Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3
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doi: 10.32075/17ECSMGE-2019-1078

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Sigalda dam leakage – a 40-year review
Fuites d'eau du barrage de Sigalda – bilan de 40 ans

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ABSTRACT: The Sigalda dam on the Tungnaá river in Iceland is a 44-m high asphalt faced rockfill dam. The volume of the associated reservoir is 195 million m^3. The dam is founded partly on hyaloclastite volcanic rocks, (*moberg* in Icelandic) and to large extent on pervious postglacial lava flows. One of the reservoir abutments consist also of thin lava flows with pervious interbeds. Construction of Sigalda rock-fill dam was started late in the year 1973 and completed in late 1975. During first impounding of the reservoir in August 1976, leakage from the reservoir was much more than had been expected, and water entered the dam body from the pervious lava flows abutment causing high pore pressure in the rockfill body. Thus, impounding had to be stopped and the reservoir could not be filled completely, even if electricity generation could commence in the connected Sigalda Hydropower Plant. After several attempts to reduce the leakage during the first years of operation, the reservoir could be filled to spillway level. Since then, the leakage has gradually decreased due to self-sealing. The paper discusses methods to locate main leakage areas in the reservoir bottom, the successful sealing measures and shows subsequent gradual decrease of the leakage during 40 years of operations of the dam.

RÉSUMÉ: La digue de Sigalda sur la rivière Tungnaá, en Islande, est un barrage en enrochement d'une hauteur de 44 m. Le volume du réservoir associé est de 195 millions de m^3. Le barrage est fondé en partie sur des roches volcaniques en hyaloclastite (*moberg* en islandais) ainsi que, dans une large mesure, sur des coulées de lave postglaciaires perméables. L'une des culées du réservoir consiste également en de fines coulées de lave avec des lits perméables. La construction du barrage en enrochement de Sigalda a débuté à la fin de l'année 1973 et s'est achevée vers la fin de 1975. Lors de la première mise en eau du réservoir en août 1976, les fuites du réservoir ont été bien plus importantes que prévu et des quantités d'eau ont pénétré dans le corps du barrage, a travers les piliers de coulées de lave perméables, causant une pression de pore élevée sur le corps en enrochement. Ainsi, la mise en eau a dû être arrêtée et le réservoir ne pourrait pas être rempli complètement, ce qui n'a pourtant pas empêché le demarrage de la centrale hydro-électrique de Sigalda. Après plusieurs tentatives visant à réduire les fuites au cours des premières années d'exploitation, le réservoir pourrait être rempli jusqu'au niveau du déversoir. Depuis lors, les fuites ont progressivement diminué grâce à l'auto-étanchement. Le document aborde les méthodes permettant de localiser les principales zones de fuite dans le fond du réservoir, les mesures prises avec succès contré l'étanchéité et démontre une diminution progressive des fuites au cours des 40 années d'exploitation du barrage.

Keywords: Sigalda HEP, dam, leakage

1 THE SIGALDA HEP

The 150 MW Sigalda HEP was constructed in 1973-78. The project is located on the glacial Tungnaa river in Southern Iceland at elevation 420-520 m a. s. l., Figure 1. Design discharge is 260 m^3/s and brutto head is 74 m. The Sigalda dam is about 44 m high rockfill dam with asphalt concrete upstream face sealing. Spillway crest elevation is at 498 m a. s. l.

During filling of the reservoir in 1976-77, large leakage developed along the relatively young lava flows on the SW-rim of the reservoir. The leakage water entered the dam body from the left abutment threatening the safety of the dam so the reservoir could only be filled to 490-492 m, which was sufficient for energy generation to begin.

In the following, the successful mitigation measures, executed in the first years of operations, are described together with historical leakage records extending over 40 years showing reduction of the leakage due to reservoir sealing measures and subsequent self-sealing of the reservoir.

Figure 1. Location map, project layout

2 GEOLOGICAL CONDITIONS

The Sigalda dam is founded on hyaloclastite rock (moberg in Icelandic) on the right abutment and the postglacial (4000-7000 years old) Tungnaá lava flows under the main dam body and on the left abutment, Figure 2. The reservoir abuts up to four of the Tungnaá lava flows with pervious interbeds.

