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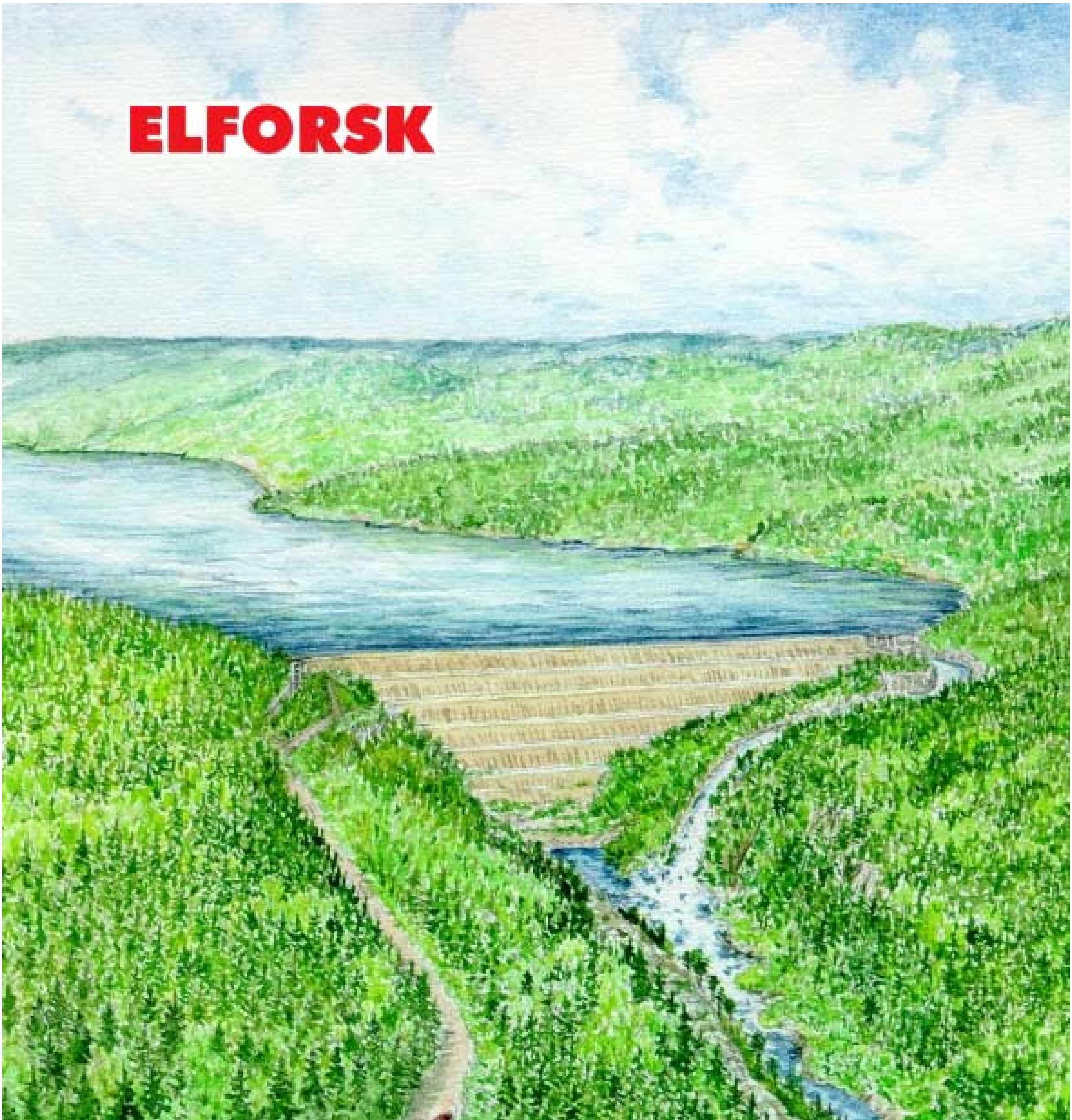

DAMMSÄKERHET

SCIENTIFIC WORKSHOP ON INTERNAL EROSION MONITORING, 13-15 JUNE, 2000

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SCIENTIFIC WORKSHOP ON INTERNAL EROSION MONITORING

13-15 June, 2000

Elforsk rapport 01:21

Editors: Marcus Bergman, Royal Institute of Technology, and
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Förord

Elforsk deltar i arbetet som bedrivs inom den s.k. Dam Safety Interest Group, DSIG, som består av ett flertal kanadensiska vattenkraftbolag, US Army Corps of Engineers samt några europeiska bolag.

Arbetet i DSIG drivs i form av projektområden där DSIGs medlemmar själva bestämmer vilka områden man önskar delta i, antingen i form av naturainsatser eller i form av rena ekonomiska bidrag. Elforsk deltar bl.a. i arbetet kring geofysiska undersökningsmetoder och driver där själv projektet ”Internal erosion monitoring”. Som en del i detta projekt har man arbetat med grundläggande samband mellan olika fysikaliska företeelser, för att öka förståelsen för kopplingarna mellan de olika geofysiska metoder som används.

Som ett led i projektarbetet har Elforsk bjudit in medlemmarna i DSIG till en vetenskaplig workshop på temat ”Internal erosion monitoring”. Till mötet inbjöds också ett antal andra personer som bedömdes som väl insatta i problematiken och som kunde bidra till diskussionerna på ett positivt sätt. Följande rapport är den dokumentation som blev följden av workshopen, som på ett konstruktivt sätt bidragit till projektets slutresultat.

Summary

Non-Destructive-Methods for investigation and examination of dams have been an important research area in several countries. However, different soil materials, monitoring equipment and application, as well as different dam construction methods, give different result for similar methods. Result and experiences from different countries seems therefore often to be contradictory, a fact that reduces a wider introduction and use of such methods. Thus, an exchange of experience and result should be valuable both for researchers in different fields and dam owners with a variety of dams. Therefore, ELFORSK invited to a SCIENTIFIC WORKSHOP ON INTERNAL EROSION MONITORING, which was held within the CEA DSIG Geophysics Research Project (T992700-0205), "Analyses of interaction between temperature, resistivity and SP at seepage monitoring in dams".

The objective with the workshop was to create a free scientific forum where researchers, and other deeply interested persons, could discuss fundamentals, problems, needs and potentials for methods that can be used or improved to detect and monitor internal erosion; and to exchange information and experience from ongoing DSIG-projects and monitoring projects within Europe.

