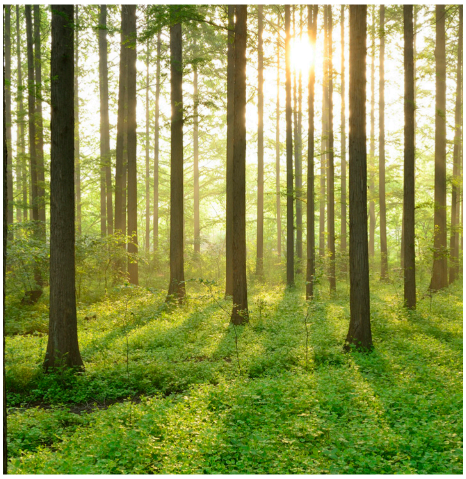
FUSE PLUG BREACH TESTS

REPORT 2018:465



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Fuse Plug Breach Tests

Can a laboratory scale test replace a field test?

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Förord

Den här rapporten är resultatet av projektet Modellförsök som metod att utvärdera en eroderbar dammdels funktionalitet. Projektet utfördes som ett seniorforskningsprojekt inom SVC Vattenbyggnad av Johan Lagerlund, Vattenfall R&D. Mats Billstein, Vattenfall R&D, Peter Viklander, Vattenfall vattenkraft och Magnus Svensson, Fortum utgjorde referensgrupp i projektet.

Det primära syftet med projektet var att utreda om fysiska modellförsök lämpar sig för att utvärdera funktionen hos en eroderbar dammdel, byggd som en konventionell fyllningsdamm, och i så fall föreslå vilken typ av laboratorieförsök som är att föredra. Eroderbar damm kallas också för ”fuse plug”. Fysiska modellförsök alternativt numerisk modellering är billigare och snabbare att genomföra än fältförsök.

Projektet genomfördes inom ramen för Svenskt vattenkraftcentrum, SVC. De organisationer som bekostade detta projekt var Falu Energi & Vatten, Fortum Generation, Holmen Energi, Jämtkraft, Jönköping Energi, Karlstads Energi, Mälarenergi, Norconsult, Skellefteå Kraft, Sollefteåforsens, Statkraft Sverige, Svenska Kraftnät, Sweco Infrastructure, SveMin, Umeå Energi, Uniper, Vattenfall Research and Development, Vattenfall Vattenkraft, WSP Samhällsbyggnad och ÅF Industry.

Oktober 2017

Sara Sandberg
Energiforsk

Sammanfattning

En eroderbar dammdel är en typ av damm som är designad för att gå till brott då den överströmmas med vatten. Den kan sägas ha samma funktion som en dammlucka men aktiveras endast i nödfall. En eroderbar dammdel konstrueras i likhet med en vanlig fyllningsdamm men med skillnaden att nedströms stödfyllning är mer lätteroderad. Detta görs för att säkerställa att den går till brott vid en viss överströmning. Av yttersta vikt är att den eroderbara dammdelen går till brott vid en förutbestämd vattennivå och tillräckligt snabbt för att på så sätt förhindra att huvuddammen överströmmas.

För att verifiera att en eroderbar dammdel kommer att uppfylla avsedd funktion kan antingen ett fullskaleförsök eller fysiska modellförsök utföras. I detta projekt jämfördes resultat från modellförsök med resultat från ett tidigare genomfört fullskaleförsök. Modellförsök genomfördes i skalorna 1:3 och 1:6 och byggnationen/genomförandet i de båda modellförsöken var helt jämförbara med det tidigare genomförda fullskaleförsöket. Modellerna överströmmades med vatten och brottförloppet dokumenterades primärt med kameraövervakning. Efter utförda försök jämfördes resultaten med fullskaleförsöket med avseende på var brottförloppet startade, hur utvecklingen av brottet skedde samt om några varningssignaler kunde identifieras inför ett förestående dammbrott. Syftet med detta projekt var således att svara på frågan om modellförsök i skalorna 1:3 eller 1:6 kan ersätta fullskaleförsök för att utvärdera funktionen hos en eroderbar damm.

Tillsammans gav de båda modellförsöken en väl överensstämmande bild med de resultat som erhölls vid fullskaleförsöket. Försöket i skala 1:3 gav en mycket god bild av hur lång tid det tog att erhålla brott samt vid vilken vattennivå det skedde. Försöket i skala 1:6 gav en god bild över själva händelseförloppet inför och under brottet.

Modellförsöken såväl som fullskaleförsöket indikerade att den eroderbara dammen gick till brott på grund av inre erosion som startade i nedströms filter vilket ledde till att nedströmsdelen av krönet sjönk in. När nedströmsdelen av krönet sjönk in accelererades hastigheten på det överströmmande vattnet vilket ledde till en kraftigt ökad erosion av nedströmsslänten. Inre erosion av filtret påbörjades när vattnet steg över krönet på den eroderbara dammens tätkärna. Vattennivån vid vilket brottet skedde styrdes till största del av kornstorleken på materialet i stödfyllningen vid krönet. Grövre material resulterade i att brottet skedde vid en högre vattennivå. Tiden för brottet styrdes till största del av vattenståndets stighastighet i magasinet.

Baserat på resultat från genomförda modellförsök är slutsatsen att modellförsök kan ersätta fullskaleförsök. Dock bör modellförsök i både skala 1:3 och 1:6 genomföras för att få en fullständig bild av den eroderbara dammens funktionalitet. Fördelar med modellförsök jämfört med fullskaleförsök är framförallt; inga miljötillstånd krävs, man erhåller resultat snabbare och de är avsevärt mycket billigare att genomföra.

Summary

A fuse plug is a type of a dam that is designed to breach when overtopped by water. A fuse plug has the same function as a spillway gate but is only activated in case of emergency. A fuse plug is constructed like an embankment dam but the downstream structural fill is finer in order to guarantee it will breach at a certain overtopping. It is very important that the fuse plug breach at a pre-determined water level and at a sufficient rate in order to protect the main dam from overtopping.

To verify that the functionality of the fuse plug is according to plan either a full, or small scale laboratory test can be performed. In this project, results from small scale testing have been compared with the results from an earlier performed full scale test. Small scale testing were performed at 1:3 and 1:6 of original size. Construction and execution of tests were comparable to the full scale test. The models were overtopped with water and the breach was primarily documented with cameras. After the tests the results were compared with the results from the full scale test with respect to where the breach was initiated, how the breach developed and if warning signs could foresee the breach. The objective of this project was hence to determine if laboratory tests in scale 1:3 and 1:6 can replace full scale tests in order to evaluate the behavior of a fuse plug.

Together, the two laboratory tests gave comparative results and verified the results obtained from the full scale test. The test at 1:3 scale gave an accurate answer on how long time it took for the breach to be initiated and at which reservoir level it occurred. The 1:6 scale test gave a similar view of the events prior to the breach initiation as obtained in the full scale test.

The scaled tests as well as the full scale test indicated that the fuse plug breached due to internal erosion in the downstream filter sand, which in turn led to the downstream side of the crest of the fuse plug to cave in. After the downstream side of the crest caved in, the velocity of the passing water was accelerated which in turn led to heavy erosion of the downstream slope. The internal erosion of the filter sand was initiated as soon as the water rose above the crest of the core. The water level at which the breach occurred was in particular controlled by the grain size of the structural fill at the crest. Coarser grained structural fill resulted in a breach occurring at a higher water level. The timing of the breach was mainly controlled by the elevation velocity of the water in the reservoir.

Based on the results from the scaled model tests it is possible to exchange full scale test with small scale model tests. However, both the 1:3 and the 1:6 scale test should be used in order to get the full picture of the breach behavior. The advantages of using small scale test instead of full scale are that no environmental permits are needed, results are obtained faster and it is cheaper.

List of content

1 Introduction

A fuse plug is an installation in connection to a dam (Figure 1) that may allow a quick release of water from the reservoir in case the inflow of water exceeds the spillway capacity for an extended period of time. It is intended to be used as an emergency measure in order to protect the main dam from overtopping. The fuse plug is activated when water in the reservoir passes its crest. Once the fuse plug is activated (start to erode) it cannot be deactivated. After activation, the fuse plug need to be completely rebuilt. A fuse plug is constructed as a conventional earthfill embankment dam, designed to be washed out completely in a predictable and controlled manner at a predetermined water level. Fuse plugs are normally a few meters high but may be up to several hundred meters wide.

Figure 1. Fuse plug (left side in the photo) at Warragamba dam in NSW Australia (www.waternsw.com)

As the fuse plug erodes the discharge capacity increases in relation to the erosion rate of the fuse plug. This will protect the main dam from overtopping and a potential main dam failure. The main difference between a fuse plug and a conventional embankment dam is the composition of the downstream shoulder material. In the fuse plug the material is more easily erodible. In all other aspects, a fuse plug and an embankment dam are constructed in the same way.

Fuse plugs often have initiation points. Pilot channels or piping devices are most commonly used. These initiation points have in common that they aim to concentrate the water flow in order to speed up and direct the erosion of the fuse plug. A pilot channel is a local immersion on the crest. When the water level passes the crest it is concentrated at this particular location. A piping device is a “tube” of easily erodible material through the fuse plug. When the reservoir level reaches the crest, the device is saturated and eroded. In this way an opening is created through the fuse plug, Figure 2.

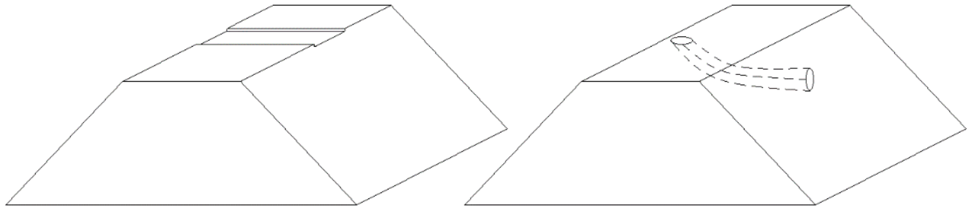


Figure 2. Pilot channel on the left and piping device on the right.