At the time of construction, the reservoir was considered to be a reconstruction of an ancient lake emptied some 3000 years ago. The top lava flows were reported as very fissured with some deep depressions down to ground water level. However, the lava flows were believed to be filled with diatomaceous earth, ash and alluvial material from the ancient lake (R. Thorlaksson et al.). Some of the ancient sealing was reported to be eroded and needed re-sealing.

3 RESERVOIR FILLING

During initial filling of the reservoir some unexpected leakage was encountered and the filling had to be done in several stages with sealing measures executed between filling attempts. The process was as follows:

First filling attempt took place in August 1976 when the reservoir level was raised to 485,5 m. Due to high water level in the dam body the reservoir was emptied and drainage ditches excavated downstream of the dam to lower the water level within the dam body.

Second filling was attempted in November 1976 when the reservoir level was raised to 487 m, then emptied again and drainage pipes arranged in rock fill placed at the dam toe.

Third filling took place in June 1977 when the reservoir was filled to a level of 490 m. Due to large leakage entering the canyon downstream of the dam, the reservoir was emptied for sealing measures as discussed in section 4.2 *Sealing measures*

Fourth filling took place in November 1977, now up to a level of 492 m, then again lowered to 490 m for operations during the winter.

Fifth attempt to fill the reservoir took place in July 1978, now up to level of 494 m, then lowered to 489 m and some 70 swallow holes identified at the edge of the reservoir were filled with sand and gravel.