This documentation contains a summary of the presentations and discussions held at the six sessions at workshop:

Session A – Monitoring in dams

Session B – Temperature

Session C – Resistivity

Session D - Streaming potential

Session E - Acoustic methods – Seismic /Cross-hole seismic

Session F - Electromagnetic methods – Ground Penetrating Radar

Sammanfattning

Oförstörande metoder för undersökning och övervakning av fyllningsdammar har varit ett angeläget forskningsområde i flera länder. Olika jordmaterial, mätutrustning, installationsmetoder, samt varierande utförande av dammarna har dock medfört svårigheter att direkt kunna jämföra resultat och erfarenheter. De resultat som erhållits vid användning av oförstörande metoder synes ofta vara motsägelsefulla Detta har begränsat möjligheterna för en mer generell introduktion av dessa metoder. Det har därför bedömts vara angeläget och värdefullt att skapa ett forum för forskare och dammägare för utbyte av erfarenheter.

År 1999 inbjöd därför Elforsk till "SCIENTIFIC WORKSHOP ON INTERNAL EROSION MONITORING", vilken hölls i anslutning till CEA DSIG Geophysics Research Project (T992700-0205) "Analyses of interaction between temperature, resistivity and SP at seepage monitoring in dams".

Huvudsyftet med mötet var att skapa ett fritt vetenskapligt forum där forskare och dammägare gemensamt skulle ges möjlighet att tillsammans diskutera och utbyta erfarenheter om olika metoders grundprinciper, behov och utvecklingspotential, förslag till förbättringar för att upptäcka förekomst av inre erosion. Dessutom var syftet också att etablera kontakter mellan forskare/dammägare inom DSIG och Europa.

Denna dokumentation redovisar sammanfattningar av de presentationer som hölls under de sex sessionerna:

Session A – Mätningar i dammar

Session B – Temperatur

Session C – Resistivitet

Session D - Strömningspotential

Session E - Akustiska metoder – Seismiska /"Cross-hole seismic"

Session F - Elektromagnetiska metode – Georadar

Content

Appendix

1 Introduction

1.1 Background

Non-Destructive-Methods for investigation and examination of dams have been an important research area in several countries. However, different soil materials, monitoring equipment and application, as well as different dam construction methods, give different result. Result and experiences from different countries seems therefore often to be contradictory, a fact that reduces a wider introduction and use of such methods. Thus, an exchange of experience and result should be valuable both for researchers in different fields and dam owners with a variety of dams.

This workshop was primarily focused on methods that can detect seepage changes and internal erosion, that is a major problem that has to be considered all over the word. There are two reasons for this limitation:

1. This area is of great importance for embankment dams. It have been studied in several projects that were carried out in the late 80ties in Sweden. A general study of possible non-destructive methods identified temperature, resistivity and Streaming Potential (SP) as the most appropriate methods to study internal erosion and seepage (Johansson et al, 1995). Those methods have since 1993 been applied in several dams for long term monitoring. Experience from these measurements have further focused on the need of a better physical understanding of the basic process and how all the fundamental parameters interact. The monitoring aspects of the fundamental internal erosion processes in a dam have been found to be more complicated than for many other applications for those methods.
2. Initial result from “A parameters study for internal erosion monitoring”, (Johansson et al, 2001) was presented as a basis for the discussions. The project was based upon theoretical studies of the internal erosion and subsequent leakage phenomena in order to identify the most fundamental parameters. The main objective is to achieve a better knowledge of the basic processes, to identify relations between parameters in order to estimate their significance, and to identify areas that can improve monitoring and evaluation methods.

1.2 Objective

The objective with the workshop was:

- to create a free scientific forum where researchers, and other deeply interested persons, could discuss fundamentals, problems, needs and potentials for methods that can be used or improved to detect and monitor internal erosion; and
- to exchange information and experience from ongoing DSIG-projects and monitoring projects within Europe.

The workshop was held in Stockholm at Silja Conference Center within the CEA DSIG Geophysics Research Project (T992700-0205), “Analyses of interaction between temperature, resistivity and SP at seepage monitoring in dams”. A study tour after the workshop including a field monitoring demonstration is arranged to Sädva Dam, in northern Sweden.

1.3 Program

Date	Time	Program
June 13	**10 –13**	**Session A – Monitoring in dams** **Introduction** Opening and presentation of the participants **Background** DSIG Geophysical Project, Ken Lum SECURE – project, Sam Johansson **State-of the art** Monitoring in dams, Elmo Debiaggio Internal erosion experience, Jean-Jacques Fry Geophysical monitoring experiences, Tai Mal Phat Presentation of the Internal Erosion Parameter Study, Sam Johansson **Discussion (All)**
	14 – 18	**Session B - Temperature** Fundamentals - Heat processes in soil, Johan Claesson Thermal properties and evaluation tools, Göran Hellström Application in dams – Ability to detect changes, Sam Johansson Monitoring equipment, Mahmoud Farhadiroushan **Discussion –** Cases/experiences, Improvements, Monitoring performance, Applications?
June 14	**8–12**	**Session C – Resistivity** Fundamentals – Dale Morgan Soil properties – Laboratory test (Dale Morgan) Monitoring equipment (several) Evaluation tools – modeling (several) Application in dams – Ability to detect changes – Torleif Dahlin **Discussion –** Cases/experiences, Improvements, Monitoring performance, Applications?

June 14	**15-19**	**Session D - Streaming potential** Fundamentals, Bob Corwin Soil properties – Laboratory test (Dale Morgan, Johan Friborg) Monitoring equipment (several) Evaluation tools (Dale Morgan, + several) Ability to detect changes, Johan Friborg **Discussion** – Cases/experiences, Improvements Monitoring performance, Applications?
June 15	**8 – 11**	**Session E - Acoustic methods – Seismic /Cross-hole seismic** Fundamentals, Bob Ballard Monitoring equipment (several) Evaluation tools (several) Application in dams – Ability to detect changes, Peter Gaffran **Discussion** – Improvements, Monitoring performance, Applications, Cases/experiences?
	11 – 13	**Session F - Electromagnetic methods – Ground Penetrating Radar** Fundamentals, Johan Friborg Monitoring equipment (several) Evaluation tools (several) Ability to detect changes (several) **Discussion** – Improvements, Monitoring performance, Applications, Cases/experiences? **Other methods (all)** Strain and pressure – Fiber optics Movements – LADAR
	14 – 16	**Discussion and conclusions** Future needs and future work Priority research areas
	16.00	**Closure**

