The Icelandic Glacier Tunneling System

H.Ö.Arngrímsson
VERKÍS Consulting Engineers, Reykjavík, Iceland

R. Sævarsson
EFLA Consulting Engineers, Reykjavík, Iceland

ABSTRACT: In the year 2010, two pioneers in Iceland came up with the idea to create the first man-made glacial tunnel as an all year around tourist attraction. After three years of planning the excavation started in 2014. The project goal was to make glaciers in Iceland safe and accessible to all and let people experience the “blue ice” found at approximately 30 meters depth, crevasses and all which a glacier has to offer. The excavation was 5.500 m^3 of ice and took 12 months to complete. The tunneling system consists of a 6 ton excavator with a drum cutter attachment and two telehandler payloaders. The maximum length excavated during one shift was 20 m/day. This article will describe the history of making the largest man-made ice cap glacier tunnel in the world, location of the tunnel, the tunneling system used, problems encountered, safety measures, investigations done on the glacier and the experience gained for future projects like this around the world.

1 PREFACE

This report was prepared by Hallgrímur Örn Arngrímsson, Civil Engineer, VERKÍS Consulting Engineers and Reynir Sævarsson, Civil Engineer, EFLA Consulting Engineers, Reykjavík Iceland. The Langjökull tunnel project is a collaboration of more than 100 individuals which all have contributed to the success of the project. Technical design and supervision were carried out by EFLA Consulting Engineers.

2 INTRODUCTION

Tourism is big in Iceland with over 2.000.000 guests a year before Covid-19. Langjökull glacier, the second largest in Europe, has long been an attraction for travellers and tourists in Iceland. Tour operations have used the glacier for guided jeep-, sled-tours and other project operations for many years. The top of the glacier is above 1.300 meters. The weather environment in the glacier can be extreme with -30 degrees frost and winds over 40 m/s. Throughout the year, low pressure storms overrun the country frequently, so the temperature is often fluctuating above and below zero. The glacier is also known for crevasses that need to be crossed when traveling in the area. All of this makes operation on the glacier a major challenge.

In the year 2010 Hallgrímur Örn Arngrímsson civil engineer and Baldvin Einarsson tour operator in Norway, came up with the idea to build an ice tunnel on the top of the glacier as an all year around tourist attraction. The idea was to excavate the tunnel down to 30 m depth to experience the dense blue ice. The tunnel would have one entrance and a circle walkway with attraction along the way. The idea was introduced to Icelandair and further developed by Hallgrímur and Reynir Sævarsson civil engineers at EFLA Consulting Engineers. For the next three years EFLA worked on the feasibility study, concept, and development design in cooperation with the Institute of Earth Science, Icelandic Glaciology Society, Icelandic Met Office, Local Community, landowners and many more. In 2013 Icelandic Tourism Fund I, owned by Icelandair, Landsbankinn and Icelandic Pension Funds, bought the project. In the spring of 2014, the technical design of the ice tunnel was finished and construction started.

3 LOCATION

There were many things considered when choosing the location of the tunnel. The surface of the glacier had to preferably be free of large crevasses to make the journey safe. Langjökull glacier is over 900 km^2 and it contains about 190 km^3 of ice. It is approximately 650 m thick at the most with an average thickness of about 210 m. Underneath the glacier is a vast landscape of valleys and mountains. Some mountain peaks reach above the ice cap. The topography affects the glacier flow and location of the crevasse zones. The flow rate varies and is highest around the glacier boundary than and where the topography underneath is steep.
The equilibrium line altitude (ELA) is located between 1150 m up to 1250 m. Above this line is where snow from previous winter does not entirely melt in the summer. The tunnel had to be located above the ELA but not too high to minimize the additional overburden pressure on the tunnel from the annual snow increase. The location for the ice tunnel is shown in Figure 1. This was the most optimal location. The tunnel is located at an altitude of 1250 m, northwest of the ice break line. The area has a slope of about 12%, few large cracks, an average annual snow precipitation of about 1-2 m per year. The tunnel moves annually about 10-12 m each year to the northwest.