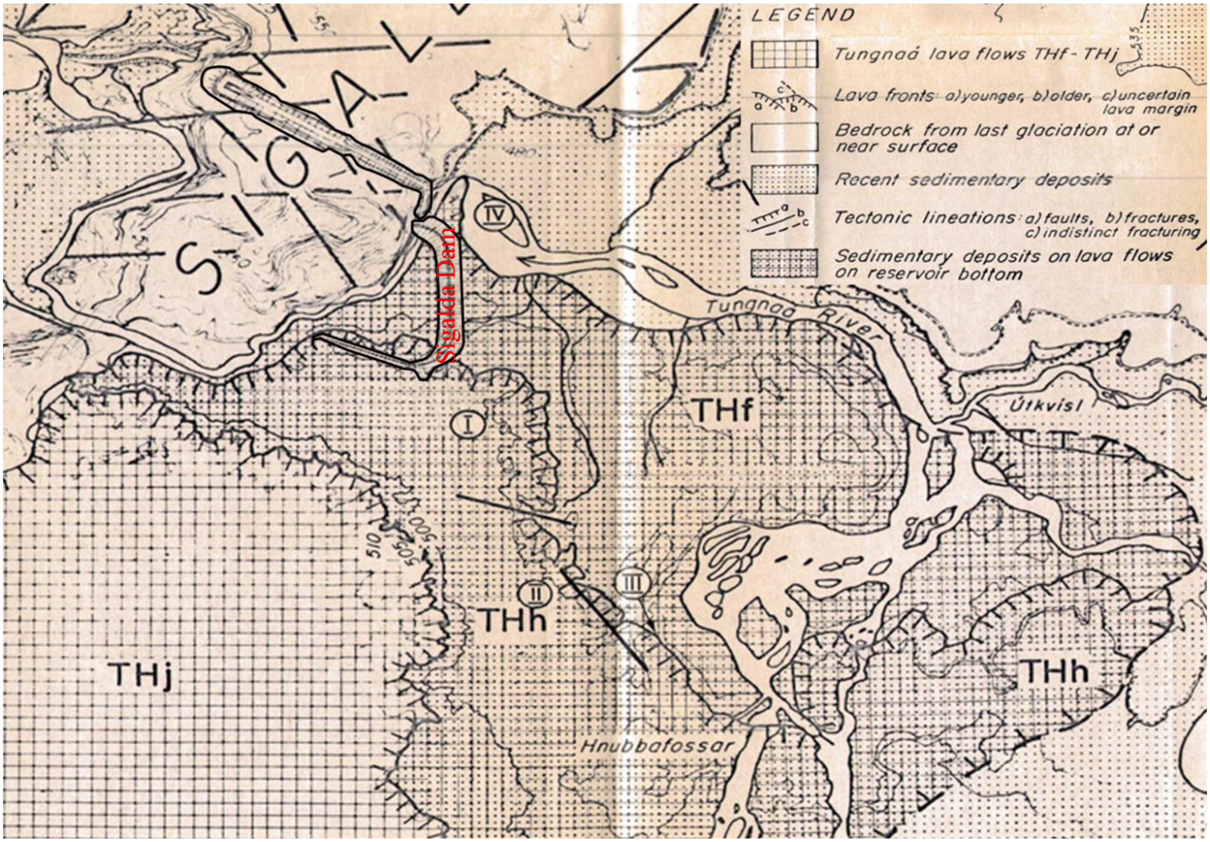


Figure 2. Geological map of the Sigalda dam and reservoir SW-rim

Sixth attempt took place in October 1978, now up to a level of 495 m, then lowered to 490 m for winter operations. In the spring of 1979, a dredging barge was placed on the reservoir which pumped about 60.000 m^3 of sand on reservoir bottom areas considered to be leaking.

Seventh attempt of filling took place in June 1979 raising the water level to 495,5 m. Subsequently, the reservoir level was lowered to 485 m and filter cloth and gravel placed on about 2500 m^2 of leakage areas between elevation of 491 m and 495 m.

Eight attempt to fill the reservoir took place in October 1979, raising the reservoir level to 497,6 m, only 0,4 m below spillway crest level.

In July 1980, the reservoir was filled completely for the first time up to the spillway crest level. After some improvement measures at the dam toe in 1983, it was considered save to allow uncontrolled reservoir filling in spring of 1984 resulting in maximum water level of 499,16 m and discharge up to about 200 m^3/sec. on the spillway.

4 RESERVOIR SEALING

After each of the filling attempts in the years 1976-1980, measures were taken to seal the reservoir bottom. After the first three filling attempts the reservoir was completely emptied and leakage areas could be visually inspected at the reservoir bottom and covered with sealing material. On the other hand, after filling attempts 4-8, the reservoir could not be emptied as generation had started. Therefore, innovative methods were developed to locate leakage areas/spots under water at the reservoir bottom. Sometimes, the reservoir level could be lowered by a few metres and leakage areas at the reservoir rim visually identified. In the following, the methods used to find leakage areas under water are described.

4.1 Survey methods to identify leakage areas

a. Side-scan survey

After the fourth filling, the bottom of Sigalda reservoir was mapped with a side-scan survey carried out by the Icelandic Marine Research Institute MRI (Kjartan Thors and co-workers). The aim of the survey was to see if the Sigalda reservoir bottom exhibited localised signs of leakage. Such signs were expected to be in the form of holes, coarse sediments or solid rock at the bottom. The side-scan sonar distinguishes such features well, as they are very reflective and give a strong, dark response on sonographs.

Because the topography of the reservoir bottom was very well known, the map from the MRI therefore emphasized features that were different from existing maps and aerial photos.

Figure 3 shows typical results of the side-scan survey. Different colours are used to describe different features.

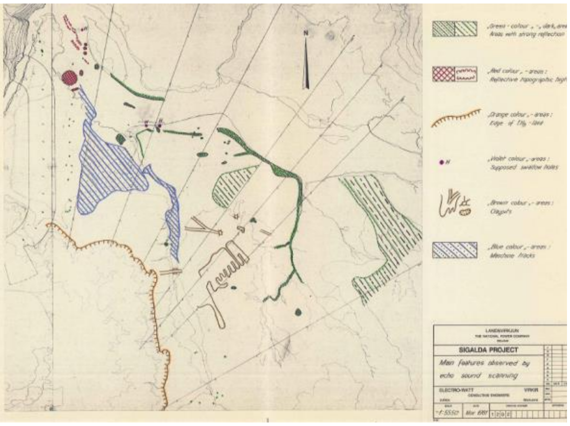


Figure 3: Typical results of side-scan survey

b. Bottom current measurements

The Laboratory of Hydraulics, Hydrology and Glaciology of the Federal Institute of Technology in Zurich, Switzerland was asked to carry out measurements of bottom currents in Sigalda reservoir. The aims were to:

- Measure the current at points of tracer injection to facilitate the interpretation of tracing experiments.
- Measure the current in areas suspected to be leaky in order to discover swallow holes.
- Perform continuous measurements with anchored current meters at three points, to get information's on long – term flow patterns.
- Measure temperature profiles in order to control density stratification of reservoir water.