1.1 FORMATION OF A BREACH DUE TO OVERTOPPING

An earthfill dam may breach due to several factors, i.e. seepage through or under the dam, overtopping of the crest, external erosion, structural instability etc. Sometimes a combination of these factors may lead to a breach which may be the case if internal erosion leads to a sinkhole that in turn causes overtopping of the crest. This study however, will only focus on the case when overtopping leads to a total failure of the dam structure, e.g. breach of a fuse plug. A fuse plug is meant to be easily eroded when overtopped, which is not the case for ordinary embankment dams. A fuse plug is constructed as a conventional zoned embankment dam on its upstream side since it must function as a normal embankment dam in terms of retaining water inside the reservoir in all cases except overtopping of its crest. The downstream side of a fuse plug is however different from a normal embankment dam. The fuse plug must be more easily eroded when overtopped, hence the material in the downstream shoulder of a fuse plug is more finely grained and as such, more prone to erosion.

An overtopping event may occur when the inflow of water into a reservoir exceeds the spillway capacity of the spillway gates over a period of time. Spillway capacity should always be designed to guarantee dam safety. However, in the case of malfunctioning or clogged spillway gates the spillway capacity is reduced. The water level rise in the reservoir and overtopping of the fuse plug is initiated as soon as the reservoir level exceeds the actual height of the core within the fuse plug. Normally, initiation of overtopping is regarded as the moment when the water is exceeding the crest of the fuse plug. This is, however, not completely true. The core of fuse plugs in Sweden are most commonly constructed with glacial till, which acts as a more or less impervious wall, keeping the water inside the reservoir. As soon as the core is overtopped, the water passing on top of it gains momentum. This will as a consequence increase the erosive forces within the structural fill placed on top of the core. If the reservoir level continue to rise, so does the water velocity and the erosive forces acting on the dam. Erosion of the dam is initiated when the erosive force of the water exceeds each grains ability to withstand it. The erosive forces will gradually erode the dam and eventually lead to a complete breach of the dam.

Fuse plugs are furthermore commonly constructed with an inclined core. The inclined core is expected to break when the downstream structural fill is exposed to undercutting. If undercutting continues, there is no support for the inclined core, eventually leading to a complete breach of the fuse plug.

1.2 OBJECTIVES

This project has been initiated in order to verify if laboratory scale tests in 1:3 and 1:6 can replace a field test in order to evaluate the breach behavior of a fuse plug.

Objectives in this project were the following;

- Determine which of the model tests were most similar to a field test.
- Verify where and how the breach was initiated.
- Determine how the breach developed.
- Find warning signs prior to a breach.

This project was supported by SVC.

2 Material and Methods

2.1 MATERIALS AND DESIGN OF FUSE PLUGS

The fuse plugs were constructed as a conventional zoned embankment dam with a core of till, protected on each side by a filter and structural fill, Figure 3. At the crest of the core (boundary zone between core and crest structural fill) insulation foam boards were placed.

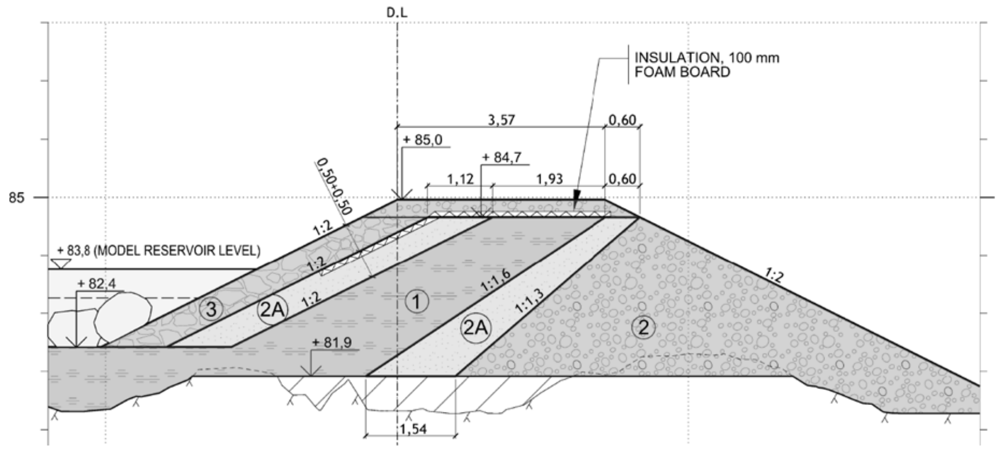


Figure 3. Design of fuse plug. Material properties in Table 1.

Table 1. Soil materials characteristics of the fuse plugs.

Material	k_{sat} (m/s)	θ (%)	γ_u (kN/m³)	E_{oed} (MPa)	E_{ur} (MPa)	φ' (°)	c' (kPa)	ν
1. Core	$1x10^{-7}$	0.321	21	70	220	38	20	0.2-0.35
2A. Filter	$1x10^{-4}$	0.330	21	50	150	30	0	0.2-0.33
2&3. Shoulder fill	$5x10^{-4}$	0.208	19	15	40	30	0	0.2-0.33
Bedrock	$1x10^{-8}$	Saturated	21	3000	9000	45	0	0.2-0.3

Properties of the different soil types used within the tests are shown in Table 1. The material properties were estimated from the literature based on grain size distribution except for the hydraulic conductivity (k_{sat}) of the till, which was measured in the laboratory. Hydraulic conductivity for filter-, shoulder fill- and bedrock material was estimated from empirical values from Vattenfall (1988) and Larsson (2008). Volumetric water content (θ) was estimated from from Fredlund and Rahardjo (1993). The Elastic moduli (E_{oed} and E_{ur}), Poisson's ratio (ν) and effective strength parameters (cohesion c' and friction angle φ') were obtained from literature based on similar types of soils (Vahdati 2014).

Glacial till (0-20 mm) was used for the impervious core, sand (2-11.2 mm) as filter, gravel (4-32 mm) as a shoulder fill for field test and 1:3 scale test. For the 1:6 scale test a finer structural fill was used (2-6 mm), see Figure 4.

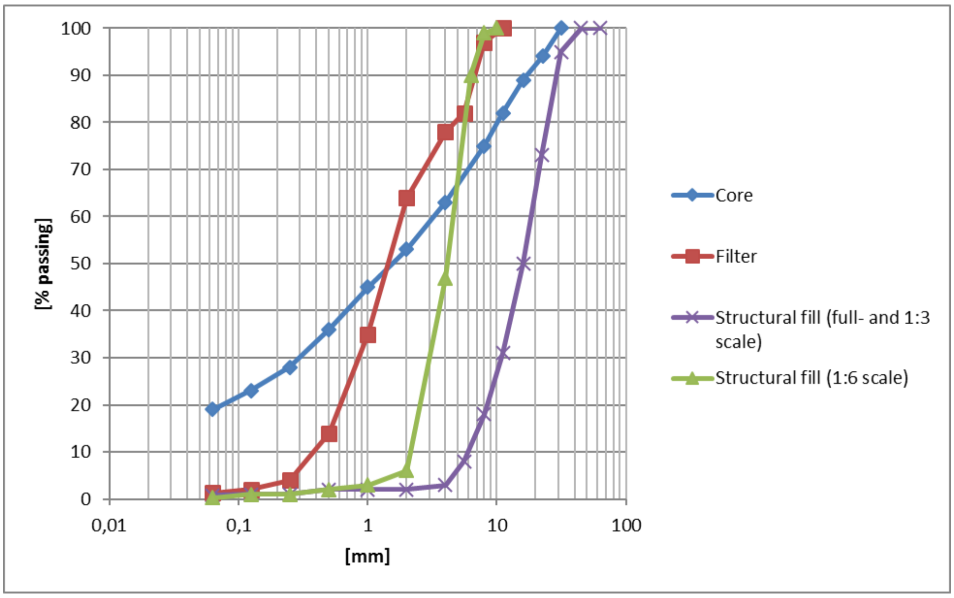


Figure 4. Particle sizes for the soils used within the tests. Note that the only difference was the structural fill.

The maximum dry density of the core was 2.08 t/m³ achieved at a water content of 5.8 %, see Figure 5.

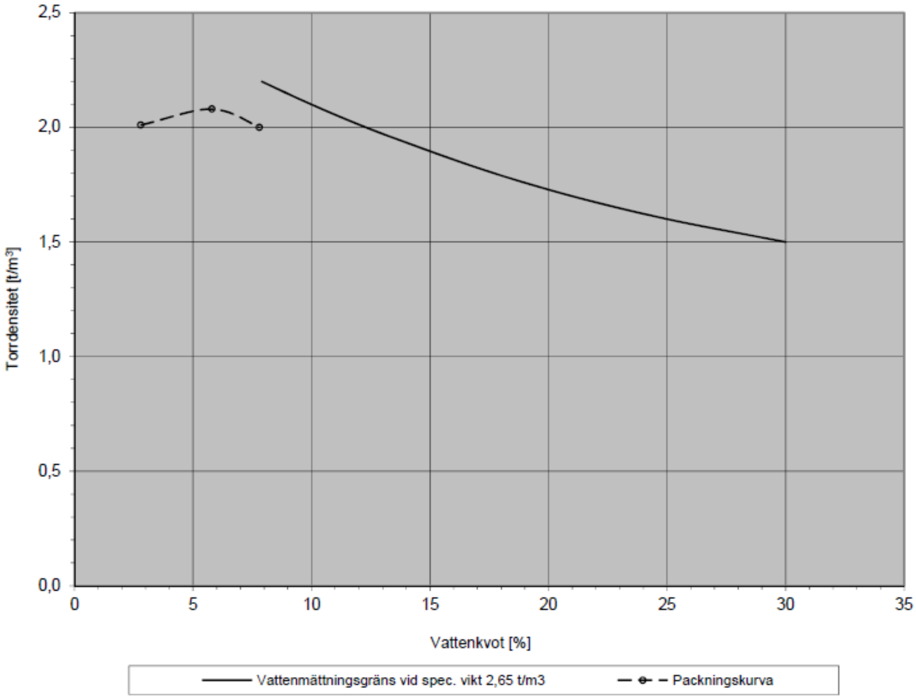


Figure 5. Optimal water content evaluation for the core soil, Proctor testing SS 02 71 09.

2.2 METHODS – CONSTRUCTION AND EXPERIMENTAL DESIGN

2.2.1 Laboratory test – scale 1:3

The fuse plug was constructed at Vattenfall AB laboratory in Älvkarleby. The flume was one meter wide and the fuse plug itself was ~1.00 m high and 1.00 m wide. The flume had a maximum water capacity of roughly 100 l/s. The construction of the laboratory test took two weeks. The total reservoir capacity during the test was 9.65 m^3, Figure 6.