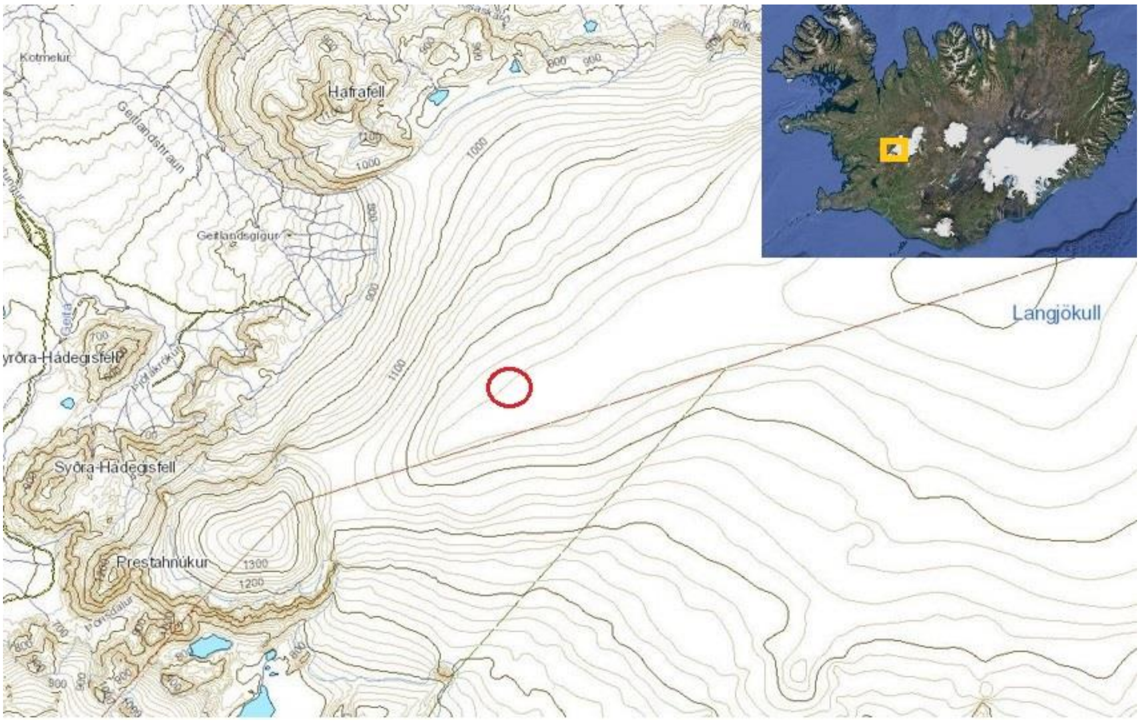

Figure 1. The ice tunnel location.

4 ACCESSIBLITY

Access to the area is very important in terms of travel time from the glacier boundary and safety concerning crevasses. The drive on the glacier is done in specially modified 8x8 vehicles that can easily drive on snow and ice on 56” tires. The tour operators use GPS navigation to travel along a safe track called the “ice road” which is maintained with a bulldozer throughout the year. The tunnel entrance is like a one eye binocular because it needs to flow with the annual snow conditions, longer tunnel in the winter and shorter in the summer. Also, the tunnel sinks down into the glacier some years which then makes the entrance tunnel longer.

5 EARLY TUNNEL DESIGN

The tunnel was designed to be the optimum glacial experience for all people visiting around the world, a visit centre for education on glaciers and global warming. In the beginning the tunnel design was 300 m long with a small cross-section of 1,2m x 2,0m. The main attraction was at the end of the tunnel at 30 m depth in the blue ice caves and tunnels. The tunnel would drain itself and no water pumps were to be used. Ventilation was to be natural, and lights would be LED powered by solar and wind.
Calculations showed that the deformation, for a circular cross-sectional ice tunnel, would increases in the third power with depth. This meant that maintenance of the tunnel would increase drastically with depth. The plan was not to exceed further down than to 30 m depth because of this. Another reason for not going deeper is because the overburden pressure closes the crevasses and then water pumps would have to be used to drain the melt water that seeps into the tunnel. This would slow down tunnel excavation and increase maintenance cost. Figure 2 shows a cross-section and a longitudinal profile of the tunnel.