1.4 Program for the Study Tour

Date	Time	Group #1	Time	Group #2
June 16	8.05	Dep to Lulea, SK004	13.10	Dep to Arvidsjaure, JZ502
	10-14	About 300 km with vans	16-18	About 150 km with vans
	15 –	Monitoring demonstration at Sädva dam	18 –	Monitoring demonstration at Sädva dam
June 17	Morning	Monitoring demonstration at Sädva dam (cont.) Visit to the power station		
	Afternoon	Sightseeing to Norway, National parks, fishing, walking, wildlife excursions etc		
June 18	Morning Afternoon	Dep from Sädva Arrival at Luleå	 15.40	Dep from Sädva Dep to Stockholm Jz 505
June 19	Morning	Visit to Luleå University Dep to Stockholm		

1.5 Participants

Standing (from left to right)

Bob Corwin, SP Survey

Ken Lum, BC Hydro

Dale Morgan, MIT

Bing Zhou, LTH/Universtity of Adelaide

Urban Norstedt, Vattenfall

Anders Isander, Sydkraft

Gunnar Sjödin, Waterregulation Enterprices and Elforsk

Torleif Dahlin, Lund University

Phong Nguyen HydroQuébec

Johan Friborg, HydroResearch

Johan Claesson, CTH

Peter Gaffran, BC Hydro

Gérard Verzeni, HydroQuébec

Malte Cederström, Vattenfall and Elforsk

Göran Hellström, Lund University

Marcus Bergman, Royal Institute of Technology

Sitting (from left to right)

Bob Ballard, USACE

Paulo Morabito, Enel

Mahmoud Farhadiroushan, Sensornet

Sam Johansson, HydroResearch

Jean-Jacques Fry, EdF

Jane Salmon, CEA

Gary Salmon, CEA

Tai Mai Phat, HydroQuébec

Participants, but not on the picture

Elmo DiBiagio, NGI

Lars Hammar, Elforsk

Jonas Birkedahl, Birka Energi AB and Elforsk

2 Monitoring in dams

2.1 Canadian Electric Association (CEA) Dam Safety Interest Group. Geophysical Research. Project Overview.

Ken Lum, BCHydro

The DSIG geophysical research project stemmed out of a workshop in February of 1999. The workshop was in Vancouver was co-sponsored by US Bureau of Reclamation and BCHydro and involved people from the DSIG and other interested parties. During the workshop the most promising techniques and areas requiring further research were identified to be self-potential (SP), resistivity, seismic and temperature. The geophysical research project objective is to evaluate, adapt and develop these techniques to improve detection of anomalous seepage, piping and internal erosion as well as enhance long-term dam safety surveillance.

The five original tasks from 1999 were:

- Self-potential (SP) R.D. Markiewics / R.F. Corwin
- Resistivity R.D. Markiewics / R.F. Corwin
- Dam crest seismic R.J. Wittebolle
- Through dam seismic P.C. Gaffran
- Temperature evaluation S. Johansson

Two additional tasks were added in the end of 1999 and early 2000:

- Parameter study S. Johansson
- Long-term monitoring S. Johansson

The long-term monitoring task is scheduled to start during 2000 and will extend into 2003.

2.2 Presentation of the SECURE project

Sam Johansson, HydroResearch

The SECURE (Safety evaluation of man-made water control Structures in Europe) is a proposed three-year project of about 4 million US dollars and it involves 15 organizations from nine countries. One of its main issues is monitoring and another important issue is data based risk analysis. Monitoring technologies are divided into a number of issues and handled in a group consisting of people from Sweden, France and Italy. Another important issue is fiber optics for strain and temperature measurements. The subject for this workshop was originally proposed a part of the SECURE project but it was instead placed under DSIG since it was a quicker way to get started. Furthermore, there is a project dealing with soil tests, porosity and SP and finally there will be a Ph.D.-project at the Chalmers University dealing with seepage evaluation from temperature and resistivity measurements.

The SECURE project has not yet been granted any funding but the application received good grading at the first application round last fall. Since then it has been cut down from 6 to 4 million US dollars and hopefully there will be a positive decision made shortly.[1]

2.3 Instrumentation of Dams

Elmo DiBiagio, NGI

Much has happened during the last century in terms of techniques for instrumentation and monitoring of dams. Since Terzaghi published his important work on soil mechanics in 1925 a number of inventions have improved our possibilities to monitor civil engineering structures. The development ranges from the first test with vibrating-wire sensors in 1928, through the first digital calculating computer in 1948, to fiber optics and integrated circuits in 1961 and the development of computers in the 80's and 90's.

Lord Kelvin formulated the importance of measurements in the 19th century when he said "When you can measure it and express it in numbers you know something about it". Dams are instrumented for diagnostic reasons, predictive reasons, legal reasons and finally research reasons. Most instrumentation applications such as construction control, design verification, calibration of prediction models and trouble shooting are in the first two categories and very few dams are instrumented for legal or research reasons.

Today, at the beginning of the 21st century we have a variety of instruments that allow us to measure all of the parameters that we need to measure on a routine basis. However, there are a number of problems that may be encountered in instrumentation of any civil engineering structure. Primarily you must know what to measure and how to do it and which instrument to use. Furthermore, there are various technical problems with the instruments and data acquisition systems and for dams especially the reliability of the instruments is a great concern since we want to monitor our dams for very long periods of time.

Finally, some future trends in instrumentation of dams:

- More automation
- New and novel communication methods
- Improved GPS measurements
- Increased use of optical cables/sensors
- Increased use of geophysical methods
- Improved/standardized processing, analysis and presentation tools

[1] No funding was received in although a higher grading was obtained at the second time, autumn 2000.

- Instrumentation of existing dams

2.4 Internal Erosion: Typology, Detection, Protection

Jean-Jacques Fry, EDF-CNEH

Dr. A. Charles asked these two very important questions related to internal erosion at the ICOLD Congress in Florence in 1997:

1. *When does internal erosion lead to failure?*
2. *What is the speed with which the hazard will develop?*

To try to answer these questions an inquiry of dam incidents was carried out in France. Since 1970 there has been 71 observed accidents at dams, dykes and levees in France. Fortunately, there has been no failure of a large dam during this period.

