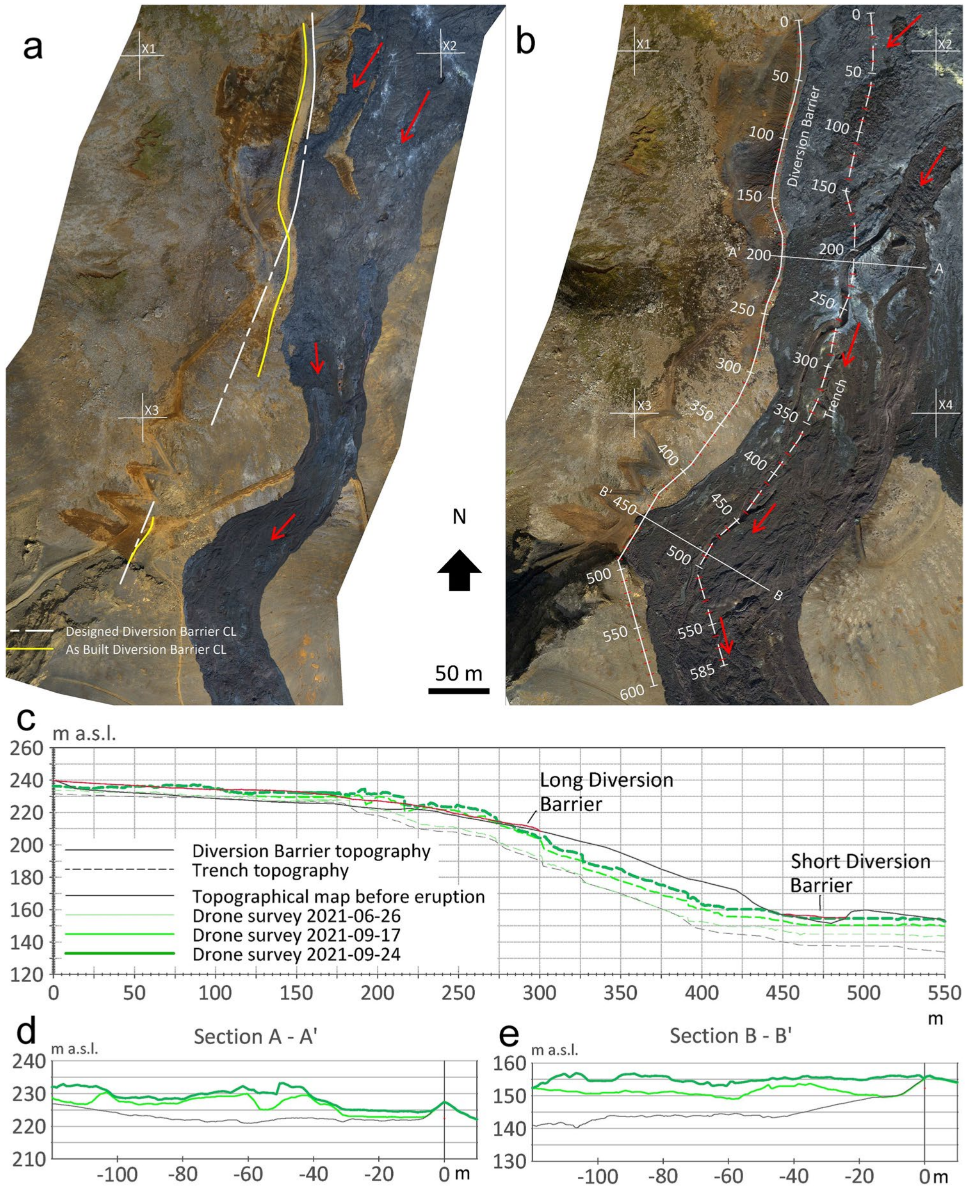


Fig. 13 The Long Diversion Barrier and the Short Diversion Barrier. (**a**) Aerial view with drone surveys from June 26. The white (dashed-dot) line and the yellow line are respectively the designed and as-built centreline (CL) of the diversion barriers. The direction of lava flow is approximately indicated with the red arrows. (**b**) Aerial view with drone surveys from September 24. Station numbers along and connecting the centreline of the diversion barrier are provided. A 60 m offset of the diversion barrier's CL is also shown with a dashed line and runs partly parallel to the lava trench (labelled "Trench"). (**c**) Longitudinal section along the two centrelines in fig. b. The different dashed lines show the topography along the trench at different times. The as-built crest of the diversion barriers is plotted with a thin red solid line. (**d**) Cross section A-A′ through the Long Diversion Barrier at station 0/200 (see fig. b). Legend is provided in fig. c. (**e**) Cross section B-B′ through the Short Diversion Barrier at station 0/475 (see fig. b). Legend is provided in fig. c. Data source: The base map is based on data from the National Land Survey of Iceland (www.lmi.is), the IcelandDEM. Data for the lava and the diversion barriers: Drone surveys by Efla

