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Groundwater Modelling for Hydropower Development in Iceland

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Groundwater problems in moberg and lava formations are frequently encountered in connection with development of hydroelectric power resources in the volcanic zones in Iceland. The paper gives account of experience by VST from design work and evaluation of performance related to groundwater and seepage at some of Landsvirkjun's projects in Southwest Iceland. The major problems encountered are: leakage under dams on lava, seepage from reservoirs on lava and moberg formations, seepage from canals and dewatering of excavations. The most relevant problems are associated with dams founded on lava and seepage from reservoirs on lava. The discussion is concentrated on three such dams, at Thorisos, Hrauneyjafoss and Sultartangi. Brief description is given of the methods used for estimating seepage and comparisons between forecasts and observations after construction. In general the reservoirs and structures have performed satisfactorily.

Introduction

The Thjorsa-Tungna River basin is located at the western margin of the eastern neovolcanic zone in southern Iceland. The hydroelectric power resources of the basin have partially been developed by Landsvirkjun (The National Power Company) in the last two decades. The development so far consists of three powerplants, Burfell, Sigalda and Hrauneyjafoss, two storage reservoirs, Thorisvatn and Sultartangi, and a storage and diversion project, the Kvislaveita Project. The average discharge at the Sigalda and Hrauneyjafoss power plants is about 150 m^3/s and about 310 m^3/s at Sultartangi dam and Burfell power plant.

Miscellaneous problems related to groundwater and seepage have been encountered during design, construction and operation of the projects. The most important problems are connected to young volcanic formations. These consist basically of two types of basalt formations: Postglacial lavaflows and Moberg formations.

The postglacial lavaflows are typically several metres thick with a massive, columnar jointed central core and scoriaceous, highly permeable layer at the bottom and sometimes on the top too. Individual lavaflows are usually separated by interbeds of sediments.

The moberg is formed by subglacial eruptions. It contains tuff, pillow lava, cube-jointed basalt, breccia and unconsolidated volcanic sediments.

The permeability of the more leaky layers of the lavaflows is typically 10^{-1} to 10^{-2} m/s. It is obvious that seepage from reservoirs and under dams on such foundations may be of major concern. Typical values of permeabilities in the moberg formation are 10^{-3} to 10^{-5} m/s. Thus the moberg formations are relatively good aquifers, but not so problematic as the lavaflows. Problems such as estimates of groundwater flow related to dewatering of excavations and leakage from canals have been dealt with by conventional methods supported by tests and observations. Groundwater conditions at Lake Thorisvatn and changes in leakage through moberg formations with fluctuations in the lake level present more complicated problems which have been under study for years. The present paper will however be limited to dams and reservoirs on postglacial lavaflows.

Five dams in the Thjorsa-Tungna basin are founded on postglacial lavaflows. In the following discussion the groundwater conditions at three of these, Thorisos dam, Hrauneyjafoss dam and Sultartangi dam, where VST has been active in the design, will be considered. The Thorisos and Hrauneyjafoss dams were designed by VST in cooperation with Harza Engineering Company International. The other two dams on lava are at Burfell, designed by Harza, and the Sigalda dam, designed by Electrowatt-Virkir.

Dams on Lava

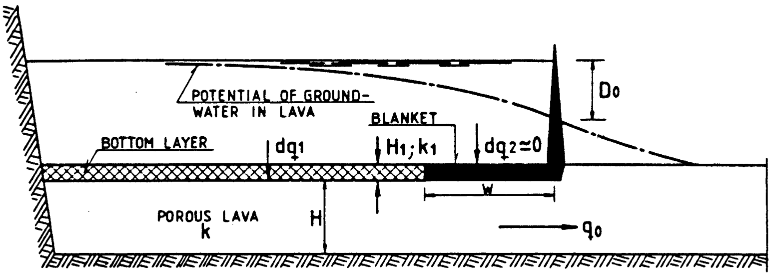
The *Thorisos dam* is located at the northern end of Lake Thorisvatn on the former outlet of the lake. It is a about 1 km long earth-rock dam with maximum height about 18 m above ground. The dam is founded on a single lavaflow underlain by pervious alluvial sediments overlying generally impermeable till and basalt which surfaces in the abutments. The areal geology, design and construction of the dam is described by Flygenring *et al.* (1976). The lavaflow at the damsite has a rather steep gradient and terminates about 1.5 km farther downstream. These conditions required a more or less positive cutoff through the lava and its underlying interbed.