The progress of internal erosion depends on detachment and transportation of particles. The two main types of material transport within dams are suffusion (or seepage erosion) and piping. Of the observed 71 accidents, 23 are explained as piping and 48 as suffusion. 17 failures occurred as a result of piping but only one as a result of suffusion.

One of the main consequences of suffusion is, according to the French investigation, the formation of holes under concrete slabs on embankments.

2.5 Investigations in Caniapiscau Reservoir La Grande Rivière Complex

Tai Mai Phat, HydroQuébec

One of *HydroQuébec*'s more recent research project is the investigation in Caniapiscau Reservoir, part of the Grande Rivière Complex. The dams in the area are founded on permafrost and there are concerns about the behavior at the dam integrity due to thawing at the interface between frozen and non-frozen till core in the event of a rise of water level.

To be prepared to intervene and restore the integrity and safety of the dams at the Caniapiscau Reservoir. HydroQuébec has initiated an investigation program with two main objectives:

- to characterize the till in the core with core sampling methods
- to determine the extent of the frozen zone with geophysical methods

The core sampling methods include for example frozen core samples from the crest, piezocone tests, installation of string of thermistors, porosity tests and photographing and documentation of soil and ice in samples.

The geophysical methods include resistivity, seismic, ground penetrating radar and transitory domain electromagnetics.

The project started in early June 2000 and the five bore holes required for the investigation were completed by the end of that month. It can be concluded that the permafrost penetrates to a depth of 7-8 m. The visual inspection of the core samples shows little or no trace of ice lenses or ice planes and there are no visible damage in the till structure.

Laboratory test has started and the result from the geophysical methods is soon to come.

2.6 Parameter Study - Internal Erosion Monitoring

Sam Johansson, HydroResearch

Monitoring of dams is made in order to obtain key information about the dam safety status and is therefore essential for the dam owners. Most common monitoring methods are seepage and pressure, which sometimes does not give enough information. The study is mainly focused on additional methods that are easy to install in existing dams. Drillings should there be avoided and installations for e.g. seepage monitoring are practically impossible to construct after the dam is completed. Methods that include installations inside the dam have therefore not been studied deeply.

Non-intrusive methods such as resistivity and Streaming Potential (SP) have been significantly improved during the last decade, and have been successfully adopted for dam investigations. However, those methods have generally been developed for other applications, and have to be further improved before they can easily be adopted on dams. Furthermore, the demand for monitoring is not the same as for investigations because long term monitoring must have a higher reliability and stability. If there are any seasonal variations they also must be considered.

The most appropriate parameters for monitoring of internal erosion are seepage, porosity, temperature, resistivity and SP. The methods that are used to measure these parameters give different resolution and accuracy and require different kind of installations. Each of these methods also depends on several primary and secondary parameters that may influence the result. Their interrelationship is complicated.

The project is based upon theoretical studies of the internal erosion and subsequent leakage phenomena in order to identify the most fundamental geophysical parameters. The main objective is to achieve a better knowledge of the basic processes for seepage monitoring and identify areas that can improve monitoring and evaluation methods. This have been done for three typical dam damages:

- Damage 1 is a cylinder with a diameter of 0.5 m;
- Damage 2 is a 1 m high seepage zone; and
- Damage 3 is a 10 m high seepage zone.

The degree of damage affects also the impact of measurable parameters. Three different seepage flow rates are therefore assumed in the study.

The location of the damage affects also the detection possibilities for the methods. Calculations have thus been made for three depths from the dam crest: 15 m, 30 m and 45 m.

The result from those 27 calculations (three damage types, three cases and three locations) for each method (temperature, resistivity and SP) will be presented later at the following sessions.

3 Temperature

3.1 An Analytical Solution for the Periodic Temperature in the Ground Around a Circular Groundwater Flow Channel.

Johan Claesson, Chalmers University of Technology

Circular erosion channels have been observed in several dams. The thermal impact of the seepage water flowing through such channels can be studied, using a new analytical solution to the periodical temperature flow in the ground around a circular channel with water flow. The question is if we can use the annual temperature variation as a sensor to detect abnormal leakage through an embankment dam.

Considering a leakage channel of any kind, there is an inlet temperature and a steady state temperature distribution along the seepage path. On top of this, there is a superimposed annual temperature variation of certain amplitude. In addition to the temperature variation along the seepage path, there is also a variation in the direction perpendicular to the flow.

An analytical solution must give both the time-varying amplitude and phase of the inlet temperature, and the extension of the damaged area. This can be achieved by detecting the decline of the temperature distribution along the seepage path.

The problem can always be solved numerically but an analytical solution would be much easier to use. Today, there is a solution available for two-dimensional flow and the work with a three dimensional solution is currently in progress. In the 2D case you consider flow in a circular pipe through a homogenous material. Then you assume a constant ground water flow in the channel. The suggested 3D solution is much more complex and includes complex functions for the periodic problems of amplitude and phase. So-called Bessel functions and eigen values occur in the solutions and you need quite a lot of mathematics to solve the problem.

In order to get the solutions, the axial heat conduction must be neglected. This is a valid assumption in the case of an elongated seepage path with a relatively small radius as is the case for most embankment dams.

According to the proposed analytical solution we should expect approx. 60% of the inlet amplitude at a measuring point 150 meters from the inlet point at a seepage flow of 0.001 m^3/s in and a radius of 2 m. At that distance from the inlet there should also be a phase lag of approximately one month.

3.2 Thermal Properties

Göran Hellström, Lund University

The paper discusses the different thermal properties of materials in embankment dams. The temperature in an embankment dam depends on the boundary conditions and the hydraulic and thermal properties of the dam material. The *thermal conductivity* of a water saturated soil is determined by its mineral composition and the quartz content is particular important. The quartz content in Swedish till is relatively constant at slightly more than 30% which gives a thermal conductivity of about 3.4 W/m,K. Since the thermal conductivity of water is only 0.58 W/m,K the thermal conductivity of a water saturated material will decrease when the porosity increases and solid material is replaced by water.

The thermal conductivity is also influenced by a *thermal dispersion* proportional to the pore velocity. The effective thermal conductivity is the combined effects of the conductivity of the liquid-soil mixture and the thermal dispersion.

The volumetric *heat capacity* (J/m^3,K) is the sum of the heat capacities of water and solids and it is turn the product of specific heat capacity (J/kg,K) and density (kg/m^3). The variation of the specific heat capacity is rather small, whereas the volumetric heat capacity is dependent on the porosity of the material and thus subjected to larger variations.