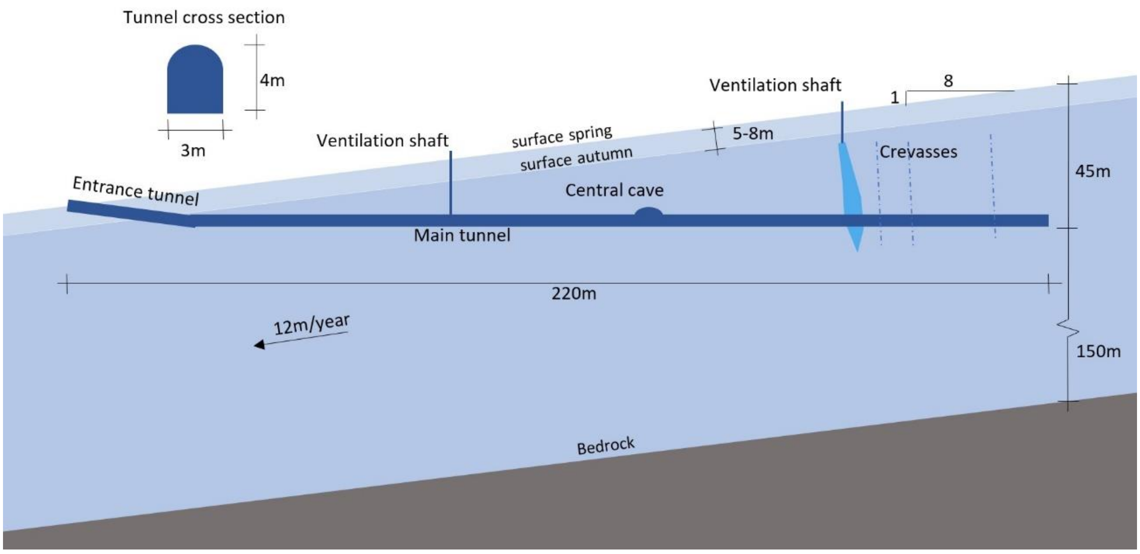

Figure 2. Cross-section and longitudinal profile of the ice tunnel.

6 EXCAVATION EXPERIENCE

6.1 *Manpower*

Local contractor was hired for the excavation. The workers were mainly farmers, mechanics, sailors and people from the local rescue team. Specialized tradesmen with mountaineering experience were also hired from Reykjavik. During the excavation, which was done in the winter of 2014-2015, the team managed to be very resourceful in difficult weather conditions, fixing equipment and traveling on the glacier.

The risk assessment for the project revealed the highest risk traveling back and forth to the tunnel site and working around the excavation equipment in small spaces. There was also the risk of falling on the icy floor in the tunnel. These risks were mitigated, and no accidents or injuries happened during construction.

Generally, the traveling time to the tunnel worksite was 1,0-1,5 hours with specially modified super jeeps. Therefore, the plan was not to have sleeping facilities on the glacier. The only site facilities during the excavation were an insulated container and portable toilet which was buried into the glacier. Those days when bad weather hit the glacier the traveling time was many hours and sometimes the workers did not reach the tunnel entrance and turned back with no excavation work done that day. It is estimated that the traveling time was between 15-40% of the daily working hours, depending on the weather. In retrospect, it would have been more economical to set up accommodation near the tunnel entrance to reduce the time spent on travel.

6.2 *Equipment*

The plan was to excavate down to 30 m depth with a minimum size tunnel. The tunnel cross-section design was only 1,2 m in width in the beginning to minimize the excavated material. In the preliminary phase the design team tested different equipment and excavation approaches. A small drum cutter machine was built based on similar equipment used in Antarctica (Walsh, 1999). The machine would grind the ice and the ice would then be vacuumed to a trailer and driven out by snowmobiles. This did not work well because Langjökull glacier is a temperature glacier with temperature at or close to 0°C. The snow, firn and ice in the top layer of the glacier was too loose and wet, different from the Antarctic conditions. Chainsaws were used in Antarctica (Walsh, 1999) and Greenland (Abel 1961) to make cutting patterns and blocks into the ice before excavation, this was tried in Langjökull with poor results.