The core was constructed in ten layers, each having a thickness of 0.10 m. Each layer was compacted manually, with a flat falling weight, until no further compression of the layer was achieved.

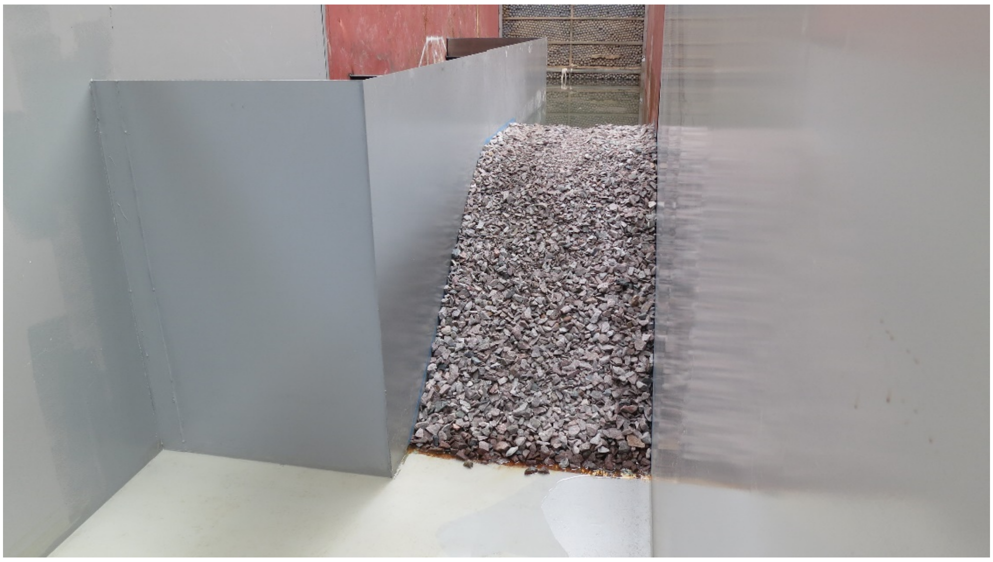
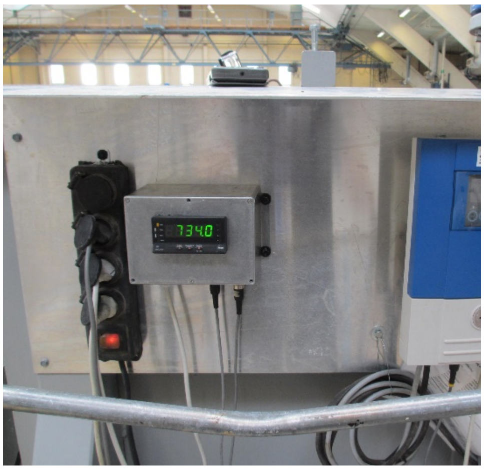


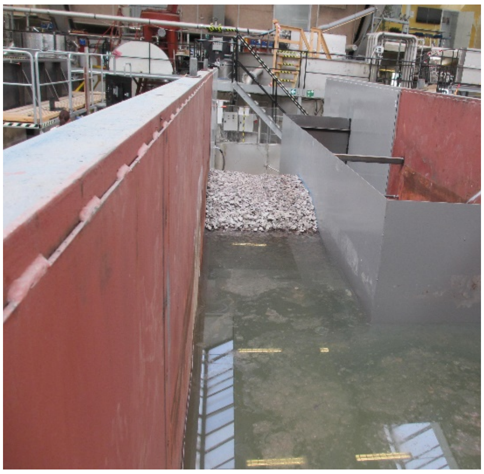
Figure 6. Fuse plug scale 1:3. Same material as in the field test.

The day before the test, the upstream reservoir level was fixed to +0.60 m, corresponding to the maximum operational level used in the field test. The reservoir level was steady until the next day when the breach took place. The leakage was neglectable. At the test day the water level was increased with 0.07 m/h until the crest of the core was reached (+0.70 m). At this level the inflow was stopped for a final control of the measurement equipment. The inflow was then opened until overtopping and breach was initiated. The inflow was thereafter manually controlled in order to keep the elevation of the upstream water level constant throughout the test. In Figure 7, some photos from the test are shown.



Upstream water level and inflow measurements.

Downstream seepage and turbidity measurement point.



Upstream view of the fuse plug

Manual control for the inflow of water

Figure 7. Various photos from the laboratory test scale 1:3.

The inflow of water was measured in a magnetic flow meter and the upstream water level with a pressure gauge. The measurements were logged throughout the test with a frequency of 1 Hz. The test was also filmed from four different angles with GoPro Black Edition HD cameras in order to document the breach pattern over time. Throughout the test, turbidity and seepage was measured downstream the fuse plug.

2.2.2 Laboratory test – scale 1:6

The fuse plug was constructed inside a 20 m long and 0.75x0.75 m flume (Figure 8) at Vattenfall AB laboratory in Älvkarleby. At the location for the fuse plug, walls of Plexiglas were placed in order to allow a side view of the test (Figure 9). The fuse plug itself was ~0.50 m high and 0.75 m wide. The flume had a maximum water capacity of roughly 100 l/s. The construction of the laboratory test took three days. The total reservoir capacity during the test was 6.75 m^3.

The core was constructed in ten layers, each having a thickness of 0.05 m. Each layer was compacted manually, with a flat falling weight, until no further compression of the layer was achieved.

Figure 8. Fuse plug scale 1:6. Same material as in field test except structural fill, which was scaled 1:6 in grain size.

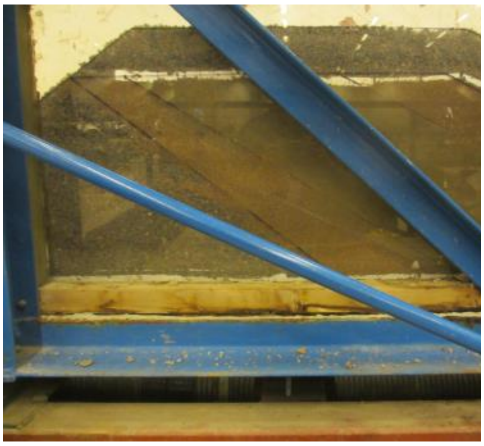
The day before the test, the upstream water level was fixed to +0.30 m, corresponding to the maximum operational level used in the field test. The water level was steady until the next day when the breach took place. The leakage was neglectable. At the test day the water level was increased with 0.04 m/h until the crest of the core was reached (+0.41 m). At this level the inflow was stopped for a final control of the measurement equipment. The inflow was then opened until overtopping and breach was initiated. The inflow was thereafter manually controlled in order to keep the elevation of the upstream water level constant throughout the test.

The inflow of water was measured in a magnetic flow meter and the upstream water level with a pressure gauge. The measurements were logged throughout the test with a frequency of 1 Hz. The test was also filmed from four different angles with GoPro Black Edition HD cameras in order to document the breach pattern over time.

Inside the flume.

Layer 1 (bottom) core and filters.

Insulation foam boards on top of core and upstream filter.



Finalized fuse plug from left side.

Figure 9. Various construction phases of the laboratory test.

3 Results

3.1 LABORATORY TEST – SCALE 1:3

3.1.1 Chronology of the performed test

The impoundment of water started at 07:00 am and the order of events throughout the test can be seen in Table 2. Note that the water levels were measured from the bottom of the flume in the scaled fuse plug. The reservoir level increased with ~0.06 m/h (1:3 of field test). From the moment the core was overtopped, increased seepage and turbidity coming out from the toe of the fuse plug could be seen. The breach initiation occurred at 12:08 pm at a water level of +102.60 cm, 7.2 cm over the crest. After the breach initiation, the water level continued to rise until 12:13 pm up to a maximum water level of +106.4 cm, 11.4 cm above the crest and 21.4 cm above of the core.

No other warning signs apart from overtopping of the crest and a large amount of seepage with turbidity from the toe of the fuse plug (Figure 10 left) could be identified prior to the breach. The breach was initiated by a sudden collapse of the front section of the fuse plug at the downstream side of the pilot channel. After this collapse, the breach developed in a straight center line in the downstream structural fill. The core was “shaved off” layer by layer throughout the breach phase. The insulation foam boards prolonged the time of the erosion process of the fuse plug since they protected the core from the streaming water and in particular the insulation foam boards placed on the upstream side of the inclined core. As soon as the insulation foam boards were washed away, the rate of erosion increased.

Table 2. Order of events in the 1:3 scale test. Core crest at +85.00 cm and fuse plug crest at +97.00 cm

Time	Event	Water level
07:00 am	Impounding started to slowly increase the reservoir level	+65,38 cm
10:19 am	Water level at core crest	+85.00 cm
10:50 am	Water level at the top of insulation foam boards	+88.00 cm
11:26 am	Water level reached the pilot channel	+95.00 cm
12:06 pm	Water overtopping the front of the crest	+101.3 cm
12:08 pm	Breach initiated	+102.6 cm
12:13 pm	Maximum water level was reached in the reservoir	+106.4 cm
12:19 pm	Maximum flow was reached (97 l/s)	+96.68 cm
12:30 pm	Test aborted	+24.28 cm

The time for the reservoir level passing the top of the core to attaining maximum level in the reservoir was **1 h 54 min**. The time for the water level passing the crest (pilot channel) to attaining maximum water level in the reservoir was **47 min**.

Breach initiation at 12:08 pm   Breach propagation at 12:10 pm

Figure 10. Breach formation and propagation during the 1:3 scale test.

3.1.2 Water level during the test

The reservoir level rose with a velocity of 0.06 m/h (1:3 rate of field test) during the main part of the test (Figure 11, 0-5,500 s). When the reservoir level exceeded the crest, the seepage through the crest increased. The inflow of water was difficult to control due to the excessive seepage occurring after the reservoir level had passed the crest of the core. The inflow of water became more and more difficult to control as the reservoir level continued to rise due to heavy seepage. At the final phase of the test the reservoir elevation velocity was 0.1 m/h.