The cutoff was constructed with the slurry backfill trench method, previously applied at the Burfell dam (Flygenring *et al.* 1976). The cutoff was considered completely successful at Burfell but this was not the case at Thorisos. However, the leakage was within acceptable limits, or less than about 1 m^3/s, and has been decreasing with time due to sealing effect of sediments. Changes in groundwater flow downstream of the dam are monitored by observation of groundwater levels in several boreholes. The flow varies linearly with the reservoir elevation and the variation is modest.

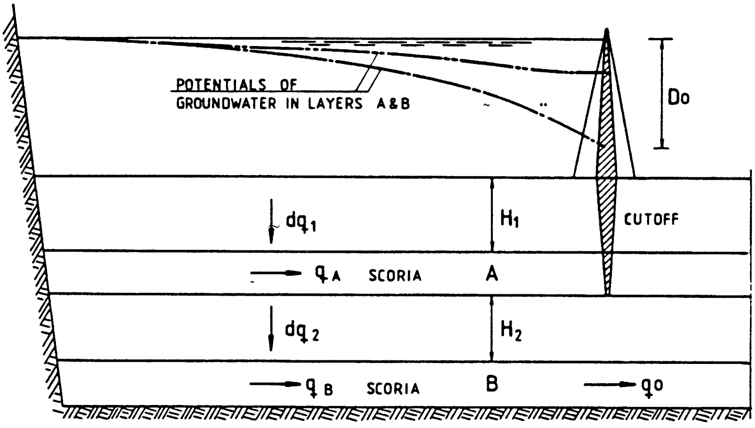
The *Hrauneyjafoss* and *Sultartangi dams* are 2.5 km and 5 km long respectively and the maximum depth to moberg or older basalts is tens of metres. The previously constructed dams at Burfell and Thorisos were designed with a positive cutoff and at Sigalda it had been assumed that lacustrine sediments from a prehistoric lake would act as an impervious blanket on the bottom of the reservoir. This assumption failed however, possibly because the sediments had never before been exposed to differential pressures. The total leakage from the Sigalda reservoir area is now approximately 25 m^3/s at normal reservoir elevation (Olafsson 1986, Kjaran *et al.* 1980). A positive cutoff was not feasible at Hrauneyjafoss and Sultartangi because of the length of the dams. The experience from Sigalda was somewhat alarming and the feasibility of the dams was even considered questionable. The conditions downstream are however essentially different from Thorisos and Sigalda; the possible groundwater gradients are much smaller and, except for one lava layer along the riverbeds, the scoria-aquifers extend for many kilometers downstream to their surface outcrops. Considering these circumstances as well as economical reasons a design with limited cutoff was adopted for the Hrauneyjafoss and Sultartangi dams. For preliminary assessment of different types of partial cutoff a mathematical model for groundwater flow from reservoirs and under dams on lava was studied (VST 1984a, 1986). The model is based on simplifying assumptions, e.g. that the flow is vertical in the semipervious layers and horizontal in more permeable layers. Typical examples are shown in Fig. 1. Qualitative conclusions can be drawn from studies of differential equations for the model flow, but realistic quantitative results are more doubtful. Regarding seepage control the main conclusions from the model study are briefly the following:

The permeability of the reservoir bottom relatively far from the dam is of little consequence for the total leakage unless there are very open leakage paths from there to downstream. For seepage control it is therefore most important to seal pervious areas close to the dam. The necessary width of an impervious upstream blanket to attain a certain degree of leakage reduction depends primarily on the horizontal transmissivity of the foundation and the ratio between the permeabilities of the bottom layer and the underlying lava.

The effect of a partial cut-off with a grout curtain or trench depends to a great deal on the transmissivity of the layer that is closed off, relative to the transmissivi-



a. Blanket on reservoir bottom $q_0 \approx \frac{D_0 H k}{W + \sqrt{H H_1 \cdot k/k_1}}$



b. Dam on two lavaflows with partial cutoff

Fig. 1. Simplified models for reservoir leakage.

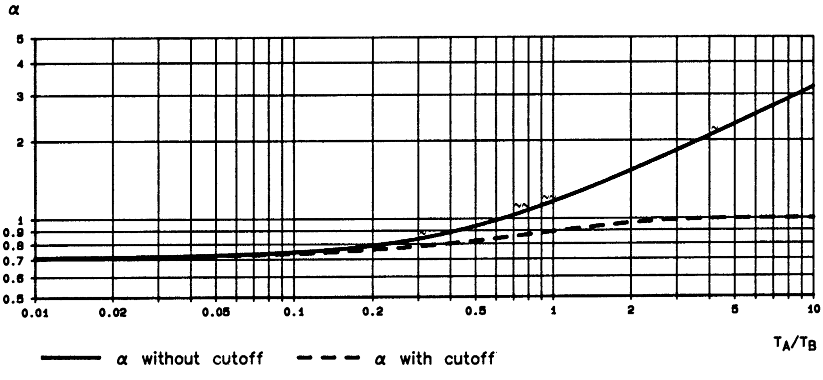


Fig. 2. Coefficient for cutoff effect.

ty of underlying layers. If the transmissivity of deeper layers is higher than that of the closed-off layers, the effect of the cut-off may be very minor.