Diversion Barrier (Fig. 15a–c) and Náthagi. The lava accumulated behind the Short Diversion Barrier within the outer bend of the lava flow (Fig. 15c) where it thickened and rose about 2 m above the diversion barrier's crest (Fig. 15b). The lava in the bend moved slower (less than 0.3 m/s) than the fast-flowing lava (at a speed higher than 1 m/s) within the lava channel past the Short Diversion Barrier. Through this effect, the Short Diversion Barrier diverted the lava. Subsequently, the lava surface behind the diversion barrier subsided somewhat. However, the next day, the lava flow continued (Fig. 14h) and one of the lava tongues crawled over the northernmost end of the Short Diversion Barrier (Fig. 15d) where the barrier crossed a hiking trail. Fortunately, the lava flow ceased (Fig. 14i), and lava did not flow further downstream to Náthagakriki.

Discussion and lessons learned

The discussion covers ten aspects: (1) securing construction sites, interactions of (2) ʻaʻā and (3) pāhoehoe lava with heaps, lava flow interactions with dams (4) before and (5) during overtopping, (6) lava pressure, (7) lava diversion, (8) design proposals versus as-constructed barriers, (9) impact of barriers, and (10) the tourists visiting the eruption site.

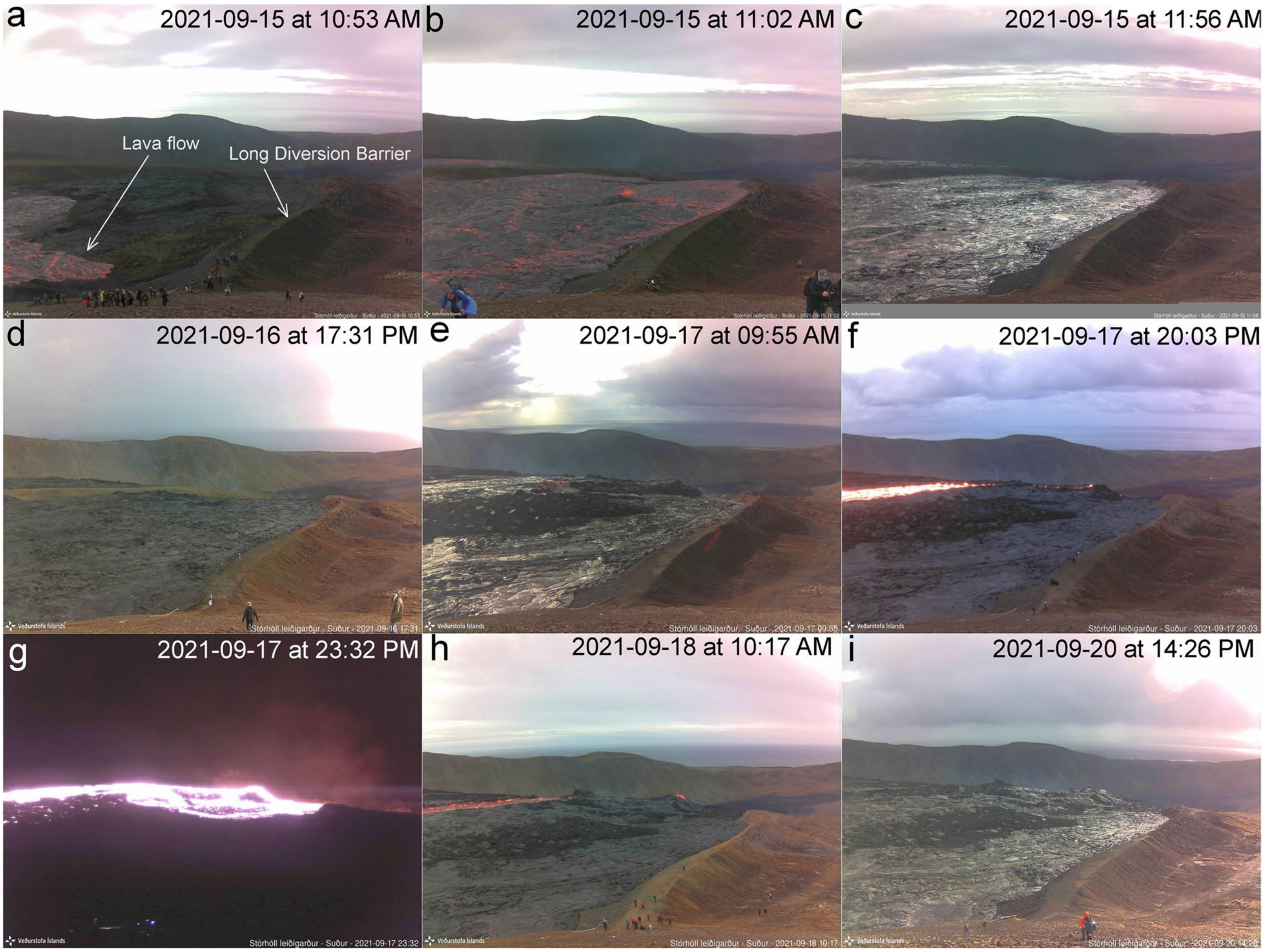


Fig. 14 Images of the Long Diversion Barrier recorded by a webcam looking towards the south (the webcam captured a still image every 10 min). Date and time of each picture frame is as follows: (**a**) 2021-09−15 at 10:53 AM first lava flow towards the Long Diversion Barrier. (**b**) 2021-09−15 at 11:02 AM first lava flow along the Long Diversion Barrier. The lava flows along the full length of the diversion barrier. (**c**) 2021-09−15 at 11:56 AM. The lava flow continues. (**d**) 2021-09−16 at 17:31 PM. The crust of the lava solidified. (**e**) 