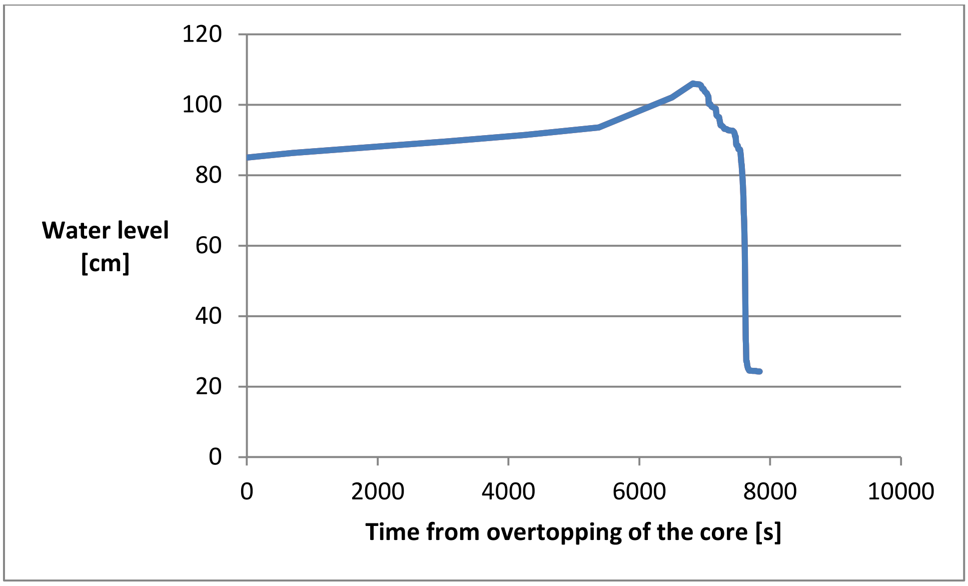


Figure 11. Water level in the reservoir from overtopping of the core to the end of the test. Breach initiation at peak.

The time from breach initiation to a sudden collapse of the fuse plug was ~1,000 s (Figure 12). After the collapse of the fuse plug it took yet another 150 s for the fuse plug to be eroded down to a height of 24 cm. The inflow of water was thus not enough to erode the fuse plug completely (Figure 13). From the initial height of 97 cm, 25 % of the height of the fuse plug remained intact after the test was aborted.

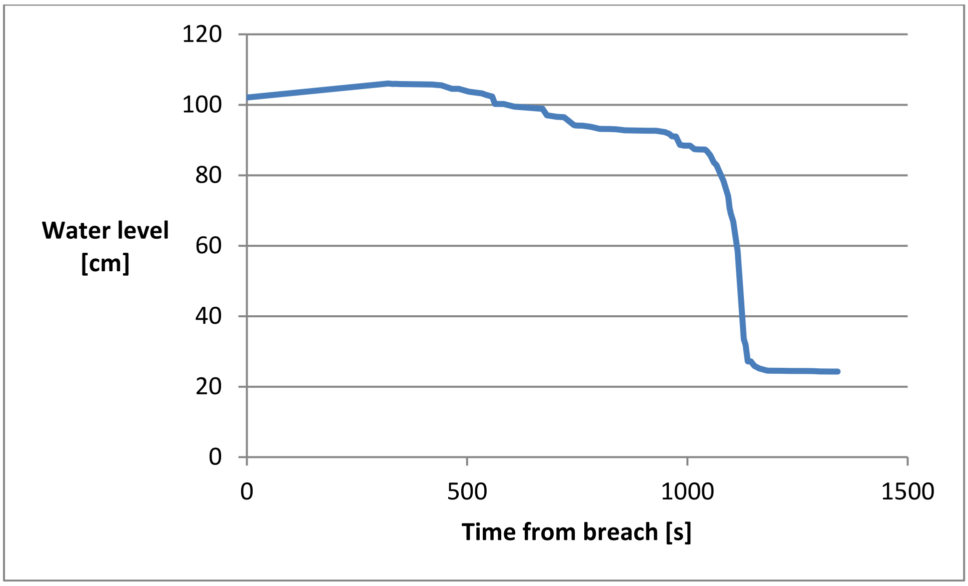


Figure 12. Water level in the reservoir from the moment of breach (breach at 0 s) to the end of the test.

Figure 13. Fuse plug after the 1:3 scale test had been aborted.

3.1.3 Turbidity during the test

The turbidity downstream the fuse plug could be measured in the flume designed for the 1:3 scale test. In Figure 14 the turbidity has been plotted together with the water level in the reservoir. The water level overtopped the core 210 minutes after the test was started in the morning (~10:20 am). 240 minutes (10:50 am) into the test the turbidity increased significantly. At 10:50 am the water level in the reservoir was at a height of 88 cm, which corresponded to the height of the core crest (at 85 cm) plus the height of the insulation foam boards (3 cm thickness). At 11:30 am the turbidity dipped but started to increase immediately. A visual inspection of the turbidity in the water (Figure 15) revealed that the turbidity was mainly from the filter and downstream structural fill. This indicated internal erosion occurring in the filter and not in the core.

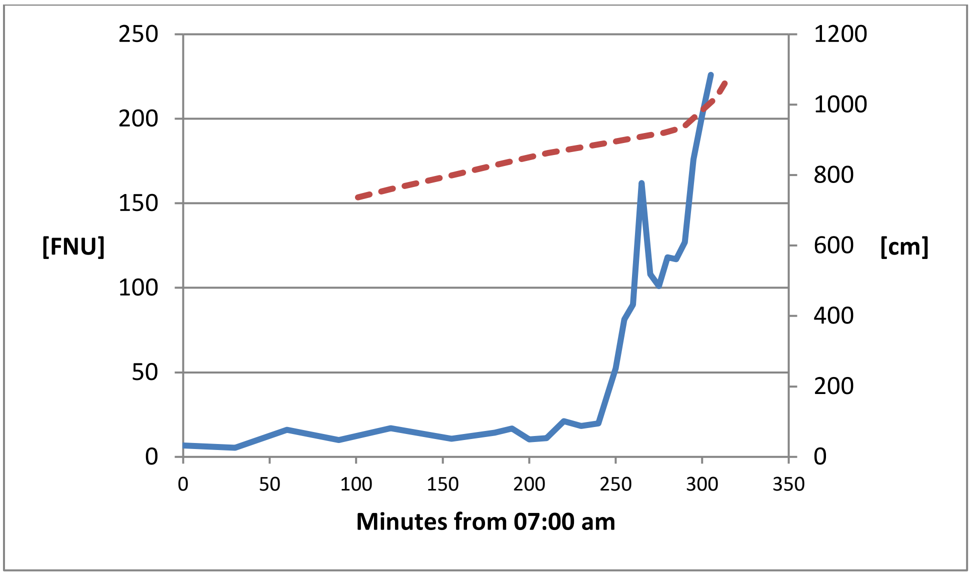


Figure 14. Turbidity (full line) compared to the water level (dashed line) during the 1:3 scale test. Test started at 07:00 am.

Worth noticing was that during the construction phase of the fuse plug, each layer of structural fill was washed with water for nearly 30 minutes. This was done with the sole purpose of diminishing turbidity from "unclean" structural fill.

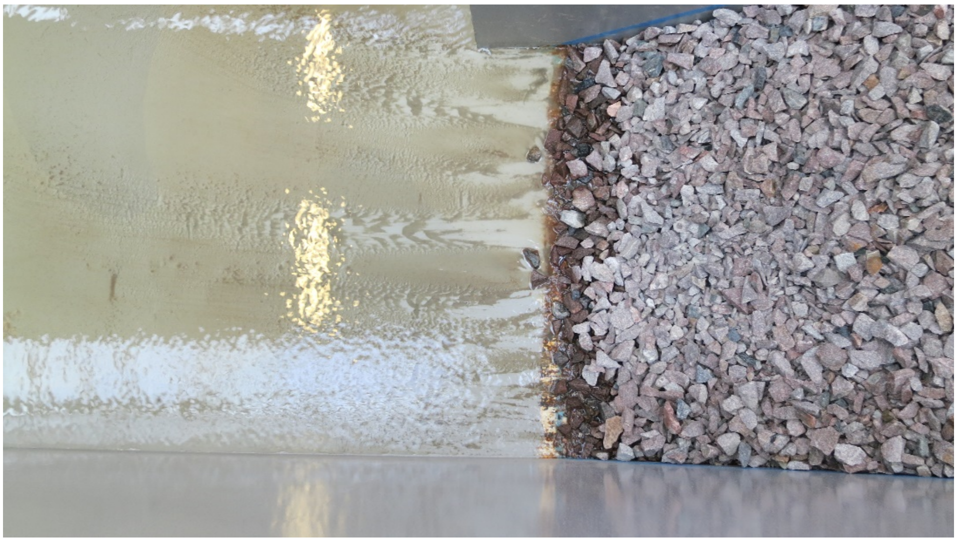


Figure 15. Turbidity coming out from the dam toe at 11:58 am

3.2 LABORATORY TEST – SCALE 1:6

3.2.1 Chronology of the performed test

The chronological order of events during the 1:6 scale test is presented in Table 3. Note that the water levels were measured from the bottom of the flume. The velocity at which the reservoir level increased was ~0.04 m/h (1:6 of field test).

Prior to the breach, a line of seeping water could be observed in the downstream shoulder 0.07 m below the crest at the boundary of insulation foam boards and core. This water line appeared first at both abutments and as the water level increased, it moved towards the centre of the fuse plug. Prior to the breach of the fuse plug, seepage with turbidity could be clearly seen on the downstream slope below the pilot channel like a spring indicating internal erosion. At the toe of the fuse plug, water with high turbidity appeared and in particular as soon as the water level exceeded the core.

The breach initiation and development happened in a similar way to that of the field test (Figure 16 and Figure 17) but slightly different from the 1:3 scale test. All events happened in the same way except for the timing, which was much faster in the 1:6 scale test. The breach in the 1:6 scale test occurred before the crest was overtopped at all places. In accordance with the 1:3 scale test, the breach was initiated by a sudden collapse of the front section of the fuse plug at the downstream side of the pilot channel. Beside the difference in the timing of the breach initiation, the development of the breach itself was similar to the 1:3 scale test.

Table 3. Order of events in the 1:6 scale test. Core crest at +41.00 cm and fuse plug crest at +49.00 cm

Time	Event	Water level
09:01 am	Impounding started to slowly increase the reservoir level	+28.30 cm
10:35 am	Impounding stopped just below the core crest	+40.76 cm
11:13 am	Impounding restarted	+39.82 cm
11:22 am	Water reached the core crest	+41.09 cm
11:41 am	Water level reached the pilot channel	+48.10 cm
11:45 am	Initiation of breach started	+50.66 cm
11:48 am	Maximum water level was reached in the reservoir	+53.49 cm
11:54 am	Maximum flow was reached (97 l/s)	+46.89 cm
12:05 pm	Water flow was stopped. Fuse plug not fully eroded	+21.76 cm

The time for the reservoir level passing the top of the crest to attaining maximum water level in the reservoir was **26 min**. The time for reservoir level passing the crest (pilot channel) to attaining the maximum water level in the reservoir was **13 min**.