The contractor then bought a small drum cutter on a 1,5 ton excavator and a telehandler with 1 m^3 shovel to drive out the firn. This increased the planned tunnel cross-section size but despite excavating more m^3 the excavation speed increased. The tunnel was now about 30-40 m long and the firn still filled with air and fairly loose to excavate. The tunnel speed was about 12 m/day. The second telehandler unit was brought on site because moving the firn out of the tunnel was slowing down the excavation. Niches were also excavated in the tunnel for equipment to pass. This excavation method worked well and was used in the design and planning of the next phase of the tunnel excavation.

Further down the firn became harder and the contractor upgraded to a 6 ton excavator which could put enough pressure on the drum cutter. By changing to a bigger machine the ceiling was made higher. The entrance tunnel was now about 100 m long and the tunnel was split into two directions with two excavation teams working simultaneously. Total of 5.500 m^3 of snow, firn and ice was excavated with an average rate of 4,8 manhours/m^3.

6.3 *Navigation*

The plan was to make a circular 400 m walking route from the end of the entrance tunnel with exhibition caves along the way. It was difficult to make the two tunneling teams connect the two tunnel fronts. Together with the contractor the project management used measurement tapes and height tripods to correct the excavation directions. The contractor “got lost” a few times so there are some extra tunnels which now makes the glacier visit a more exciting experience.

6.4 *Tunnel Entrance*

The excavated material was dumped outside the tunnel entrance and a bulldozer was used to even it out. The excavation started in the spring of 2014 with winter snow melding on the surface during the summer. When it started to snow in the area and driftsnow accumulated around the tunnel entrance the bulldozer proved to be necessary to clear the snow and maintain the opening of the entrance. The drift snow moving on the glacier was always blocking the entrance and much time went into opening it when starting each shift. To solve this a timber culvert was built to extend the tunnel entrance further away from the surface and drift snow.

6.5 *Crevasses and Bridge*

After 4 months of excavation the team had not experienced any crevasses in the tunnel. Suddenly after excavating 120 m into the glacier the team hit a giant crevasse. The crevasse was closed in the top and therefore not visible on the surface. The length of it was about 150 m and the width span that needed to be crossed was about 5 m. A bridge was designed over the crevasse with a roof that could support heavy snow/ice fall.

6.6 *Ventilation*

The machines used diesel fuel which meant that all the staff had to always wear gas monitors. Ventilation was a constant challenge with the risk of snow blocking openings on the top and changing tunneling conditions. During construction there were three ventilation units operating in the tunnel. Ventilation ducts, diameter 300 mm, were placed in the ceiling and extended along with the excavation on the tunnel front. In three locations shafts were drilled vertically up to the surface with commercial ice drills with extensions. Ventilation pipes were always observed during each shift because of the risk of snow blockade. The exhaust from the excavator at the front was connected directly to the ventilation with a flexible steel duct that could withstand the exhaust heat. This worked well. After hitting the crevasse, a ventilation hole was placed at the top which improved the natural ventilation in the tunnel and after that air quality was not a problem.

6.7 *Light design*

The tunnel is completely black without lights. A diesel generator was placed in a niche in the tunnel entrance. The generator charges a battery pack unit that services the lights in the tunnel. During construction Christmas LED lights were placed in the ceiling. For the final light design the electrical distribution was through cables placed in the floor and walls. The cable routes and lights were made with a steam gun unit. All the lights are LED which minimizes the melting of the ice surrounding the lights. The lighting design in the Langjökull ice cave tunnel took the top spot in two categories of the prestigious international lighting design competition, The 2016 Darc Awards. The design was the winner of the category „Spaces: Best Landscape Lighting Scheme" and was also voted best project of the year „Darc Awards: Best of the Best". The lights are maintained annually because of the ice deformation and melting of ice around lights and cables.