It can be concluded that internal erosion will affect the thermal properties less than the seepage itself. At engineering evaluations it may then be acceptable to just consider a temperature change (i.e. an increased temperature variation or a sudden temperature change) as a result of increasing seepage. However, corrections must be made for eventually changed boundary conditions such as differences in water levels and maximum temperature differences between studied years.

3.3 Application in dams

Sam Johansson, HydroResearch

The temperature in an embankment dam depends mainly on the temperature in the air and in the upstream reservoir. These temperatures vary seasonally and create temperature waves that propagate through the dam.

The seepage flow is normally small in embankment dams (hydraulic conductivity often less than 10^{-6} m/s) and the seasonal temperature variation in the upper part of the dam depends essentially on the air temperature at the surface. The influence from the air is however less than 1^{o}C for depths in the dam body that exceed 10 m and is therefore negligible beyond such depths. This process must however be considered in small dams, with heights less than about 20 m. In larger dams with heights above 100 m the geothermal flow must be considered, as well as the thermal stratification in the reservoir.

Temperature acts as a tracer with the seasonal temperature variation as source. Low seepage flows will not affect the temperature in the dam that will be constant. At increasing seepage flows the temperature in the dam will begin to vary seasonally. The amplitude of the variation is dependent on seepage flow, the seasonal variation at the inflow boundary, and the distance from the boundary to the measuring point.

The thermohydraulic behavior of an embankment dam is complex. It includes such basic thermal processes as heat conduction (from the dam crest and from the foundation due to geothermal flow), advection and radiation. The first two processes are partly coupled to each other because viscosity and density are temperature dependent. The problem is further complicated by the variation in material properties in the dam, and the different conditions in the saturated and unsaturated parts of the dam. In order to analyze the problem, certain assumptions generally have to be made. However, the general problem can be studied using coupled transport models (based on FEM or FD).

Both heat conduction from the surface and geothermal heat can be ignored at many applications. The evaluation method presented below can then be used to evaluate the seepage from temperature measurements in the dam.

The most fundamental parameter for a temperature change is the seepage flow. Other thermal properties (thermal conductivity, thermal dispersion, and heat capacity) are less important, as well as the influence from temperature dependent parameters such as viscosity, density, and buoyancy flow.

Seepage flow rates less than 10^{-6} m^3/s will not affect the temperature variation. Thermal effects can then be ignored because the temperature will be constant for a given point. However, at stratified reservoirs a seepage change may move the entrance point for the seepage to the measuring point. The mean inflow temperature of the seepage water may then change as well as the mean temperature in the dam. This may be possible to evaluate at long term monitoring, but it will probably be complicated, and not appropriate as a general tool.

A seasonal temperature variation at large depth from the surface always indicates seepage, but the sensitivity depends on several factors that are described above. For the studied damage types the detection level will be between 10^{-5} and 10^{-6} $m^3/s,m$. The detection level can be further improved with a higher monitoring accuracy. However, a ten times higher accuracy (0.1ºC) will only increase the detection level two to five times, as indicated in the figure.

3.4 Monitoring Equipment

Mahmoud Farhadiroushan, Sensornet Ltd.

The theory behind fiber optics is briefly discussed and new developments in its applications to dams are presented. Fiber optics can be used in a number of ways in monitoring of dams and their performance. Stress and strain as well as temperature measurement can be obtained in a distributed area along the fiber. This is one of the great advantages with fiber optical measurements in contrast to more traditional methods where it is only possible to get data from discrete point. The accuracy in temperature measurements depends on the surrounding temperature and is 0,2°C at 22°C.

The cost for 1 km of fiber optical cable is approx. 1000 Pounds and the installation cost is 2-3 times the cable cost. The evaluation of the acquired data requires expensive data equipment but fortunately it does not have to permanently installed at one location but can be moved between different dams.

Even if the methods have some difficulties to give absolute values in reinforced structures, it is still suitable for relative measurements in such structures. The fibers are coated with different materials for different purposes and this coating is important for the life span of the fiber, which is normally about ten years in a dam. It is often desirable to monitor a dam for much longer periods than that and one possible solution could be some kind of replaceable fiber. However, there are no replaceable fiber optical systems available for application to dams today.

4 Resistivity

4.1 Resistivity Imaging The State of The Art

Frank Dale Morgan, MIT

What can and cannot be done in resistivity imaging?

Archie's law describes the relationship between soil properties and resistivity:

$$\rho_{soil} = \frac{\rho_{sollution}}{\Phi^2 \cdot S_w{}^2}$$

Conventional pseudo-section data gather, preferentially resolves targets located within the V-shaped capture zone, which leads to edge effects and target pull-ups. Resistivity Array Imaging (RAI) was introduced to correct these problems. It was found to perform better than the pseudo-section data gather.

Resistivity data analysis involves the processes of modeling, inversion and the efficiencies of these processes.

There are a number of ways to solve the resistivity equation and one of them is to transform the 3-D electrical model into a transmission network. If Kirchoff's law is applied to the this network the result is the linear equation:

Kv = s

where
s = current vector
v = potential vector
K = real symmetric matrix of distibuted impedances

It is also possible to use an inverse algorithm where an optimization problem with Tikhonov regularization is solved leading to a robust, stable and fast inverse algorithm.

Today there are good ways of evaluation resistivity by modeling and inversion using 2D/3D Finite Difference or Finite element methods. Understanding of data acquisition and resolution must however be improved. We must also carefully consider the use of 2D approach at dam monitoring.

4.2 Resistivity Data Acquisition for Dam Monitoring

Torleif Dahlin, Lund University

This paper presents the principles of resistivity surveying and methods for data acquisition. The principles for surveying with a multi-electrode system are outlined and exemplified by the installations at Lövön and Hällby Dams.

Solute transport within a dam is an advective process related to the seepage flow. The seepage flow is coupled to the temperature field, which is formed as a result of advective flow and heat conduction. Therefore, it is necessary to consider a set of coupled transport processes for heat and solute.

The seasonal variation of the absolute resistivity in the reservoir water is separated into two parts when the seepage water, q, passes through the dam. The solutes penetrate into the dam with the pore velocity v_n (=q/θ, where θ is the porosity) while the temperature travels with the thermal velocity v_T (=qC_w/C, where C_w is the volumetric heat capacity in the water and C in the soil). The resistivity variation in the dam is therefore a combined result of these two transport processes.