Figure 16. Seeping water line with arrows marking their propagation and breach initiation (circle), where the sudden collapse of the structural fill took place.

Figure 17. Breach propagation.

The side view of the 1:6 scale fuse plug revealed in detail how the breach progressed (Figure 18). Heavy undercutting of the core due to erosion of the downstream structural fill/filter took place and the core was “shaved off” layer by layer during the breach phase. The side view furthermore revealed how seepage from the boundary layer between the core /insulation foam boards/structural fill was focused and entered the downstream filter sand. Even though the core was undercut, it did not break.

Breach initiation. A small portion of the structural fill has been eroded

Erosion of core has begun on its downstream front edge

Water has begun undercutting the core

Erosion progresses backwards

Downstream filter material is almost completely eroded. Note that the insulation foam boards on the right side slowed down the erosion process.

Fuse plug almost completely eroded

Figure 18. Propagation of the erosion process of the fuse plug.

3.2.2 Water level during the test

The increase of reservoir level was aimed at a velocity of 0.04 m/h during the main part of the test but in the end it was difficult to control due to waves forming inside the flume. The reservoir level increased with 0.25 m/h ~500 s prior to breach initiation (Figure 19).

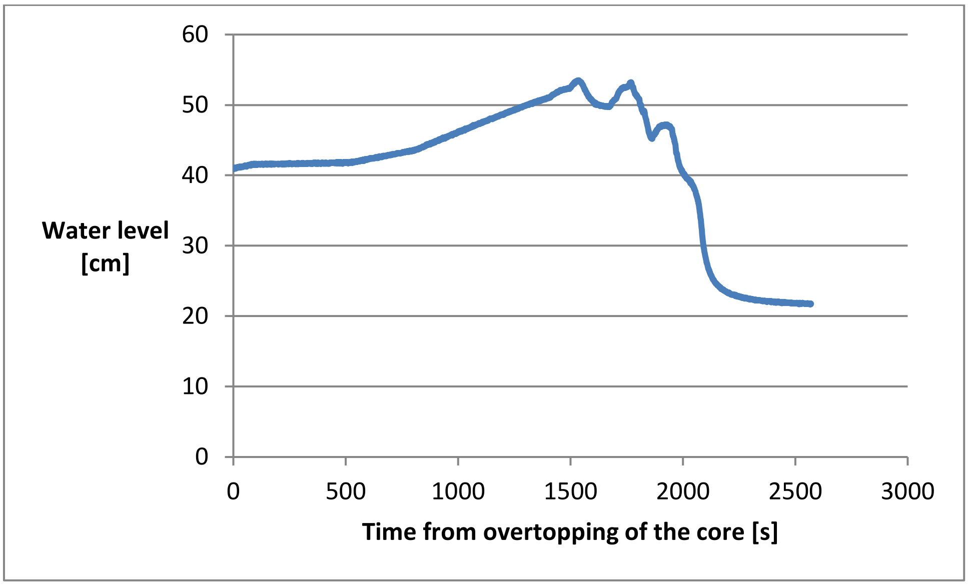


Figure 19. Water level in the reservoir from overtopping the core to the end of the test. Breach initiation at 1.500 s from overtopping the core.

The time from breach initiation to a sudden collapse of the fuse plug was ~200 s (Figure 20). After the collapse of the fuse plug it took another 600 s for the fuse plug to be eroded down to a height of ~22 cm. The inflow of water was thus not enough to erode the fuse plug completely (Figure 21). From the initial height of 50 cm, 44 % of the height of the fuse plug remained intact after the test was aborted.

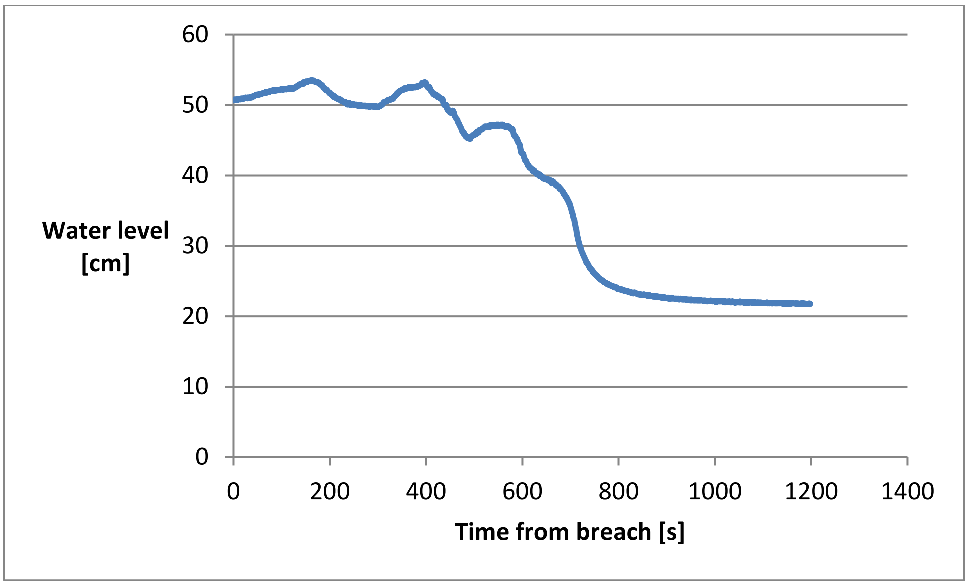


Figure 20. Water level in the reservoir from the moment of breach (breach at 0 s) to the end of the test.


Figure 21. Fuse plug after the 1:6 scale test had been aborted.

4 Analysis and Discussion

4.1 BREACH MECHANISM

As soon as the reservoir level exceeded the core crest, internal erosion started. The design of the fuse plug allowed the overtopping water to pass through the intersection core crest/insulation foam boards down to the unprotected downstream filter sand, initiating its erosion. This affected the fuse plug at all points sideways, a fact that became evident due to the propagation of the breach from the center of the pilot channel and outwards towards the abutments (Figure 22). The breach was concentrated to the center of the fuse plug because of the pilot channel. If there was no pilot channel the breach initiation would have occurred at a random or several random locations in the crest but at the same height as the breach formation in the field test.

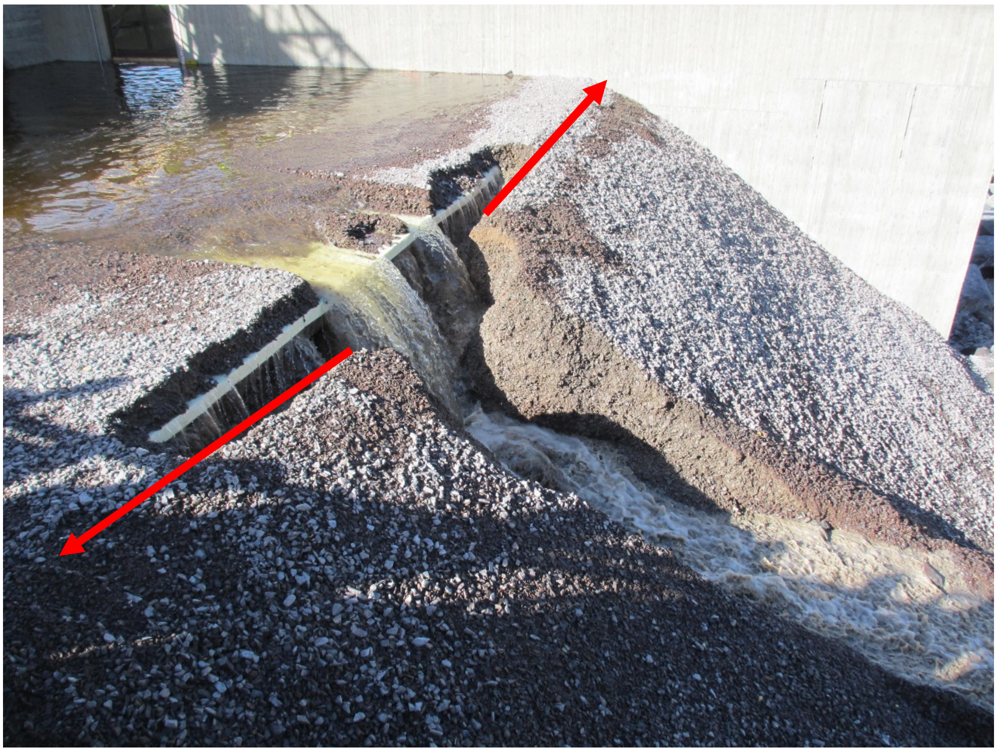


Figure 22. Propagation of breach sideways from the center of the fuse plug and outwards toward the abutments (red arrows). Photo is taken from the field test.

In the field test and in the 1:6 scale test the breach initiation was very similar, see Figure 23. In these two different tests a pipe was formed below the pilot channel in the downstream slope at a corresponding height to the core/insulation foam board interface. After the formation of this pipe, the structural fill caved in at the downstream side of the pilot channel, thus opening up the breach. In the 1:3 scale test this was not the case. The fuse plug crest in the 1:3 scale test was completely overtopped by water before the crest imploded, followed by a pushing action of the water on the structural fill. After this, the breach propagation in the 1:3 scale test was however similar to the field and 1:6 scale test. The amount of seepage through the 1:3 scale model was higher than during the other two tests prior to the breach initiation.

Moment of breach 1:6 scale test

Moment of breach 1:3 scale test

Moment of breach field test

Figure 23. Moment of breach initiation for the two model tests compared to the field test. Note the difference between the 1:3 scale test compared to the other.

The difference in events leading up to breach initiation may be explained by the ratio between maximum grain size of the structural fill and the width of the experimental setup. The ratios can be seen in Table 4. A probable explanation is that arching might have occurred to a higher degree during the 1:3 scale test. If arching occurred in the structural fill in the 1:3 scale test, this might explain why it could withstand a higher degree of overtopping than the field and 1:6 scale test.