7 THE ICELANDIC TUNNELING SYSTEM

The project had many trials and errors but based on the experience from this tunnel project in Langjökull, Iceland now has a tunneling system that can hopefully be used to make ice tunnels in other glaciers around the world. The optimal tunnel cross-section is approximately 3,0-3,5m wide and 3,5-4,0m high. The excavation is most efficient with a 6 ton excavator mounted with a drum cutter. This type of machine is mainly designed to be used for excavation of soft rock.
When about 1-2 m of the front has been excavated the excavator moves from the front so the telehandler unit can dig out the material. When the telehandler is operating the excavator is working on caves in other parts of the tunnel to minimize down time. The ventilation needs to be observed during construction and adjusted with the tunnel excavation. Vertical shafts should be

installed up to the surface at intervals along the tunnel to increase the natural ventilation. Ventilation unit should be directly connected to the excavator if possible, to prevent soot. Workers should always be equipped with air quality detectors that measure high concentration of CO_2 and low concentration of O_2. For electricity and lighting the project used a diesel generator, battery packs and LED lights. The generator is placed in a niche in the entrance tunnel and the exhaust goes vertically to the surface. Lights should be LED to minimize melting of the surroundings. For site facilities it is important to have a dry, warm and isolated area for workers to rest during the shift. To minimize traveling time a temporary base camp facility should be excavated on the surface with kitchen and accommodation.

8 DEFORMATION CALCULATIONS AND MEASUREMENTS

Ice deformation measurements were carried out in tunnel caves in 2015 and 2016 in cooperation with the University of Iceland and Into the Glacier. This was done to help estimate the lifetime of the tunnel and compare deformation to theoretical models. Measurements were done three times over a two month period in four different locations. There was about 8 m of snow that accumulated on the surface the first two years after opening of the tunnel. Deformation increased by 15-20% between the two years. Deformation in the deepest part of the tunnel at 50 m depth was 50-70 cm/year horizontal and 20-60 cm/year vertical (Pétursdóttir, 2015 & 2016). Further deformation research is needed with more accurate measurements of overburden pressure and ice density to be able to correlate data with current theoretical models of ice deformation behaviour.

9 LIFETIME OF THE TUNNEL AND MAINTENANCE

In the beginning it was estimated that the lifetime of the tunnel would be about ten years. After seven years in operation the tunnel and caves have deformed and the areas that have not been maintained have vanished. The entrance tunnel is much longer, overburden pressure is higher, and water is becoming difficult to divert into open crevasses. Maintenance work has always been a big part of the operation and walls and ceiling are constantly being excavated out during the low tourist season. With annual maintenance the lifetime of the tunnel is now estimated to be 20 years.

10 CONCLUSION

Despite many challenges during construction the project was a success. The length of the tunnel is about 500 meters with a designed cross-section of 3,0m x 3,5m. This makes it the largest manmaid ice tunnel in the world (Into the Glacier, 2022). Approximately 5.500 m^3 of snow and ice was excavated with an average excavation rate about 4,8 manhours/m^3. Figure 3 shows the final plan layout of the tunnel. There was a lot of downtime because of snowstorms which increased the traveling time. A camp site should be constructed on site for the next project. There is a possibility for improvement of the ventilation system which can be simpler with less maintenance. Electrical excavators might be considered but the heat from the excavators was beneficial for the workers and the exhaust was not a problem. The location of the tunnel is perfect regarding snow accumulation and glacial movement. Deformation in the tunnel was as expected. The total construction cost was about 2,8 million euros. The lifetime of the tunnel is now estimated to be around 20 years with annual maintenance. The project which is now called “Into the Glacier” has proven to be one of the most successful tourist attractions in Iceland and is still operating.