Fig. 1b shows an example of a dam founded on two lava layers with pervious bottom scoria layers and/or interbeds and cutoff through the upper layer. The calculated leakage discharge under the dam is in this case

$$q_0 \equiv \alpha \sqrt{\frac{k_2 T_B}{H_2}} D_0$$

where T_B is the transmissivity of the scoria layer and k_2 is the vertical permeability of layer H_2. The coefficient α with and without cutoff is shown in Fig. 2 for the case that layers H_1 and H_2 have similar characteristics. It is seen that the partial cutoff has very limited effect if the lower scoria layer has equal or higher transmissivity than the upper one.

The effect of downstream blankets has also been considered in these studies.

A layout and typical section of the *Hrauneyjafoss dam* is shown in Fig. 3. This is an earth-rockfill dam, 2.5 km long with maximum height about 15 m. The design and foundation treatment is described by Olafsson *et al.* (1985a).

The dam is founded on a sequence of lavaflows separated by interbeds of various origin. The lavaflows are enclosed by the moberg formation. Groundwater contours indicate a dissimilar groundwater regime in the moberg as compared to the lavas. The mathematical model described above was originally developed to compare various alternatives of foundation design. The final design was with different methods for seepage control along different sections of the dam: a grout curtain through the uppermost lavaflow, a blanket to connect the impervious core of the dam to a natural blanket on the reservoir bottom and excavation of a core trench down to sound lava. In addition to seepage control the design was aimed at ensuring the safety and integrity of the dam. Estimates of seepage were made with the finite element method. With the permeabilities assumed during the construction stage the total calculated seepage was 3 to 7 m^3/s, depending on performance of the grout curtain. The groundwater conditions before, during and after filling of the reservoir were closely observed with a monitoring system consisting mainly of forty electric sensors for monitoring the porewater potentials under the dam and the reservoir and some sixty boreholes downstream (Olafsson *et al.* 1985b). The groundwater rise upon filling of the reservoir ranged from about 20 m at the dam to near zero some 2 km downstream. The finite element calculations were revised to fit the calculated potentials to the observations. The revised estimate of the total seepage was 3 to 4 m^3/s (VST 1984b). The collective leakage discharge of downstream springs is about 2 m^3/s (Olafsson *et al.* 1985b). A closer study of the groundwater conditions (VST 1986) indicates that the discharge capacity of the lavaflow and interbed aquifers is 0.5 to 1 m^3/s at the gradients observed and within the expected range of permeability. This is in fairly good agreement with the revised calculations.