The specification of the instruments was: range 0 to 2,5 m/sec, resolution 2 mm/sec.

Thermistor range: -2 to +38^{0}C, resolution 1/100 ^{0}C. Compass resolution 3^0.

The result of the measurements was that the correlation of wind activity and bottom current records showed clearly that the wind was the dominant factor driving the water masses of the reservoir. The similarity of the temperature records that shows long- and short term changes are not due to local effects but was the result of temperature changes on a larger scale. In a strong wind the lake was wholly mixed up. Thus, the bottom current measurements could not be used to identify leakage areas.

c. Tracing tests

Tracing tests were carried out during the summer 1981 and 1982. They turned out to be an excellent method to localize seepage spots at the reservoir bottom. For the tracing test, Fluoresceine and Amidorhodamine were used. For every injection 3 to 5 kg were applied. As a third tracer, radioactive Iodine J-131 was used but it was not as successful as the Fluoresceine and Amidorhodamine. In general, Fluoresceine yielded better results than the other tracers.

The tracer injections were carried out from a boat which was only used for this purpose to prevent any contamination. Main equipment used was a pump, fire hoses and a funnel, shaped like an umbrella, that was lowered to the injection spot previously marked by a buoy. The method allowed a very clean operation and the system prevents any spilling and was furthermore easy to work with. A separate container should be used for every dye.

The outcome of the tracing tests showed that the main seepage occurred along the lava fronts and the original pervious riverbed. The infiltration water travels mainly along the bottom scoria and the interbed of THf/THc-lava and daylighted within a few hours at the downstream dam toe. A special water conveying system appeared to be the river diversion canal, used during construction of the dam, which acted as an artificial drain. The diversion canal was blasted into the THf-lava and afterwards refilled with rather coarse material according to the tracer tests. The THf-lava exhibits furthermore in this area a very pronounced top scoria with numerous open joints, providing well developed leakage paths. Connections to the lower THf-bottom scoria are possible, however according to the tracing tests not very pronounced. It was obvious that the up to 15 m deep grouting curtain was not very effective in this area.

4.2 Sealing methods

After the first two filling and emptying of the reservoir in 1976, the main concern was safety of the dam body. Thus mitigation measures were directed at ensuring its safety by excavation of drainage ditches at the dam toe and install toe drain rock fill with a drainage pipe. After the third filling, sealing of the reservoir bottom was started by placement of a sealing blanket of about 100.000 m^2 on the edge of the THh lava flow at elevation 485-491 m, Figure 4. Simultaneously, the river course, where the ancient fine material was eroded, was covered with 0,5 m thick clay layer.

After the fifth filling attempt in 1978 some 70 swallow holes at the reservoir rim were filled with sand and gravel.

In the spring of 1979 (after the 6th filling attempt), a dredging barge was used to dredge sand and gravel and dump over suspected leakage areas at the reservoir bottom. A total of 60.000 m^3 were dumped covering an area of about 40.000 m^2.

After the 7th filling attempt in the summer of 1979, the reservoir was lowered to 485 m and leakage areas covered with filter fabric, sand and gravel. A total of 2500 m^2 of the THh lava edge between elevation 491-495 m was covered in this way.