2021-09−17 at 09:55 AM. The levees of the lava channel are overtopped with flow towards the diversion barrier. (**f**) 2021-09−17 at 20:03 PM. Lava flows within the channel. (**g**) 2021-09−17 at 23:32 PM. Overtopping of the channel's levees and lava flows towards the lower part of the Long Diversion Barrier. (h) 2021-09−18 at 10:17 AM. Lava flows within the channel. (**i**) 2021-09−20 at 14:26 PM. Solidified lava surface (Photocredit: Webcam/The Icelandic Met Office)

Securing the construction site

The elongated heaps at the West Dam site hindered the advancement of the ʻaʻā lava front during the whole construction time (May 13 to 21), while the heaps pushed against the lava front at the East Dam were partly subjected to overflow from pāhoehoe lava before the construction of the dam was finalized. Also, the heap HA (Fig. 10) created May 19 was partly overtopped the following day. Likewise, the heaps H1 and H2 (Fig. 12a) were quickly overtopped by pāhoehoe lava flows. In each case, the pāhoehoe lava flows overtopping the heaps approached along the margins of the existing lava field.

At the construction site for the Long Diversion Barrier, the scarcity of building material influenced the site engineer's decision to locate the heaps H1 and H2 close to a pāhoehoe lava field, aiming to keep a larger area with potential building material free from lava flow. Conditions would have been more favourable just 1 or 2 days earlier when the lava front was further from the construction site. Therefore, timely decision-making is essential.

The experience with the elongated heaps of the present study aligns with Macdonald's (1958) findings for similar barriers in Hawaii during the Kīlauea eruption 1955, which aimed mainly to divert lava flow but also to delay it. These barriers were also made of available site material,