Table 4. Ratio between grain size and width of each test.

Test type	Ratio (d_{max}/fuse plug width)
Field test	**0.002**
1:3	0.03
1:6	0.008

The insulation foam boards decreased the erosion rate of the fuse plug, and in particular the insulation foam boards in the upstream slope (Figure 24). As soon as the insulation foam boards in the upstream slope was washed away, the erosion rate increased and the total collapse of the fuse plug was imminent. The insulation foam boards are not expected to delay the breach initiation, only to delay the total collapse of the fuse plug.

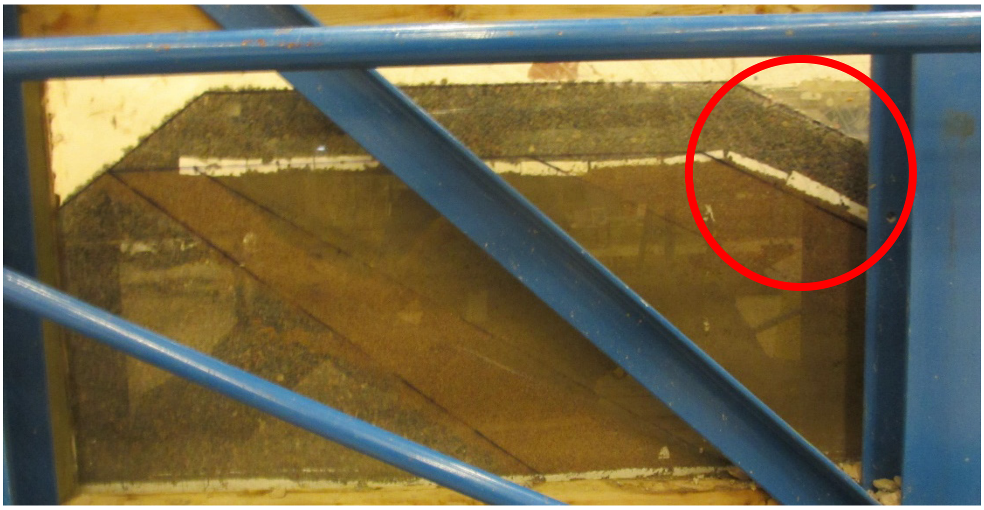


Figure 24. Insulation foam boards seen from the left abutment in the 1:6 scale test. The insulation foam boards on the upstream slope inside the red circle were in particular slowing down the erosion rate of the fuse plug.

4.1.1 FEM calculations

FEM calculations were only done on the field test (full scale test) since calculations on the scaled models proved difficult due to scale factors. For further information regarding the field test, the results are found in the Appendix. FEM calculations were done for two moments;

1. Water level reached the pilot channel (11:16 am, +84.70 m)
2. Moment of breach (11:41 am, +84.99 m)

The fuse plug failed due to overtopping at 11:41 am, 25 minutes after the reservoir level exceeded the upstream side of the pilot channel, as shown in Figure 25. However, the assessment of the breach mechanism and test observations indicated that the top part of the shoulder fill may have developed internal erosion at 11:16 am.

Figure 25. Field test fuse plug at 11:41 am, upstream water level +84.99 m.

The results indicating internal erosion prior to overtopping are highlighted below. The simulations presented in Figure 26 to Figure 28 represent the situation at 11:16 am in the field test, i.e. when the reservoir level reached the pilot channel.

In Figure 26 it is shown that high seepage velocity occurred as expected at the top of the downstream filter as water started to overtop the core. Hence, it was obvious that the high flow through the coarse material dragged the finer particles from the core-filter interface by contact erosion (ICOLD, 2013).

Three main factors that control the internal erosion are: material, hydraulic gradient and shear stress ratio. Grain size, specific gravity and elastic properties represent material parameters, whereas the hydraulic gradient represents the height of the water column in the saturated part of the fuse plug.

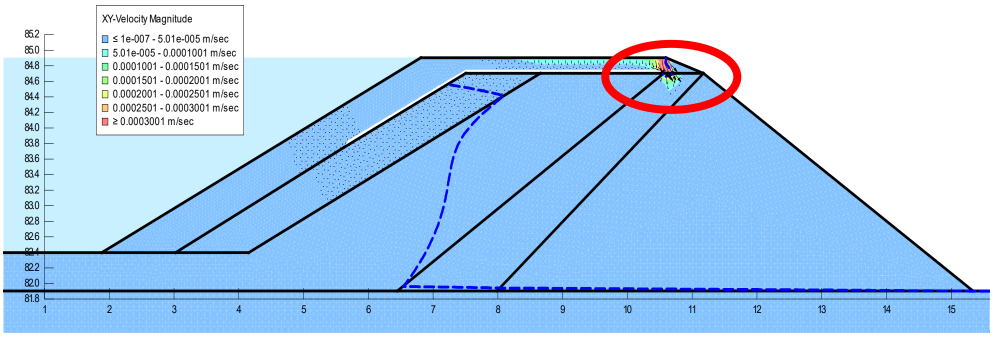


Figure 26. Seepage velocity at 11:16 am.

The shear stress ratio (*q*/*p'*; where *q* is the deviatoric stress ($\sigma_1 - \sigma_3$); and *p'* is the mean effective stress) at the crest was lower than 1.2 (Figure 27) as expected as effective stress was minimum. On the other hand, the shear stress was maximum at the core of the fuse plug within the filter. It is worth mentioning that horizontal stresses may have developed within the fuse plug due to the weight of the embankment based on "gravity loading" concept (e.g. Twiss and Moores, 2007) in addition to the weight of the water column upstream and within the saturated zones. When the shear stress was high, it meant that the horizontal stress component, which was parallel to the bedding (surfaces parallel to the compacted layers, see Figure 13), overcomes the normal stress component.

If given enough time, this effect should have led to water breakthrough given the hydraulic gradients were high enough within the core of the fuse plug (Figure 28). It is evident that horizontal fractures will be opened at shallow depth when the principal horizontal stress becomes higher than the principal vertical stress as demonstrated in Äspö HRL (Talbot & Sirat, 2001). This can probably explain the mechanism of internal erosion, which is also consistent with the results obtained by Chang and Zhang (2012),where the shear stress ratio and hydraulic gradients in their test were within this range. Hence, by time, piping could likely occur at any point of the crest if the reservoir level was kept between the top of the core and dam crest.

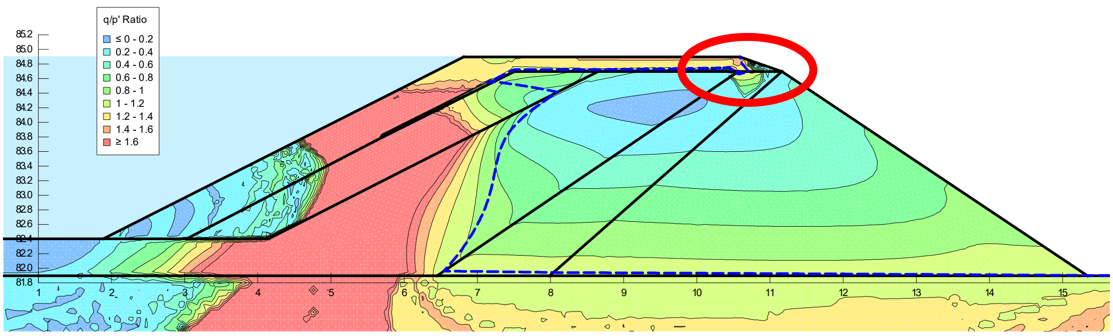


Figure 27. Shear stress ratio (q/p') at 11:16 am.

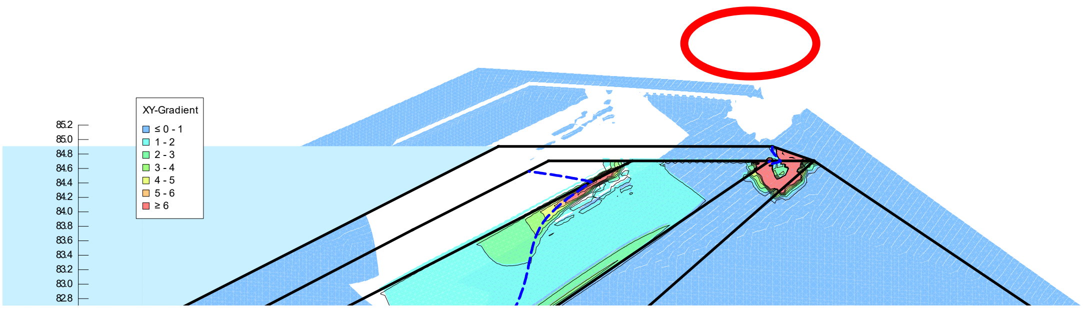


Figure 28. Hydraulic gradients at 11:16 am.

Further, when the pore-water pressure at the crest was equal to the total stress and the soil had no strength, i.e. effective stress was zero, the particles could be transported with the seepage flow. Hence, failure could occur when the downstream shoulder was fully saturated. Furthermore, there was no filter downstream the insulation foam boards which increased the likelihood for fine particles from the top of the filter-core interface to flow through the voids of the coarser material.

A significant observation that seepage occurred faster at the abutments than in the pilot channel, most likely indicates that internal erosion may have occurred earlier in the core and abutments, with weak parts in the soil/side wall interface with limited compaction. This phenomenon was also discussed in a 3D seepage model by Chen and Zhang (2006).

4.2 COMPARISON BETWEEN FIELD AND SCALED TESTS

The velocity at which the water level was increased in each test was vital to be able to properly compare the field test with the scaled models. It was difficult to control the inflow of water in the scaled tests since this had to be done manually by opening and closing a control valve. Each scaled test aimed at elevating the water level at 1:3 and 1:6 velocity compared to the 0.2 m/h in the field test. The operation of the valve became more and more difficult as the water level increased above the crest of the core due to excessive seepage through the top part of the fuse plug.

The elevation velocity of the water was "correct" in each of the scaled test until the reservoir level exceeded the core crest. The actual velocities from there on until the breach initiation is seen in Table 5. Compensation for the scale factors has been done for the 1:3- 1:6 scale test. As seen in Table 5, the velocity at which the water in the reservoir rose was higher in both scale tests and in particular during the 1:6 scale test.

Table 5. Water elevation velocities from time when passing the core crest to breach initiation. Scale factors included.