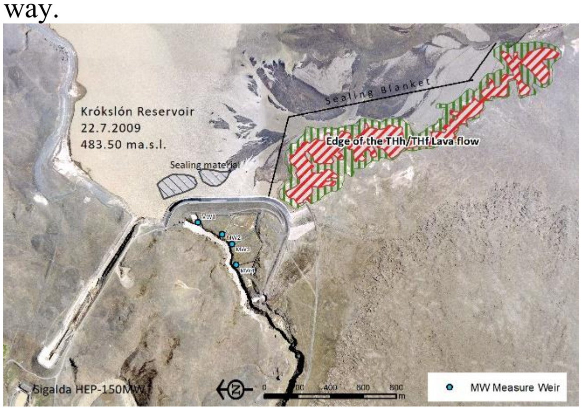
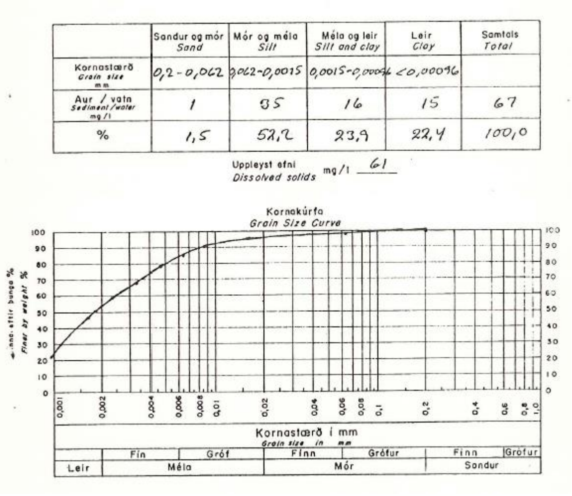


Figure 4: Reservoir bottom areas sealed in 1977-82. Areas sealed in 1981-82 with a barge are uppstream of dam. Leakage monitoring weirs downstream of the dam are shown with green dots.

After identifying leakage spots by tracer tests in 1980-81, a self propelled, splitted, 150 m^3 capacity barge was brought to the reservoir. The barge was used to dump moberg (hyaloclastite rock material) followed by dumping sand into areas previously identified by tracer tests as suspected leakage areas, shown as two area just upstream of the Sigalda dam on Figure 4. The sealing works were executed during August-October 1981 and June-August 1982. The areas were covered by 2 m thick moberg and 1 m thick sand. Total areas covered were 55,390 m^2. A tracing test on the sealing carpet showed that the carpet was effective and the turbidity measured in leakage water reduced after placement of the carpet. A typical turbidity in reservoir water over the summer time is shown on Figure 5.

Figure 4 shows all areas of the reservoir bottom which were sealed with various measures in 1977-1982. Figure 4 also shows location of the 4 measuring weirs to monitor leakage downstream of the dam.



	Sandur og mór Sand	Mór og méla Silt	Méla og leir Silt and clay	Leir Clay	Samtals Total
Kornastærð Grain size mm	0,2 - 0,062	0,062-0,0015	0,0015-0,00096	<0,00096	
Aur / vatn Sediment/water mg/l	1	35	16	15	67
%	1,5	52,2	23,9	22,4	100,0

Uppleyst efni
Dissolved solids mg/l 61

Figure 5: Grain size of material dissolved in reservoir water in summer time

5 LEAKAGE HISTORICAL RECORDS

Leakage from the Sigalda reservoir (Krókslón) has been carefully monitored from first attempt to fill the reservoir in 1976. There are four seepage collection points with overflow weirs where the seepage is monitored. During the first years of operations, there were manual readings, at first 4 times during each 24 hours, later once a day and then once a week. Since 1986, the readings have been automatic.

Figure 6 and 7 show a comparison of dam toe leakage in 1994 and 2015.

Figure 8 shows development of leakage rate at one of the four measuring weirs downstream of the dam. The leakage at this particular weir has reduced from from about 1500-1600 l/sec. to 400-500 l/sec. in 40 years.

Figure 9 shows development of the total leakage from the reservoir in 1977-2018. It shows that the sealing measures were effective in reducing the leakage during first 10 years of operations and since then self-sealing has reduced the leakage significantly or from about 15 m^3/sec. to about 6 m^3/sec. Self-sealing is still reducing the leakage after 40 years of operations.