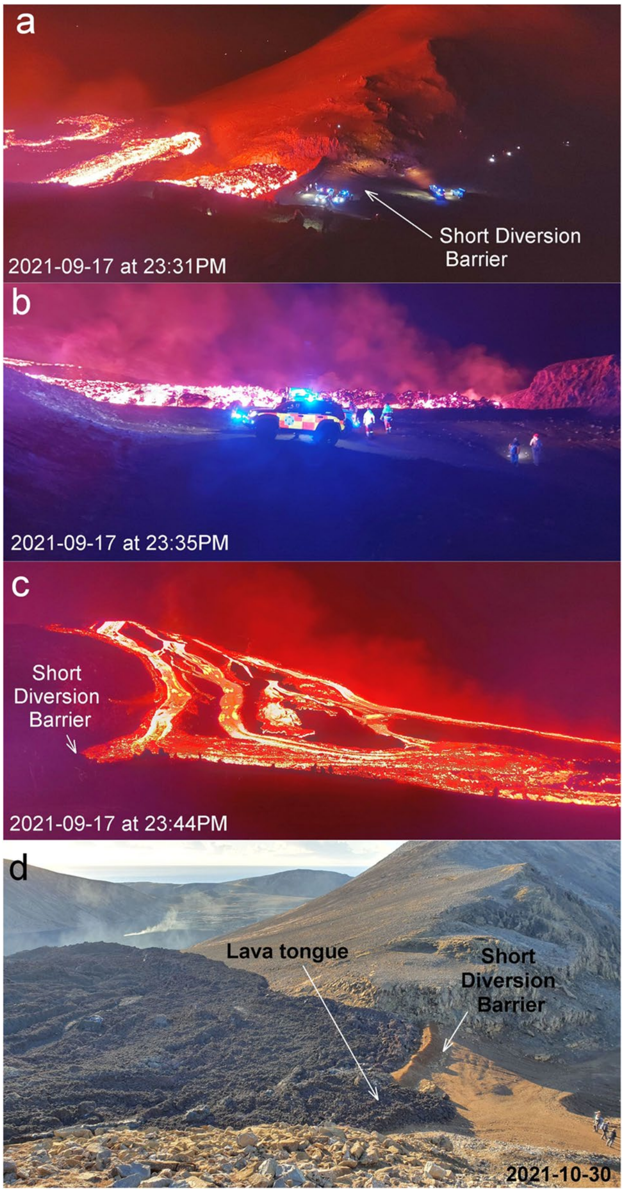


Fig. 15 The Short Diversion Barrier and lava flows. (**a**) View towards south-southeast over the Short Diversion Barrier and the lava flow on Sept 17 at 23:31 PM. The cars are parked on the Short Diversion Barrier's mild downstream slope (courtesy of Hlynur Lind Leifsson). (**b**) Lava rising above the thin crest wall of the Short Diversion Barrier on Sept. 17 at 23:35 PM. (view towards southeast) (courtesy of Hlynur Lind Leifsson). (**c**) The downhill lava flow on Sept. 17 at 23:44 PM (view towards northeast) (courtesy of Hlynur Lind Leifsson). (**d**) View on Oct 30 towards south-southeast over the Short Diversion Barrier and the hardened lava. The lava tongue at the northernmost (NNE) end of the diversion barrier is the result of a lava flow on Sept 18

constructed quickly and sometimes with the bulldozers working close to the lava front. While sometimes successful, the alignment of the Hawaiian barriers (elongated heaps), constructed under time pressure and without advance planning, was not always optimal, as was the case for heaps H1, H2, HB, and HC. Some of the Hawaiian barriers were overtopped. Similarly, all the provisional heaps of the present study, including those against ‘a‘ā lava, were overtopped or bypassed by pāhoehoe lava.

Colombrita (1984) reports on emergency measures consisting of provisional barriers and concludes that emergency works can be organized successfully. The purpose of these measures was to guide lava flows towards existing diversion barriers, allowing work to continue elsewhere. Similarly, heaps H1 and HA were partly aimed at diverting the lava, while the heaps pushed against the lava front to secure the construction site aimed at temporarily delaying its advance. The present case further demonstrates that heaps can be useful in an emergency response to lava flows or to temporarily secure an area such as a construction site. However, alignment and placement of the heaps need to be considered carefully, taking lava type into account and possible lava pathways. This requires time for planning and decision-making. Also, in eruptions with different lava types (pāhoehoe and ‘a‘ā), it is a possibility that tightly placed heaps at an ‘a‘ā lava front may later be bypassed along the margins of the existing lava field by flowing pāhoehoe lava.

ʻAʻā lava thickening and interaction with heaps

At the site for the West Dam, the heaps were pushed against the ‘a‘ā lava front that already was creeping up a slightly inclined slope (3 to 4°). The slow creeping of the ‘a‘ā lava against the heaps was generally not noticeable to the naked eye. The heaps were generally quite voluminous and with a moderately inclined downstream slope (12–15°). In the period from May 13 to 21, the lava thickened under chilled outer crust with the lava margin rising 2 to 4 m above the top of the heaps, or up to twice their height. A few lava fragments rolled over or onto the heaps. The May 18 measurement in Fig. 6c and Fig. 9c shows the surface outline of the lava, as well as the top and downstream slope of the elongated heap upstream of the West Dam and East Dam, respectively. The May 18 measurements show the rise of the ‘a‘ā lava directly behind the heaps, particularly at the West Dam site (Fig. 6c).

Similar behaviour of lava margin standing above the barriers was reported by Macdonald (1958, 1962) and Jónsson (1992). Also, Dietterich et al. (2015) found, through laboratory experiments, that lava flow thickens immediately upslope of an obstacle. The location of the heaps on a mild uphill slope is likely to have slowed down the advance of the lava front, possibly enhancing the thickening of the lava. Simulations of lava flow such as by Hinton et al. (2019) show how lava thickens on the upstream slope of a mound on an inclined slope.