Field test	202 mm/h
1:3 scale	291 mm/h
1:6 scale	1498 mm/h

4.2.1 Overtopping the core to breach initiation

As seen in Table 6, the time from overtopping the core crest to breach initiation varied between the three tests. The 1:6 scale test was the fastest to breach and the 1:3 scale test remained intact the longest. The velocity at which the water rose in the 1:6 scale test was by far the fastest in the three experiments (Table 5). Compared to the field test the velocity was roughly 7.5 times as fast. Furthermore, in the 1:6 scale test a smaller grained structural fill was used, which made it more prone to breach earlier due to its lower ability to withstand the hydraulic forces from the seepage. These factors combined made the 1:6 fuse plug breach earlier. The structural fill in the field and 1:3 scale test was similar but arching phenomenon may have delayed the breach formation in the 1:3 scale test due to the smaller geometry of the 1:3 scaled model. The elevation velocity of the water was similar between the 1:3 scale test and the field test.

Table 6. Time from overtopping the core to breach initiation.

Field test	86 min
1:3 scale	109 min
1:6 scale	23 min

4.2.2 Breach initiation to collapse

The scaled tests of the fuse plug could not provide such hydraulic forces at which the fuse plug was completely eroded. The fuse plug was thus only completely eroded during the field test. In the scaled tests the fuse plugs were eroded down to a height of 24 cm (1:3) and 22 cm (1:6) respectively. The nature of the core and the inflow capacity of 97 l/s/m (1:3) and 98 l/s/m (1:6) were the only two decisive factors with regard to the complete erosion of the fuse plug. During the field test the inflow capacity at maximum was 5160 l/s/m, offering much higher hydraulic forces on the particles in the fuse plug. Neither the structural fill nor the filter sand had any impact on the complete erosion of the fuse plug.

Table 7. Time from breach initiation to a complete/partial collapse of the fuse plug.

Field test	25 min
1:3 scale	17 min (no further erosion)
1:6 scale	10 min (no further erosion)

4.2.3 Water level above crest at breach initiation

Since the water is flowing over/through a porous medium, i.e. the structural fill, overtopping of the upstream side of the crest happens before overtopping of the downstream side of the crest. The water levels were measured in the reservoir upstream so the actual height of the water level at the downstream side of the crest could not be measured at all. The actual height of the water at the location of the breach was therefore lower than the measured heights. It could therefore be assumed that if the width of the crest was bigger, the overtopping height would be higher before obtaining a breach.

In the field and 1:3 scale tests where the structural fill was similar, the same overtopping height of water was obtained when the breach occurred. In the 1:6 scale test, the corresponding height was lower (Table 8). The structural fills ability to withstand hydraulic forces was a key factor in this height.

Table 8. Height of water level above the crest at breach initiation.

Field test	7.0 cm
1:3 scale	7.6 cm
1:6 scale	2.6 cm

4.2.4 Scaling of material and dimensions

Within the 1:3 test no material was scaled down – only the geometrical dimensions of the fuse plug. The core soil, filter sand and structural fill had the same particle size distribution as in the field test. Since the dimensions of the fuse plug in this test was scaled down, so was the elevation velocity of the water reservoir. By doing so, the timing of events in the 1:3 scale test were in good agreement with those in the field test.

Only scaling of the structural fill was possible in the 1:6 scale test. If the filter sand and the core soil had been scaled down, their characteristics would have been completely changed compared to the original filter sand and core soil, e.g friction soil to a cohesive soil. Scaling of the structural fill did however not change the characteristics of the material in that way. Scaling of the structural fill only transformed the coarse gravel into a finer gravel but with its principal characteristics maintained.

Exactly the same set-up as used in the 1:3 test could have been used in a 1:1 test where only the top meter of the fuse plug would have been considered. The only difference between a 1:3- and 1:1- test would then have been the elevation velocity of the reservoir, i.e. a higher elevation velocity in the 1:1 test. Although only the upper 1.0 m of the fuse plug would have been part of this set-up, it is the initiation of the downstream structural fill/filter that is critical. If initiation of breach occurs and continues there will be a full breach and the rate at which the fuse plug is eroded will be dependent on the elevation velocity of the water in the reservoir.

5 Conclusions

The investigated fuse plugs breached due to a combination of internal erosion of the filter sand and a structural fill not able to withstand excessive seepage. The internal erosion made the downstream crest of the fuse plug to “cave in”, thus initiating the breach. When the crest caved in, water velocities through the structural fill increased and pushed it down the downstream slope. The inclined core did not break as intended even though it was undercut. Instead, it was “shaved off” layer by layer. The breach was self-regulated, i.e. the breach spread sideways only if enough upstream water was available in the reservoir. The described order of events during the breach and propagation phase occurred in both scaled tests and were in agreement with the field test.

The time for the breach to occur after the core was overtopped was partly dependent on the velocity at which the water in the reservoir rose. Due to the differences in reservoir elevation velocities between the two tests, the 1:6 scale fuse plug breached much earlier than the 1:3 scale fuse plug. The reservoir elevation velocities in the field and 1:3 scale test were similar, hence, the time until breach was similar.

The height of overtopping water during the breach initiation depended on the grain size in the structural fill since larger grained structural fill could withstand higher seepage forces. As a consequence of this, the reservoir level above the crest at which the breach was initiated was higher for the 1:3 scale test compared to the 1:6 scale test in which a finer grained structural fill was used. The grain size of the structural fill in the 1:3 scale test was the same as in the field test, hence, they breached at a similar overtopping height.

The insulation foam boards did not delay the breach initiation. They did however delay the erosion of the fuse plug after the breach initiation. The insulation foam boards gave protection for the core against the passing water. As soon as they were washed away, the erosion rate of the fuse plug was increased. The insulation foam boards affected all tests in a similar way.

Warning signs prior to breach included a higher seepage rate at the toe of the fuse plug, increased turbidity and a development of a phreatic line of seepage just below the crest of the fuse plug on the downstream side. The height where this seepage was visible corresponded to the height of the interface core/insulation foam boards. The 1:6 scale test exhibited all the warning signs as experienced during the field test while the 1:3 scale test failed to reveal a line of visible seepage. Apart from that, both models behaved as the field test fuse plug.

Based on the results from the scaled model tests it is possible to exchange field test with small scale model tests. However, both the 1:3 and the 1:6 scale test should be used in order to get the full picture of the breach behavior. The advantages of using a small scale test instead of field test are that no environmental permits are needed, gives faster results and it is cheaper.

6 References

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Appendix A: Fuse plug field test

CONSTRUCTION OF FUSE PLUG

The construction of the field test was carried out at Lanforsen hydropower plant. Prior to the construction of the fuse plug, the bedrock downstream the spillway was cleaned, sealed and levelled with concrete due to excessive fracturing of the bedrock. A concrete plate was constructed to support the foundation of the core and a concrete abutment and a new retaining wall, both in concrete, acted as side supports for the fuse plug (Figure 29).

The core was constructed in ten layers, thoroughly compacted with a vibration compactor to a thickness of 0.30 m. Insulation foam boards were placed on top of the core and a part of the upstream side of the filter (see Figure 3) For each layer the degree of compaction and water content was measured to ensure the design proposal. After finalizing construction the fuse plug was scanned with a laser scanner in order to obtain an exact surface geometry.

Five days before the test, water was slowly pumped into the “reservoir” between the spillway gate and the upstream slope of the fuse plug at a rate of 0.2 m/h. The pumping continued until the water level reached maximum operation level of the fuse plug (+83.8 m, level adjusted for the test). After reaching the maximum operational level it was kept steady until the day of the test. The leakage was neglectable. During the test, the water level was increased by 0.2 m/h until the core crest was reached (+84.7 m). At this level the pump was stopped for a final control of the measurement equipment. The pump was then restarted until the crest of the fuse plug was reached (+85.0 m). When the water level reached the crest and the breach was initiated, the spillway gate was manually operated and the water level was increased continuously by 0.2 m/h.

Ground improving work and construction of left side concrete wall. View from downstream.

Fuse plug constructed. Water at operating level (+83.8 m). View from upstream.

Figure 29. Various construction phases of the field test in Lanforsen.

The inflow of water to the reservoir had to be estimated since it was manually controlled by a spillway gate. Water pressure gauges were installed on both sides of the spillway gate and a device for measuring the opening of the spillway gate. These three measurements were logged throughout the test with a frequency of 1 Hz. From these measurements it was possible to calculate the discharge capacity of the fuse plug throughout the breach phase.

The test was also filmed from four different angles with GoPro Black Edition HD cameras in order to document the breach pattern over time.

The behavior of the fuse plug was furthermore analyzed using Finite Element Modelling (FEM) to determine the theoretical seepage and stress conditions in the fuse plug prior to breaching. The calculations were performed with the software Geostudio 2012 in two parts: 1) 2D Steady-state and transient seepage with Seep/w and 2) 2D Stress/deformation models with Sigma/w; coupling the seepage results for each 0.2 meters of water elevation. Similar analyses but for another laboratory test have been done by Vazquez (2015).

DEGREE OF COMPACTION

The demand for degree of compaction set on each layer of the core was 92 %. All ten layers were compacted above this level, see Table 9.

Table 9. Degree of compaction and water content for each layer of core in the fuse plug

Layer	Level (RH70)	Degree of compaction [%]	Water content [%]
10	+84.7	95	9
9	+84.5	97	8
8	+84.2	95	8
7	+83.9	95	8
6	+83.6	96	9
5	+83.3	97	8
4	+83.0	101	8
3	+82.7	97	7
2	+82.4	94	6
1	+82.1	99	6

CHRONOLOGY OF THE PERFORMED TESTS

The impounding of water was started at 5:02 am and the order of events throughout the test can be seen in Table 10. The velocity at which the reservoir level increased was ~0.2 m/h. Prior to the breach, a line of seeping water could be observed in the downstream shoulder 0.4 m below the crest at the boundary of insulation foam boards and core (Figure 30). This water line first appeared simultaneously at both abutments but as the reservoir level increased, it moved towards the center of the fuse plug. Prior to the breach of the downstream side of the crest, seepage with turbidity could be seen on the downstream slope below the pilot channel like a spring, indicating internal erosion. The breach initiation occurred at 11:41 am at a level of +84.99 m, equaling the crest height of the fuse plug. After the breach initiation, the reservoir level continued to rise until 11:59 am up to a maximum reservoir level of +85.12 m, 13 cm above the crest of the fuse plug and 43 cm above the crest of the core. Further breaches then took place all along the crest in a similar way to the first breach initiation.