4.3 Resistivity Data Processing - Dam Monitoring and Results from Sweden.

Torleif Dahlin, Lund University

Since time variations effect the resistivity data acquisition, permanent installations are preferred. In the Hällby case there are about 100 electrodes permanently installed in the dam. The author continues by presenting some results from resistivity measurements from three Swedish dams (Lövön, Hällby and Sädva). He focuses primarily on the processing and interpretation of 2D data. He concludes that time-based analyses of resistivity data can be indicative of seepage zones and that data quality and density is essential in this process.

4.4 Dam Monitoring Parameter Study - Resistivity

Torleif Dahlin and Bing Zhou, Lund University

Results from the modelling in the parameter study shows that resistivity imaging from surface electrode measurements can be used to locate anomalous seepage provided that:

- The variation in temperature and thus resistivity is large enough.
- The disturbed zone is large enough, so that the total change in conductance or resistance is sufficiently large.

- The depth to the zone is not too large in relation to the size of the zone and the magnitude of the change.

For Damage Type 1 the only case that can possibly be detected using surface electrode layouts is Case 3 and Location 1. Any other combination will result in a variation that is too small to be detected in practice. In practice, even the seepage channel in Location 1 may be difficult to detect, unless the damage is also manifested through a larger zone of variation in the filter and upstream support fill, but on the other hand this is likely to be the case.

For Damage Type 2 the modelling was carried out for surface electrodes only. The results indicate that both Case 2 and Case 3 can be detected for Location 1. For Location 2 Case 3 should be possible to detect, whereas Case 2 is close to the resolution of the data with 1.4% variation in the apparent resistivity. The variation in apparent resistivities for Location 3 is even smaller, with Case 3 giving 1.7% total variation and Case 2 a few tens of a percent. For the latter cases electrodes installed below or inside the dam core should enhance the detectability dramatically.

The shallow location of Damage Type 3 is a bit easier to detect from the surface than Damage Type 2 due to the larger amplitudes in apparent resistivity variation. However, it cannot be expected that Damage Type 2 and Damage Type 3 can be distinguished from each other from surface measurements alone due to the principle of equivalence.

Some practical difficulties were revealed in the 2D numerical modelling presented above, namely that the change in model response due to the anomalous zone was in some cases in level with or below the accuracy of the modelling. However, as the change in resistivities are small the errors will be very similar in the different model response calculations for each case, and if the differences are analyzed the errors are to a large extent removed as the forward or inverse models are subtracted from each other. This approach is valid for an assessment of the practical applicability of the methods, as the same the technique is the most suitable for evaluation of real data.

Different electrode arrays offer relative advantages over each other in different situations, and in some of the cases presented above other array types may have a better resolution than the Wenner array. However, in a real measurement situation some electrode arrays, like e.g., the dipole-dipole array is very sensitive to noise, which may in many cases reduce the applicability of that array. Furthermore, the dipole-dipole array is more sensitive to 3D effects (Dahlin and Loke, 1997), which can be a major consideration in dam monitoring applications. Nevertheless, the use of combined and non-conventional arrays can be a way ahead for improving the resolution and enhancing the information content near the ends of the investigated lines. The combination of surface and borehole/buried electrodes is a powerful way of improving the resolution at depth, and will be mandatory for detecting damages that are relatively small at larger depths.

The quality of the data is essential for the resolution, and the importance of keeping the noise level low in real measurements cannot be overemphasized.

4.5 The Formation Factor - Legge di Archie

Paolo Morabito, Enel

The formation factor, F, is defined as the ratio between electrical resistivity of a natural soil and that of the pore fluid. This is described in Archie´s law:

$$F = \frac{\rho_s}{\rho_w} = n^{-m}$$

where:

ρ_s =	electrical resistivity of the natural soil
ρ_w =	electrical resistivity of the pore fluid
n =	porosity
m =	1,2-1,8 in sand
	1,8-3,0 in clay

If a soil have different formation factors in the vertical and the horizontal direction it is said to be anisotropic. The main implication of anisotropy, in resistivity measurements, is on the interpretation of the results where it will effect the apparent thickness of the layers. Unfortunately there is no way to determine the anisotropic behavior of a soil from the surface with generally available software.

There is a direct connection between anisotropy and permeability which is important to consider in embankment dams since they may have anisotropic behavior due to the compaction of the material in layers. Both the hydraulic conductivity and the electrical conductivity of a soil may be subjected to anisotropy but the effect is largest on the hydraulic conductivity.

5 Streaming potential

5.1 General Background to SP in Dams

Robert F. Corwin, SP Survey

Streaming potentials (SP) is a simple method for measuring the flow through a dam as far as the equipment is concerned. All you need is two electrodes, a voltmeter and some wire. Unfortunately, there is much more to it than that.

As water seeps through a dam, electrical charges is transported by the water and thus creating an electrical field in the dam body. Consequently, there is always a potential field in a dam and SP surveying searches for anomalies above the background noise. With modern equipment it is possible to detect variation of 10 mV in the SP field. Metal objects, such as steel pipes, in the dam will give far greater SP-values than any leakage through the dam a fact that makes the method work poorly in some cases.

Measurements can be performed on the surface of the dam using portable or permanent electrodes. Measurements can also be performed offshore from a boat in the reservoir just upstream the dam.

The result can be evaluated from data plots of the measured SP-field, and by using evaluation software, such as SPPC.

SP surveying is a hard work at the dam site and time variations in the electrical field can result in poor data. These are the main explanations to why SP is not used more frequently in dams. However, these problems can be solved if a permanent monitoring systems is installed.

5.2 SP –Theory, experimental arrangements, and parameter study

Johan Friborg, MALÅ GeoScience

The author refers to his PhD work where a model was set up in order to study the variation of the streaming potential cross coupling coefficient with temperature. A vertical column of soil was subjected to a water pressure of 500 kPa. The streaming potential coefficient is defined as the ratio of the electrical potential over the pressure difference; C = ΔV/ΔP. The cross coupling coefficient, L, is then calculated by multiplying the streaming potential with the bulk conductivity of the soil sample; L = C*σ_B.

$$L = \frac{\varepsilon \cdot \xi}{\eta} \cdot G \quad \left[\frac{mA}{kPa \cdot m} \right]$$

Thus, L is a function of the dielectric constant (ε), zeta potential (ξ), dynamic viscosity (η) and an undefined geometric factor (G). A parameter study has been carried out regarding relative the temperature dependency of theses parameters with the assumption that the geometry of the flow can be neglected. A first idea of the temperature dependency of L can be achieved simply by putting together the temperature dependencies of these parameters.