No signs of yielding or cracking under the thrust of the ‘a‘ā lava could be observed on the downstream part of the heaps. However, the solidified crust of the ‘a‘ā lava front did at some locations act as a bulldozer on the heap’s upstream slope (facing the lava front), pushing material from the heap in a similar manner to that observed for the overburden seen in Fig. 2. The solidified crust of the lava margin against a heap also caused minor deformations of the loose uppermost part of the heap.

Pāhoehoe lava interaction with heaps

The heaps withstood well the pressure from the pāhoehoe lava, even though they were constructed of loose material (not compacted). No yielding or deformations were observed. The pāhoehoe lava flow on May 20 against the heap HA (Fig. 10e) was closely observed on-site. The very slow (< 0.3 m/s) flow ponded behind the heaps until it found passage through the lows in the uneven surface. No erosion was noted as small tongues of pāhoehoe lava crept very slowly (< 0.05 m/s) over the fine-grained and loosely placed heap material. However, when the fluid lava carried with it broken, solidified crust of lava floating on the surface, it occasionally pushed against material from the heap’s top or downstream slope, causing minor downslope slides of single stones and soil particles.

Lava flow interaction with the dams prior to overtopping

The dams were subjected to pāhoehoe lava, first flowing alongside the dams and then piling up and reaching almost to the crest in two to three lava flow incidents. Hence, the dams initially functioned as diversion barriers and then as dams. Barberi et al. (1993) describe thin pāhoehoe lava flows being similarly diverted laterally, then piling up slowly against a 21-m high dam, with overlapping thin flows filling the valley upstream within a month. However, for the dams in this study, the lava piled up relatively fast, or up to about 6 m thickness in a single lava flow incident, forming a storage of molten material behind the dams resembling a lava lake. The lava began to solidify as evidenced by the outer crust seen on the surface. The spilling with overtopping of the barriers occurred as soon as the lava storage was full.

During a site visit on May 25 and June 1, the elevation of the lava surface behind the West Dam was still approximately at the same level as the bulldozed dam top as well as sloping down towards the dam. Comparison of pictures taken from the same point on June 1 and web pictures from early June 5, before the overtopping, did not reveal notable changes to the lava front against the dam, i.e. no thickening of the pāhoehoe lava was noted. Furthermore, no signs of cracking or yielding of the dam could be identified during inspection of the downstream dam slope during the site visits May 25 and June 1. Likewise, Macdonald (1958) observed no yielding of the barriers under the pressure of flowing pāhoehoe lava. Barberi et al. (1993) and Barberi et al. (2003) describe earthen barriers resisting the thrust of lava without mentioning details such as yielding or deformations.

Lava overflow interaction with the dams

The East and West dams, as well as all the heaps constructed to secure the construction site, were subjected to overtopping by pāhoehoe lava. This aligns with previous experiences with dams such as described by Barberi et al. (1993) and Macdonald (1962). Overtopping is inevitable as soon as a pāhoehoe lava field rises above the crest of a dam, given that the volcanic eruption continues. This is consistent with Barberi et al. (1993) regarding lava containment by dams. Colombrita (1984) similarly explains that lava overtopping occurred for the barriers constructed during the Mt. Etna eruption 1983 when it was no longer possible to raise the barrier, and the space behind a barrier had been filled with fresh lava.

Overtopping of the East Dam and West Dam started at the lowest and weakest part of the defences. The lowest part was in both cases the elongated heaps that were pushed up in emergency response to lava flow. The defences were heightened in this manner and simultaneously lengthened, to the west on May 19 at the East Dam site and to the east on May 21 at the West Dam site. The lava passed the East Dam when overtopping heap HB (Fig. 9a). Similarly, lava passed the West Dam at the easternmost end of the dam, where it had been extended with emergency heaps (Fig. 8a) without reaching the abutment (Fig. 6b).

During the overtopping of the East Dam, at least two main detrimental processes were identified by studying video recordings from one of the webcams operated by the media (RÚV, n.d.). Firstly, lava flow caused slides on the downstream slope as it pushed against the loose heaps. Consequently, a flood of pāhoehoe lava broke through. This initial slope failure and breaching of the heap was possibly partly triggered by hardened crust floating on the surface of the pāhoehoe lava flow as well as lava pressure. However, close-up images were not available to confirm this hypothesis for the failure initiation. Secondly, soil dust plumes, driven by the high temperature of the lava, rose from under concentrated lava flow over the heaps forming the crest of the East Dam (Fig. 11). Similar plumes were also observed as lava rushed down mountain slopes. The soil lofted from under the lava indicates a mechanical or thermo-mechanical erosion process as described by Gallant et al.(2020) for lava flows down steep-sided volcanos. Turbulent eddies were present in the lava flow in the area where the soil plume originated on the East Dam. Such eddies were seen in a video by Ólafsson (2021). Area with the eddies was observed just below a sharp change in the downstream slope, which was caused by the heap. Glaze et al. (2014) explain that such eddies are produced by the angular momentum generated by the slope change.