Figure 6: Leakage at dam toe at full reservoir in 1994

Figure 7: Leakage at dam toe at full reservoir in 2015

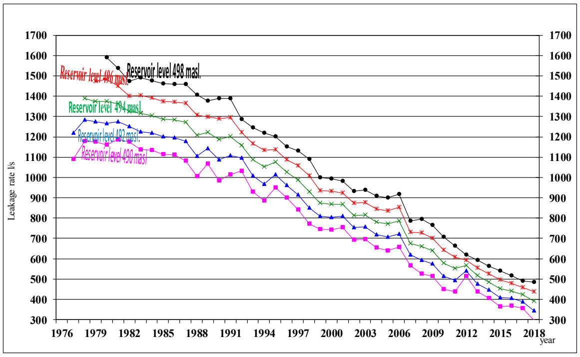


Figure 8: Leakage at one measuring weir downstream of dam

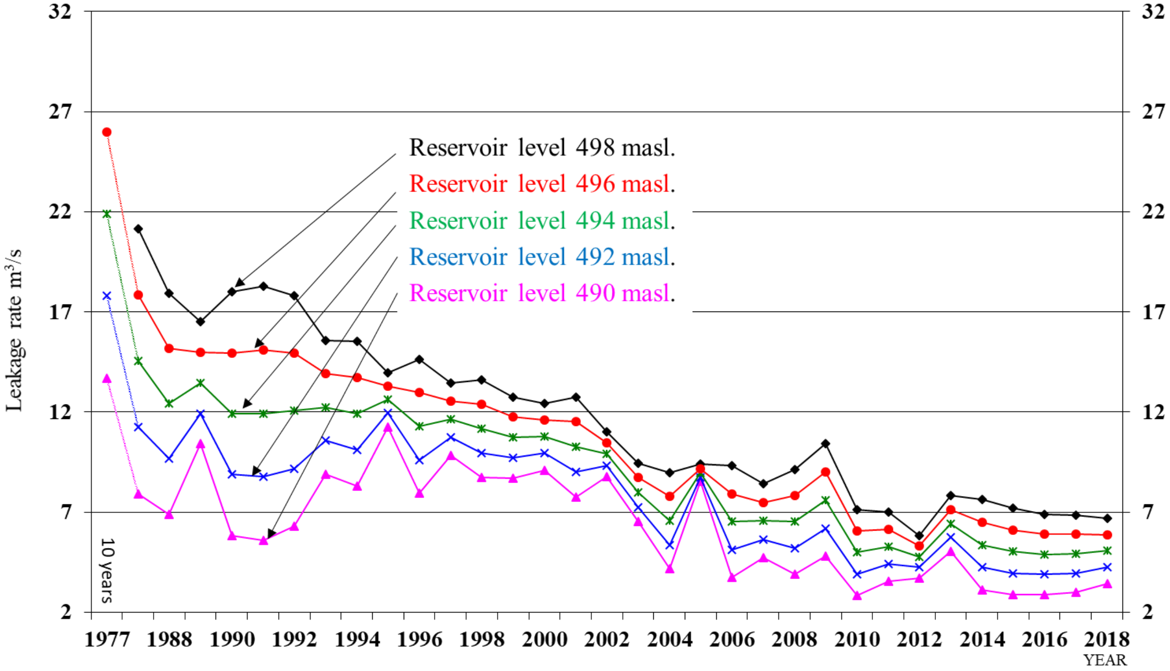


Figure 9: Total leakage from the reservoir during 1977-2018. Note: first interval shows 10 years

6 CONCLUSIONS

The Sigalda HEP was commissioned in 1978. During filling of the reservoir, leakage from the reservoir turned out to be much more than was expected. First mitgation measures concentrated on securing the safety of the Sigalda dam, followed by several seasons of reservoir sealing mesures. Most effective sealing material was the moberg rock material (ripped pillow lava containing significant sand fraction). The reservoir could be filled to spillway crest in 1980. The sealing measures were successful in reducing the leakage significantly and in the 40 years of operation, the glacial river water has continued to fill voids in the lava flows abutting the reservoir. Thus, the leakage has been gradually reduced from more than 20 m^3/sec. to about 6 m^3/sec. in the last 40 years.

7 REFERENCES

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