The application of the temperature dependency of L on dams were studied on a simplified dam model by using the same combinations of damage type and location as described in section 3.3 above. The results indicate that small leakage can not be detected by using the cross coupling coefficient. For the case of leakage through a small cylindrical pipe with a diameter of 0.5 m (type 1) at the deepest location (location 3), the SP anomaly at the surface is only 0.015 mV, which is impossible to measure. However, the SP anomaly for larger damage zones (type 2 and 3) is in the range of a 2-4 mV and should be possible to measure on existing dams.

5.3 Self Potentials → Streaming Currents → Fluid Flow. Examples.

Frank Dale Morgan, MIT

There are three different causes of self potentials. One is the diffusion potential where a voltage is generated between fluids of different concentration. The maximum value of SP anomaly is 60 mV per degree of decade in concentration difference. The second type of self potential is the thermoelectrical potential. A maximum of 0.5 mV/°C can be generated between high and low temperature areas. The third mechanism is the streaming potential, which has to do with fluid flow. Fluid flow will generate self potentials since positive charges are pulled along the flow path. This results in an electrical current that flows through the resistivity structure of the earth to produce potential differences. One way of thinking of this is to see the fluid flow as a constant current source, which flows through the resistivity structure of the earth resulting in a voltage that can be measured in the field.

The author gives a number of examples to demonstrate that a fluid flow will generate self potentials. The first example is of water well pumping in Texas. A set of electrodes was arranged at the ground surface above a well with a depth of 100 meters. The pump with a capacity of 100 gal/min was then turned on and off and SP was measured both in the N-S and E-W directions. There was a 20 mV difference in the N-S direction, which is an indication of anisotropy in the earth in that direction.

SP has also been used to map fluid flow as a result of hydro fracturing. The petroleum and water industry use this method to re-open dried out wells. The wells are pumped at very high pressure, which results in fracturing of the rock and opening of large conduits beneath the earth surface through which water or oil can flow back to the wells. During a case of hydro fracturing at a depth of 800 m, the SP anomaly during the pumping was three times larger than what was measured before and after the pumping.

The author also gives examples of how SP can be used various ways where you have fluid flow, e.g. mapping of the pumping of oil from deep reservoirs, treatment of contaminated water through a process referred to as "pump-and-treat" and cave mapping where the ground water flow creates a potential field.

The author also refers to the construction of a pilot dam, built in Germany during the mid 80's for the purpose of testing if self potentials would be useful for monitoring leakages in dams. Measurements of SP in the well-defined physical model were compared with computed values. It was concluded that our theories for understanding streaming currents, resistivity etc. can produce the right sort of numbers.

Finally, the author discusses the question of SP inversion. Instead of going from fluid flow, streaming current and resistivity structure to self potential, inversion is to going backward by measuring the self potential. If the resistivity structure and the cross coupling properties are known, it is possible to determine the source geometry.

5.4 Sources of Noise / Time Variation in SP Monitoring

Robert F. Corwin, SP Survey

A useful SP dam monitoring system must take the different sources of variation in electrical field into consideration. Dams often have conduits with electrical cables, which is terrible for SP data. More distant sources such as electrical train rail systems or even magnetic storms that can cause variations of approx. 1000 mV also influence the electrical field.

The SP electrode stability is somewhere around ± 3mV. A larger anomaly than that could indicate seepage through the dam. A SP monitoring system should be based on a pattern over several years giving the correlation between SP values and reservoir elevation.

Another problem with long-term monitoring systems in dams is that the electrodes must have a very long lifetime, since it is hard or even impossible to replace them if they are destroyed. However, there are commercial electrodes used by for example the corrosion industry that has proved to be stable under ground for decades.

6 Acoustic methods

6.1 Seismic / Acoustic Methods for Site Characterization

Robert F. Ballard, Jr., USACE

Early site assessments for dam construction were boring, trenches, laboratory testing and surface observations. Later, standard penetration tests and cone penetrometers were added. Crosshole seismic was introduced in the 70's and the main attention was given to the distribution of P- and S-waves. Initially, there were problems regarding the optimal spacing of the boreholes. Uniform test procedures and data analysis methods were introduced by the American Society of Test of Material (ASTM) in mid 80's. At about the same time electrical, electromagnetic and gravity techniques were also introduced as valuable site assessment tools. Current practices uses all of the above plus tomography and sophisticated computer data analysis and modeling. The use of Biot theory have also made it possible to modify the elastic wave theory to deal with liquid between particles.

Safe and cost-effective design of dams is limited by the lack of accurate upstream and downstream site condition parameters. Geophysical methods often offer cost effective solutions to this problem. Broad areal site coverage is generally more representative of true site conditions than discrete data points obtained through boring or push probes.

Seismic methods can either be applied on the ground surface or in boreholes. The main advantages of the surface methods are that they have a broad areal coverage and that they are noninvasive. This especially important if the survey is carried out on an embankment dam where every intrusion in the core is a potential risk. However, the resolution is not that good and there are also problems with blind zones or equivalence problems. Borehole methods have higher resolution and also the possibility of 2-D and 3-D tomography and volume characterization. The main disadvantages are the higher cost and the fact that it is invasive.

It is concluded that seismic methods offer an effective assessment of earth dam in situ conditions

6.2 Crosshole Seismic. Applicability in Dams. Ability to Detect Changes

Peter Gaffran, BChydro

On the 14 of June in 1996, a sinkhole was discovered at the crest of the Bennett Dam. Some month later a new sinkhole appeared at the opposite side of the canyon. Investigations stated immediately in order to establish the extension and cause of the damage. The author shares his experience with cross hole- and through dam seismic and discusses some of the difficulties that was encountered during the investigation of the Bennett Dam

Crosshole seismic were used to create tomograms over the damaged area. The accuracy of such tomograms are dependant on a number of factors, such as drill hole separation, number of ray paths, number of tomogram cells and orientation of the ray path with respect to the zone of interest just to mention a few. There are also a number of sources of errors in the crosshole seismic data accuracy. For example, there can be delays in the trigger or in the geophone. The picking error refers to the inaccuracy in registration the time between wave generation and registration. Theoretically, the picking error should be in the range of 0,5 - 4 ms depending on the quality of the signal. During the Bennett investigation the picking errors were sometimes as large as 9 ms. Another source of error is the fact that shear wave velocity is stress dependent i.e. it varies with depth.