Soil dust plumes also emerged from the main lava flow over the east end of the West Dam as seen in Fig. 8d. Apart from the east end, the overtopping of the West Dam was very slow. The main dam body remained intact and did not breach, or experience slope failure as observed on the East Dam. Pāhoehoe lava creeping slowly (at a speed < 0.1 m/s) over the heap forming the crest of the West Dam did not cause noticeable erosion or failure of the soil material (Fig. 8), even though this was loosely placed. This interaction between the lava and the dam was identified by studying the still images from the webcam operated by IMO at the West Dam site (Fig. 8). The slow initial lava flow that covered the downstream slope of the West Dam can be considered to have formed a shield, protecting the dam against potential erosion under subsequent and continuing lava flow.

Details of the overflow are generally not described for the past cases, such as those reported by Macdonald (1958 and 1962), Barberi et al. (1993), Barberi et al. (2003), and Colombrita (1984). The webcams and videos from the mentioned sources enable the more detailed description presented here. However, Barberi et al. (1993) explain that the lava flow towards the 21-m high dam built during the 1991 eruption in Etna was very slow and gradually covered and buried the dam by successive series of lava flows, similar to the West Dam overtopping. They further explain that lava never broke through the 21-m high dam, unlike the weak upper parts of the East Dam.

Pāhoehoe lava versus ʻaʻā lava pressure on dams

The East Dam and West Dam withstood well the pressure exerted by pāhoehoe lava as, e.g., the 21-m high dam described by Barberi et al. (1993). However, neither the dams in the present case nor Barberi et al.'s (1993) 21-m high dam were subjected to loading as reported by Jónsson (1992) for the 1973 Westman Island eruption, where a 25-m high dam breached due to the thrust from ʻaʻā lava. There, the thickness of the lava front against the dam was about twice the dam's height. Thus, it is important to consider the type of lava approaching the dams. One must carefully consider the potential load from the lava in the design of lava defences such as a dam. The authors did not find an in-depth study on this matter. The model used by, e.g., Scifoni et al. (2010) assumes the lava behaves as a Newtonian fluid exerting static pressure on a barrier. However, this model appears insufficient for a creeping ʻaʻā lava front against a barrier. Hence, it seems that further research is needed to better establish the load from the thrust of an ʻaʻā lava field.

Lava diversion

The diversion barriers were successful in diverting lava flow. The angle between the lava flow (advancing at a speed higher than 0.3 m/s) and the diversion barriers was relatively low, or about 20°, for the Long Diversion Barrier in the September 15 lava flow. However, the dams also diverted pāhoehoe lava advancing at an angle of about 45° (and a speed of about 0.3 m/s). Low angles between the lava flow and barriers are generally recommended for more effective diversion (Dietterich et al. 2015; Fujita et al. 2009). While lava diversion is generally more effective at low angles, the lava was also diverted at higher angles at the West Dam site on May 21, where the flowing pahoehoe made an almost right-angle turn along the margins of the existing lava field.

When the 2021 eruption ended, the freeboard capacity of the Short Diversion Barrier was at its limit, with a small lava tongue already crawling over the northernmost end, i.e. the upslope end of the diversion barrier. Thus, the capacity could have been improved with a higher elevation of the northernmost end than provided. In contrast, the Long Diversion Barrier is likely to have been able to divert more lava flow had the eruption continued. Further development and potential spilling of lava over the Long Diversion Barrier would have been dependent on the evolution of the lava field as well as the lava channels upstream and running along the Long Diversion Barrier.

Design proposals and as-constructed barriers

The design proposals presented the minimum recommended cross section; however, the crest of the dams, e.g. as measured on May 18 (Figs. 6c, 9c) for Phase I (Fig. 3), was wider than the minimum. This wider crest allowed for faster construction with the available equipment, as similarly reported by Colombrita (1984). When the height of the East and West Dams was increased with emergency bulldozing of the downstream dam slope, the new crest of the dam comprised loose, uneven heap of soil material. Furthermore, to keep up with the increased height from the bulldozing of the dam slopes, the dams were extended with heaps. In the rush of the emergency responses, the extension of the dams did not in all cases reach the abutment and the crest was uneven, with up to 2 m height difference (Fig. 6b and Fig. 9b). While the bulldozing was intended to increase the time during which the dams contained the lava flow, the heap at the top of the dam can neither be considered a safe structure nor effective against pāhoehoe lava flow as at the East Dam site. Hence, the final cross-section of the dams was not as originally designed, but represented emergency measures as introduced by Colombrita (1984).