The breach progressed in the center of the fuse plug (Figure 31) in a "pushing action" caused by the water on the structural fill. The erosion then gradually spread sideways all along the crest of the fuse plug as the reservoir level slowly continued to rise (Figure 32). The structural fill on top of the insulation foam boards was quickly washed away. The insulation foam boards slowed down the erosion process of the core beneath them. The insulation foam boards were washed away one by one, gradually leaving the core exposed to the passing water. The insulation foam boards that were placed on the upstream side of the inclined filter sand were in particular responsible for protecting the core against erosion (Figure 33 left). As soon as these insulation foam boards were washed away the core was quickly eroded. The core in the beginning of the erosion process was "shaved off" layer by layer. After some progression of the erosion the core finally "broke" into larger pieces as intended. At this stage the erosion rate was increased (Figure 33 right).

Table 10. Order of events in the field test. Core crest at +84.7 m and fuse plug crest at +85.0 m.

Time	Event	Water level (RH70)
05:02 am	Impounding with pumps started	+83.81 m
08:51 am	Impounding stopped just below the core crest	+84.59 m
09:26 am	Impounding restarted	+84.60 m
10:15 am	Water reached the top of the core	+84.70 m
11:16 am	Water reached the pilot channel	+84.92 m
11:41 am	Initiation of breach started	+84.99 m
11:44 am	Gate was opened to increase the capacity	+84.98 m
11:59 am	Maximum water level was reached in the reservoir	+85.12 m
12:08 pm	Gate was fully opened (1.34 m)	+83.67 m
12:10 pm	Maximum flow was reached (68.6 m^3/s)	+83.15 m
12:11 pm	Gate began closing. No reading from pressure gauge downstream gate	+82.91 m
12:12 pm	Gate was fully closed. Fuse plug fully eroded	n/a

The time for the water level passing the top of the core to attaining maximum water level in the reservoir was **1 h 44 min**. The time for water level passing the crest (pilot channel) to attaining the maximum water level in the reservoir was **43 min**.

Figure 30. Orientation and movement of seeping line of water (arrows) and breach initiation (circle)

Figure 31. Progression of breach just after initiation.

Figure 32. Breach initiation and propagation. Note the more excessive erosion at the center due to the pilot channel.

Complete erosion of downstream structural fill at 11:55 am

Fuse plug totally eroded at 12:12 pm

Figure 33. Propagation and complete erosion of the fuse plug.

WATER LEVEL DURING THE TEST

The upstream water level rose with a velocity of 0.2 m/h during the main part of the test (Figure 34, 0-5,000 s). When the water level exceeded the crest, the seepage through the crest increased. At 11:44 am (3 min after breach initiation the spillway gate had to be opened in order to aid the pumps (Figure 34 at ~5,200 s), thus compensating for the increased seepage.

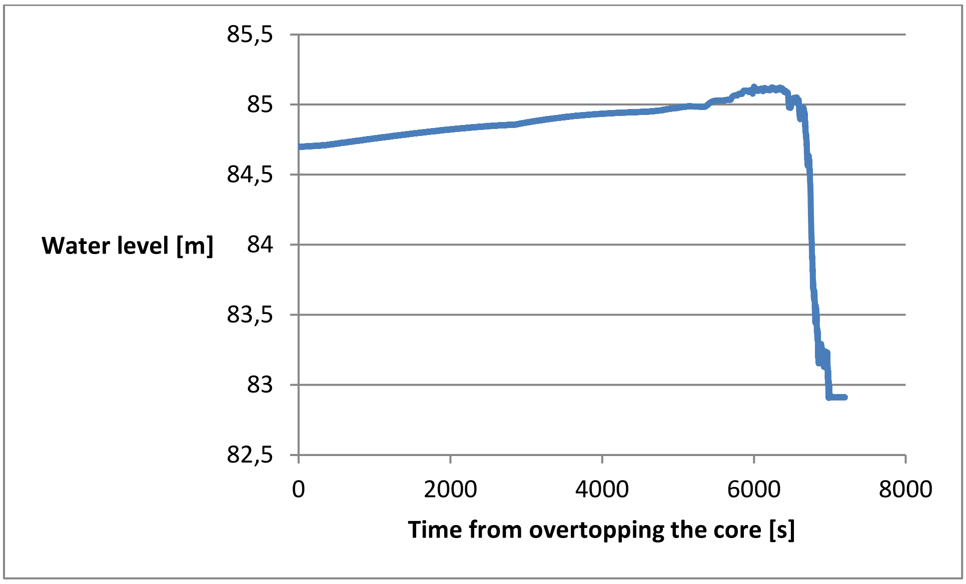

Figure 34. Water level in the reservoir from overtopping the core to the end of the test. Core was overtopped at 10:15 am.

The time from breach initiation to a sudden collapse of the fuse plug was ~1,500 s (Figure 35). After the collapse of the fuse plug it took yet another 300 s for the fuse plug to be fully eroded. The time from breach initiation to a complete collapse was thus ~1,800 s (30 min).

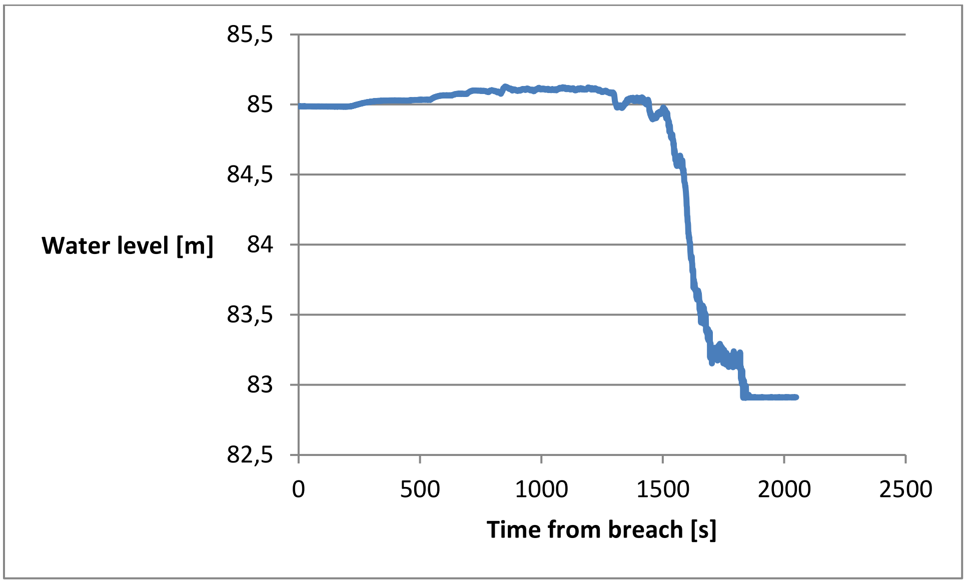

Figure 35. Water level in the reservoir from the moment of breach to the end of the test. Breach occurred at 11:41 am.

DISCHARGE DURING THE TEST

The discharge during the test had to be calculated. The calculation was based on the difference in water level between the water level up- and downstream the spillway gate in combination with the actual opening width of the gate itself. The estimation was performed for the whole width of the fuse plug, i.e. 13.00 m. The maximum discharge of 68.6 m³/s (for the 13.0 m wide fuse plug) was attained ~1,600 s (25 min) after the spillway gate was opened (Figure 36). The time for the maximum discharge was 12:10 pm, 29 min after breach initiation. For each meter of fuse plug, the maximum discharge capacity during this test was 5169 l/s.

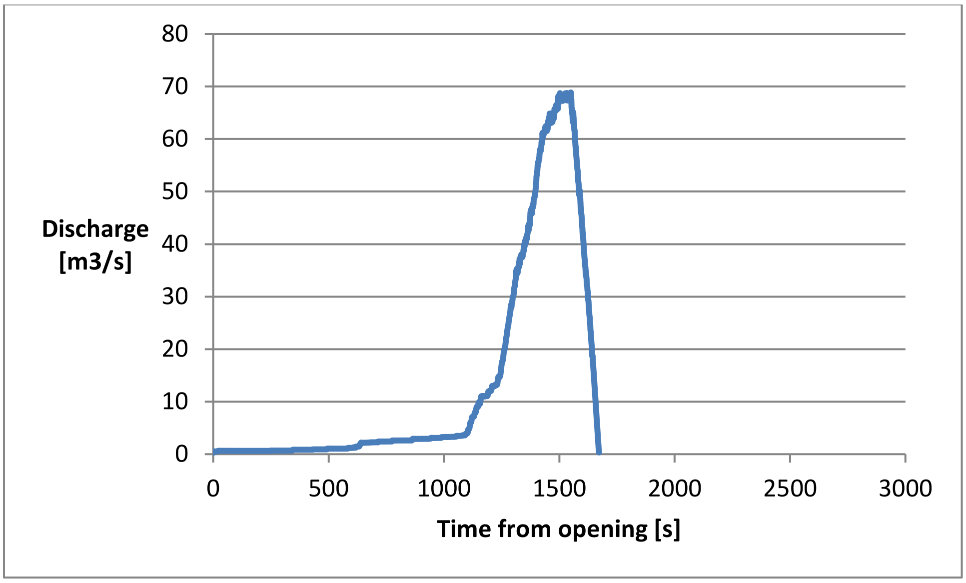

Figure 36. Discharge during the test after the gate was opened. Gate operation was started at 11:44 am.

Since the upstream water level decreased rapidly during the test the calculated discharge capacity from the test is to be regarded as a conservative measurement. In reality, it will be higher.

FUSE PLUG BREACH TESTS

A fuse plug functions like a normal embankment dam during its life span but is expected to breach during extreme flows in order to protect the main dam. A fuse plug can thus be said to function like an emergency spillway gate.

Field- and laboratory tests indicate that the size of the structural fill determines at what overtopping height the breach of the fuse plug is initiated. The elevation velocity of the water in the reservoir determines when in time the breach initiation will occur. The design of the fuse plug determines how the erosion process occurs after the breach initiation.

Insulation foam boards to protect the core oil from frost and thaw does not affect the breach initiation of the fuse plug. The insulation foam boards will however slow down the complete erosion process.

Field tests can be replaced with scaled tests in a laboratory. This will make the process of designing a fuse plug cheaper and faster.

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