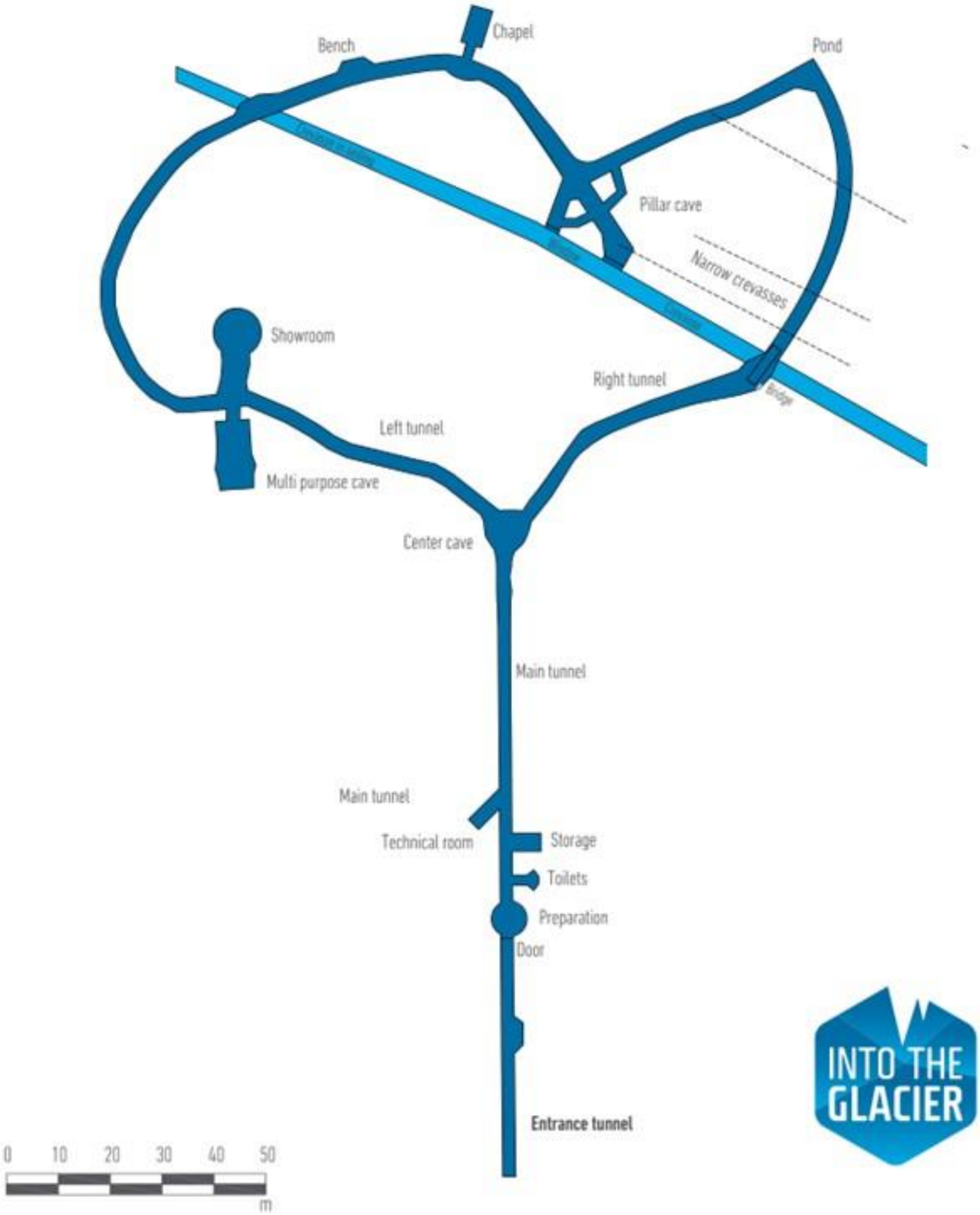

Figure 3. Plan drawing of the ice tunnel (Into the Glacier, 2022).

11 REFERANCES

Abel, J.F. 1961. Under-Ice Mining Techniques. *Technical Report 72*. U.S. Army Cold Regions Research and Engineering Laboratory. Corps of Engineers.

Into the Glacier. *About Into the glacier*, 2022. URL: http://www.intothegalcier.is/about/. Last checked 16th of October, 2022.

Pétursdóttir, S. 2015. *Aflögumælingar í ísgöngum í Langjökli bornar saman við líkön Van Der Veen og Nye með næmnigreiningu.* B.Sc. thesis. Reykjavík. The Faculty of Earth Sciences University of Iceland.

Pétursdóttir, S. 2016. *Aflögumælingar í Langjökli 20. apríl – 14 september 2016.* Memo done for Into the Glacier.

Walsh, M. R. 1999. The CRREL South Pole Tunneling System. *CRREL Rep. 99-1*, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.