It is important to decide on constructing lava defences in a timely manner and to ensure that the dam reaches its full height with the intended cross-section. Even though timely decision-making may result in the barrier not being subjected to lava flow, such as was the case for the South Dam in Nátthagi (Fig. 1), an existing barrier may be of use in the next eruption, either at the location originally constructed or by reusing the material to build another barrier.

It is recommended to carefully weigh the pros and cons of emergency bulldozing of a lava barrier. In some cases, a more robust barrier may be preferable, while in others the risk associated with a higher but weaker dam crest comprising heaps may be acceptable due to the potential time gained. Nevertheless, it is important to consider the consequences of detrimental processes that can be related to the heaps, such as the slope failures observed on the East Dam. Slope failures that allow lava to break out could influence the intended gain in time. The recommendation is not to weaken a dam that serves as the primary defence, unless the consequences have been thoroughly contemplated. In the situations described, necessitating quick responses, it is important to have clear communication routines between the design team, the site engineer, and the Civil Protection for enhanced risk management.

Impact of the dams and diversion barriers

The lava flows into SM Valley, between May 18 and the first overtopping of the dams on May 22, would likely have advanced towards Nátthagi if not for the dams. A rough estimate of the volume of lava retained by the dams can be derived from 3D DEM models of the lava field in the SM Valley from May 18 (Fig. 4b) and June 2 (Fig. 4c), but the June 2 model is the first one available after the East Dam overtopped on May 22. The resulting difference in the lava volume in the SM Valley is 1.96×10^6 m^3.

The East Dam delayed the flow towards Nátthagi by up to 4 days (from the first lava flow towards the dam on May 19 to the overtopping on May 22), while the West Dam delayed it by up to 16 days (from the first lava flow towards the dam on May 21 to the overtopping on June 5). However, even a single extra day before an area is inundated by lava can make a crucial difference for emergency responses. In the present case, the benefits of the delayed lava flow are debatable, as the eruption ceased before lava reached the South Coast Road. For future preparedness in the area, however, it was essential to show that lava flow can be delayed to provide more time for emergency responses in the downstream area. This is further supported by Barberi et al.'s (1993) report on how dams slowed the advance of lava flow from Mt. Etna for about 1 month during the 1991–1992 eruption.

The diversion barriers successfully prevented lava from entering Nátthagakriki, though they would have been overflowed during a prolonged eruption as simulated by Pedersen et al. (2023). The effectiveness of the lava diversion for barriers when oblique to the lava flow has previously been described by Barberi et al. (2003), Barberi et al. (1993), Colombrita (1984), and Scifoni et al. (2010) for actual cases in the field as well as demonstrated in the laboratory by, e.g., Dietterich et al. (2015) The main advantage of constructing the diversion barriers of the present study was to demonstrate locally the effectiveness of lava diversion, which could support and impact decision-making for potential future measures in the area. This was essential for preparedness before the Sundhnúkur Fires in 2023, when decisions were made to protect important infrastructure and the town of Grindavik.

Tourists

Hundreds of tourists were present at the eruption site during some of the lava flow incidents. On the night of September 17 and the early hours of September 18, tourists used the diversion barriers as platforms for viewing the magnificent lava flow. The situation was critical with rescue teams attempting to direct the people away and into safety. The rescue team's vehicles were parked on the Short Diversion Barrier (Fig. 15a, b), while the lava was rising above the top of the barrier, and tourists were also crossing over it. The tourism at the eruption site and the tendency to use the barriers as platforms for viewing the lava flow was a constant subject of concern, also considering potential unexpected development of the lava, as well as the response of the barriers to this. The risk involved must be clarified to decide whether public and rescue team should be allowed to use barriers when subjected to lava flows.

Concluding summary

The measures taken during the 2021 eruption to divert and/or contain lava flow by diversion barriers/dams constructed from in situ material demonstrated that such defences can be effective in controlling lava in the field. This aligns with previous experiences reported by Barberi et al. (1993, 2003), Jónsson (1992), Colombrita (1984), and Macdonald (1958, 1962).