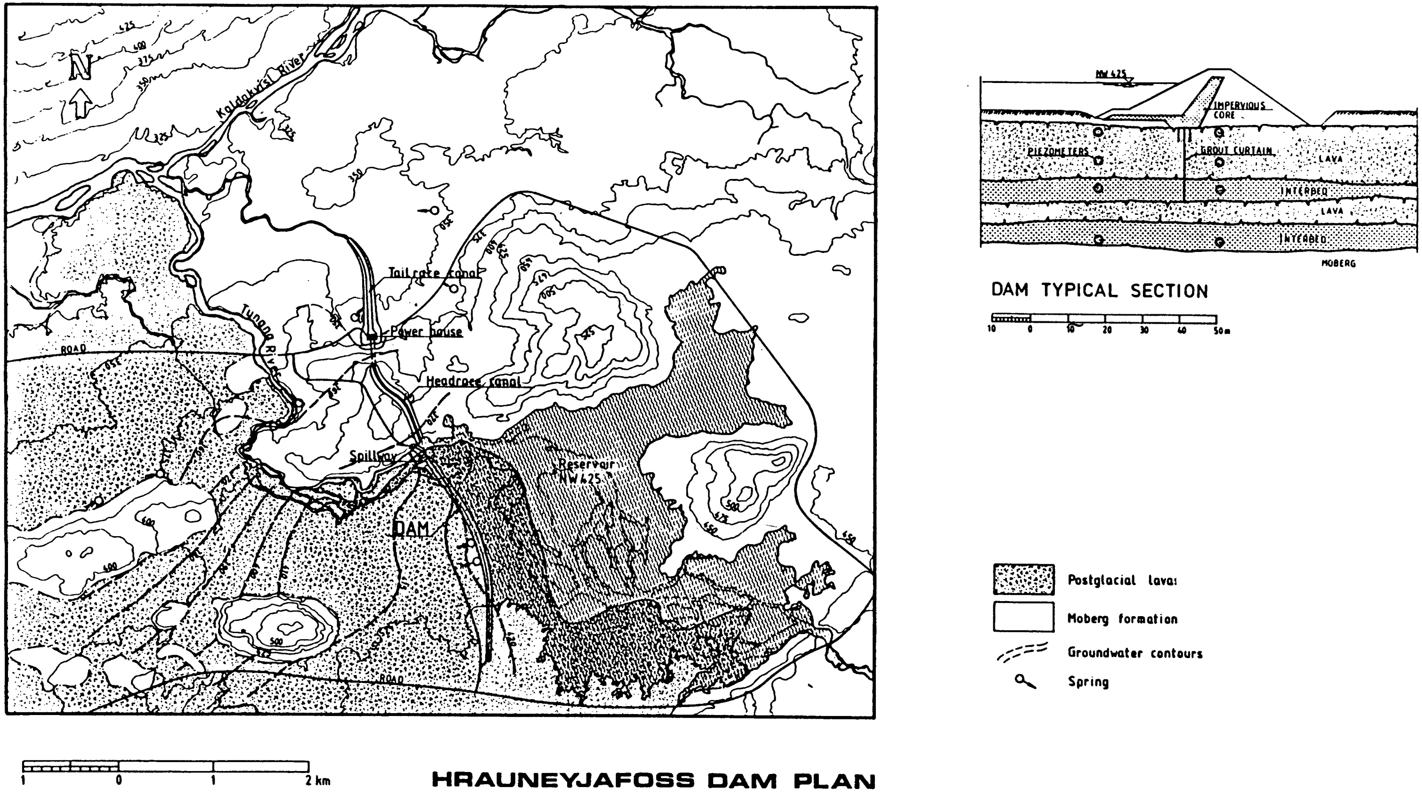


Fig. 3. Hrauneyjafoss dam plan.