The two dams in this study delayed lava flow by 4 to 16 days, respectively. Furthermore, the diversion barriers successfully diverted and changed the direction of pāhoehoe lava flows. The dams and heaps also altered the direction of the pāhoehoe lava flow before and as the lava piled up. The present case demonstrated that a successful outcome is governed by considerable unforeseeable factors relating to the eruption, the lava flow, and the site conditions. It was valuable to experience the variety of loading from the lava, depending on both the lava types/phases and types of barriers (heap/dam/diversion barrier) throughout the eruption.

The dams and diversion barriers were mainly subjected to pāhoehoe lava flow, while some of the heaps were subjected to ʻaʻā lava fronts and others to pāhoehoe flows. No signs of yielding or cracking on the downstream part of the barriers were observed under the thrust of neither ʻaʻā nor pāhoehoe lava prior to overtopping. An ʻaʻā lava front thickened considerably behind the heaps with the lava margin standing up to 2 to 4 m above a heap's top. However, the pāhoehoe lava piled up behind the dams and heaps. In the case of the dams, the lava piled up relatively fast, reaching thickness of 6 to 7 m in the largest lava incidents prior to overtopping. At the West Dam site, for example, a 6-m deep local storage of lava formed in about an hour in a single lava incident. The spilling with overtopping of the dams occurred in subsequent lava flows as soon as the lava storage behind them was full.

Pāhoehoe lava creeping slowly over dams and heaps did not cause erosion or damage, while the overtopping of fast concentrated flow could cause erosion and slope failure in locations with a weak crest of heaps formed through emergency bulldozing. Hence, emergency bulldozing to rapidly increase the height of a dam that serves as the primary defence is not recommended without careful analysis and recognition of the consequences. An insubstantial dam is more prone to failure compared to a robust one. Given that the lava stored behind a dam is a ponded molten material, like a lava lake, a dam failure can result in rapid large sheet flow from it as it falls. However, pāhoehoe lava piling up slowly against a dam, with overlapping thin flows as described by Barberi et al. (1993), is unlikely to cause failure of a dam. The same applies for relatively small dams, such as the ca. 8-m high dams in this study, which are subjected to very slow lava overtopping, like the West Dam.

The importance of considering the lava type in the design of lava barriers is highlighted. There is a need for investigations and measurements to confirm important aspects relating to the thrust of ʻaʻā lava on barriers, as well as erosion potential of lava flow, and to further develop design criteria for lava defences.

One of the lessons learned relates to how to potentially tackle lava flows into the construction site with emergency responses comprising the elongated heaps. The alignment and placement of the heaps need to be considered carefully to ensure a successful outcome. In general, when dealing with pāhoehoe lava, it is more beneficial to locate the heaps at some distance from the existing lava front to provide space for the diversion of new lava flows. Moreover, the heaps should be aligned to divert lava flows.

The risk associated with construction work at an eruption site must be assessed to identify safety precautionary measures for the workers. Thus, it was important to gain experience in working under the threat of lava flows, including glowing lava, as well as under the threat of toxic gas conditions. It was also useful to explore the possibilities and limitations of the construction equipment used under challenging conditions as well as the construction methods. The available construction equipment was at the minimum. Still, the construction was relatively fast with a bulldozer and an excavator if sufficient construction material comprising overburden was available at the site. This reasonably aligns with past experiences such as reported by Barberi et al.(1993), Colombrita (1984), and Macdonald (1962).

Based on the experience from the measures taken during the 2021 Geldingadalir eruption, it is recommended to consider physical measures to mitigate lava flow for populated areas (and important infrastructure) prone to volcanic risk, and to do so in a timely manner. For the present case, the benefits of timely decision-making would have been accessibility of construction material on the lava side of the defences and being able to finalize the construction without lava flows into the construction site. The likelihood for effective lava flow mitigation increases with the time given to strategically plan, design, and construct potential defences. However, it should be recognized that early defences built in advance may not be subjected to lava flows, e.g. if fissures open at a different location than anticipated, or if lava stops flowing in the direction of the defence, or the eruption ceases as, e.g., was the case for the South Dam (Fig. 1) in Nátthagi.

It is strongly advisable, for areas at risk, to have a mitigation plan ready beforehand (see, e.g., Chirico et al. (2009)). With increased risk, the need increases for engaging a construction contractor of high capacity to carry out the measures, while planning, design, and continuous study of the lava flow should be in the hands of a team of technicians, engineers, and earth scientists. Furthermore, in the case of a volcanic eruption threatening a populated area, it is of utmost important that decisions are made quickly, and that authoritative issues do not cause delays in the decision process for the construction of mitigation measures.

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