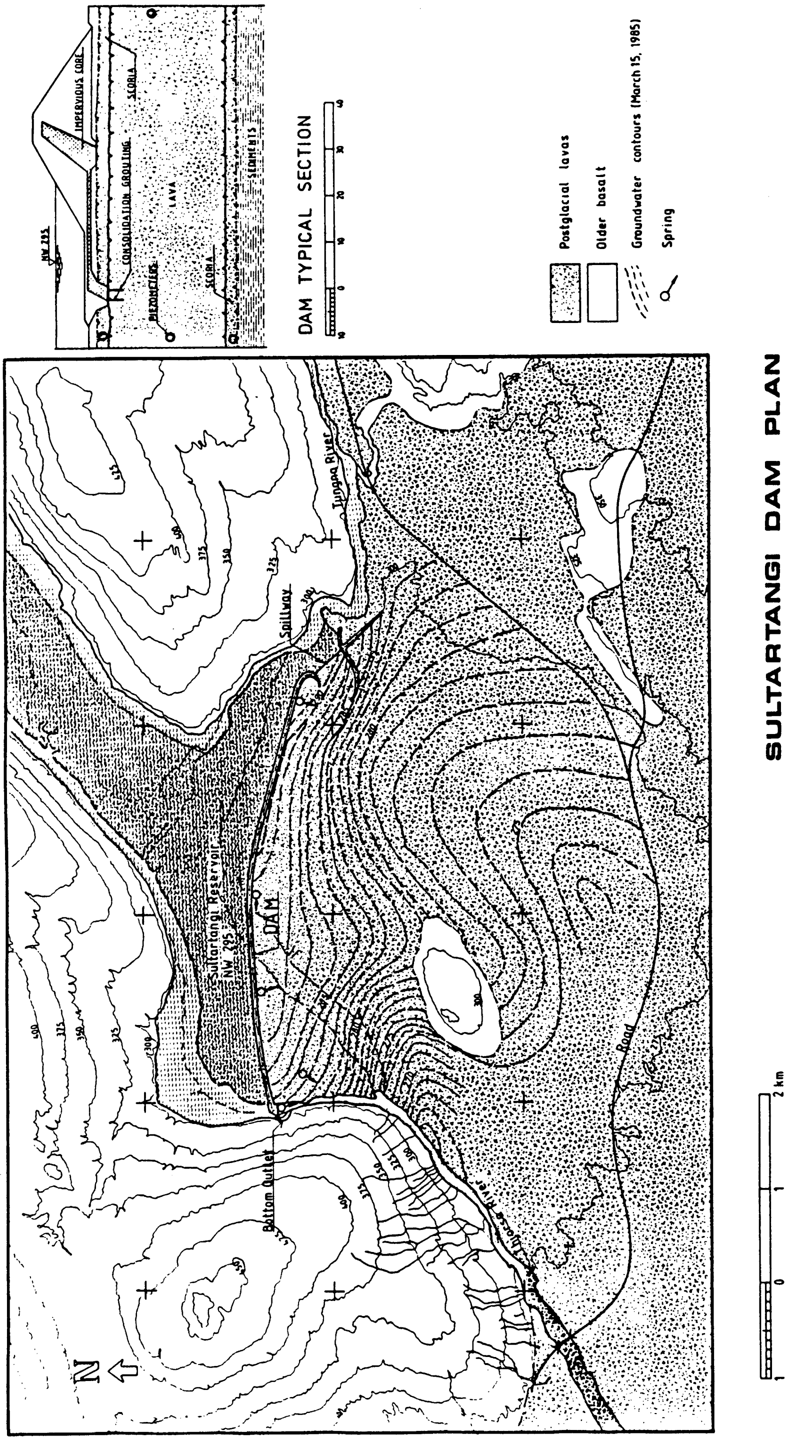


Fig. 4. Sultartangi dam plan.

The *Sultartangi dam* is on the Thjorsa and Tungna rivers, about 1 km upstream of the confluence. A layout and a typical section are shown in Fig. 4. The dam is founded on one lava flow, approx. 25 m thick with leaky scoria zones at the bottom and on the top. A relatively tight sediment layer covers the lava over extensive parts of the damsite and the reservoir bottom. The dam is approximately 5 km long with an average height of about 12 m.

Extensive measurements of the permeability of the foundation were carried out by The National Energy Authority (NEA) (Ingimarsson 1980, 1981, 1985). The main results were that the different layers might be characterized as follows:

Surface sediment	$k \simeq 10^{-5}$ m/s
Top scoria	$k \simeq 3 \times 10^{-2}$ m/s
Central core of lava	$k \simeq 5 \times 10^{-4}$ m/s
Bottom scoria	$k \simeq 2 \times 10^{-2}$ m/s

Measurements of the groundwater gradient across a test grout curtain were also made by NEA (Ingimarsson 1981). These showed a minor effect of the grouting unless the curtain reached down through the bottom scoria. Thus the theoretical studies on a partial cut-off were confirmed. A relatively great initial leakage could be accepted as a powerplant is not to be built until at a later stage. The reservoir is presently an ice- and sediment trap and regulating storage for the downstream run-of-river powerplant at Burfell. Estimates of leakage from the reservoir were made with the finite element method assuming a cut-off through the top scoria only, along with some sealing effect of the surface sediment. The main results were that an initial leakage up to 10 m^3/s might be expected (Landsvirkjun 1981). On the other hand the leakage was expected to decrease with time because of the sealing effect of the river sediments. Up to 20% of the initial leakage was supposed to flow underground out of the Thjorsa river basin.

Several pressure gauges were placed in the foundation at various depths on both sides of the dam axis. The groundwater potential has been monitored regularly since the first impoundment of the reservoir in the fall 1983. The observations show gradually decreasing potential, especially immediately upstream of the partial cut-off, indicating increasing sealing effect of the reservoir bottom. Direct measurements of surface leakage discharge downstream of the dam also indicate decreasing leakage. In November 1984 the total surface leakage discharge was estimated about 5 m^3/s whereof the major part was measured directly. Discharge measurements one year later indicated a decrease of approximately 0.5 m^3/s. Subsurface leakage discharge is estimated 1 to 2 m^3/s.

Conclusion

For dams on lava foundations with permeability up to 10^{-2} m/s or higher, a positive custoff under the dam or sealing of the reservoir bottom is obviously advisable. This may however not always be feasible, and at favourable sites such as at Hrauneyjafoss and Sultartangi a design with partial custoff is practical if a certain leakage can be accepted. In addition to leakage reduction the safety and integrity of the dams and foundations must be considered in the design.

Preconstruction assessments of leakage under dams on lava can be made with simple mathematical models and finite element calculations supported by geological and hydrological investigations. The observed and estimated seepage under the Hrauneyjafoss and Sultartangi dams is now about 3 and 6 m^3/s respectively, which is well within the limits predicted at the design stage.

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