At present an annual set of common depth crosshole measurements is carried out in the repaired zone at the Bennett Dam to see if the arrival time is constant or subjected to changes. 1999 has been established as benchmark year and ΔT = arrival time year i - arrival time 1999. ΔT has so far been accurate within plus or minus 2 ms, which is less than the error in data. Larger variations in arrival time have been observed, but always within 25 m of the surface. This is a zone of little or no grouting and it is also within the operating zone of the reservoir, which results in variable saturation conditions in the core. The variable effective stress can account for as much as 5 ms of shear wave travel time.

According to this crosshole testing program it can be concluded that the integrity of the sinkhole grouting repairs is being maintained.

6.3 Through Dam Seismic. Applicability in Dams. Ability to Detect Changes

Peter Gaffran, BChydro

The main reasons why through dam tomography (TMT) may fail is summarized below:

- seismic signals may not make it through the dam
- sinkhole may retard arrival time of signal by an amount less than the accuracy of the system
- rays may refract around the sinkhole
- wavelength of signal may exceed size of target
- ray path coverage may be insufficient to resolve the target

Experiences from Bennett Dam show that the production of shear waves is complicated. For best result a high frequency, high amplitude, low attenuation shear wave should be generated without generating other forms of seismic waves. Another observed difficulty with shear wave TDT is that there can be a mode conversion from S- to P-waves at material boundaries. Furthermore there can be geometric constraints in multi-geophone tomography applications and also problems with coupling of geophones to embankment dams on rip rap slopes.

The author concludes his presentation of the Bennett Dam investigations by presenting some preliminary results from field trials in Edmonton and Calgary and he also outlines the next step of the investigation, which is field trial at a zoned embankment dam.

7 Ground Penetration Radar and miscellaneous

7.1 Radar Techniques - Problems and Possibilities

Johan Friborg, MalåGeoScience

This presentations presents the basics about radar technique with application to dams. The radar system consists of transmitter and a receiver both situated at the ground surface. A pulse of 50 – 600 volts is generated and it will travel by the speed of light through the medium. The receiver registers the time for the pulse to return to the surface and also the change in pulse amplitude do to refraction and reflection in the medium.

The resolution of a radar system depends mainly on the frequency of the pulse. A high frequency gives high resolution but a short penetration depth. The penetration depth in soil, using a 50 MHz antenna, is 25 m, while it is only 1,5 m if a frequency of 1000 MHz is used. The reflected radar signal can be hard to interpret and it is absolutely necessary to have good estimates of the velocity by which the radar waves travel through the investigated media.

Radar techniques can be used on dams to detect damages within the dam body. The table below shows how the reflected energy changes by an increasing porosity. Such increase can for example be a result of internal erosion in the dam body. If the reflected energy is larger than 15 % it is possible to detect by radar.

Porosity, Φ	Dielectrical constant, ε_r	Velocity of radar waves, v	Reflected energy
0.18 (undamaged)	11	91 m/microsek.	0 %
0.21	12	81 m/microsek.	6 %
0.26	15	77 m/microsek.	20 %
0.70	17	71 m/microsek.	23 %

A typical embankment dam has a protective layer of coarse material on top of the crest. This may cause problem during a radar investigation since it reduces the efficiency of the radar.

7.2 Localization of Internal Erosion

Elmo DiBiagio, NGI

Localization of internal erosion is one of the most sophisticated tasks in the field of dam monitoring. There are a number of measurement methods and concepts that can be used once leakage has been detected. A commonly used method is to vary the reservoir level to determine the elevation at which the leakage occurs. Intrusive methods such as penetration tests and boring are also often used. However, this presentation describes methods for localization of internal erosion using tracer, temperature measurements and geophysical methods.

Common tracer materials are for example Rhodamine B, NaCl, fluorescein, and bromide. The basic principle is to introduce the tracer at one location and measure it when it arrives at a selected measuring point. It can either be injected into bore holes or distributed under water on the upstream side of the dam. If there are several erosion channels, it can be a problem to localize them using tracers.

Leakage and internal erosion can also be detected by thermal imaging at the surface of the embankment. However, the image is often disturbed by vegetation, precipitation and evaporation. A more efficient method is to study the temperature distribution by gradient measurements. The temperature is measured at discrete points in the dam and the result is compared with the theoretical heat flow through the dam. Deviations from the theory may indicate that abnormal leakage is taking place or that the dam is not homogenous. A monitoring system for dams, using this principle, requires a large number of measuring points to cover the whole dam. Additionally, the measurements must be correlated for seasonal variations and thus, measurements over a long period of time are required.

Another way of using temperature to detect internal erosion is the heat transfer concept. The presence of flowing water will influence the heat transfer between a heat source and a nearby temperature sensor. If a continuous heating element is installed parallel to a string of temperature sensors in the dam, the response at each sensor can be measured after the heating element has been heated up. This method is suitable for both detection and localization of leakage. New technology based on distributed fiber optic temperature sensing will make the concept very attractive in the future.

7.3 Monitoring of Dams and Geophysical Methods. Review of Hydro-Québec Experience

Tai Mai Phat, and Phong Nguyen

Geophysical techniques can be used in a larger scale for dam safety purposes, as a complement tool, to investigate anomalies and discontinuities throughout the dam and its foundation. However, if geophysical methods will be used for permanent monitoring of dams many improvements must be done. The authors stresses the importance of better data acquisition procedures as well as improved conversion processes in order to obtain useful engineering values. It is also important to establish correct rules of interpretation of geophysical data and their physical limits. Emphasis must be put to obtain global, direct measurements of evolutionary parameters (leakage and displacements).

8 Discussion

Direction of future research?

Gary Salmon:
The first thing I would like to do is to go over the people who made the presentations and to see if we think that there would be any connections with what their presentation was and how to extend it to what we are doing. For instance, there was the presentation on the anisotropy and how could we include that. I probably won't ask people who are working for Sam on the basic correlation of the parameters, but rather the people who are guests. And the first one I would invite would be the representative of SECURE. So, Sam would you say something about what SECURE are doing that might tie in with what we are doing and how we could extend our works.

Sam Johansson:
As you know, we have not got any approval yet as far as we know today but there are some interactions, especially the work that is proposed for the laboratory test which are a bit similar to what is discussed within the geophysical project. That should be a good way to interacting and I hope that we can find ways to do that. We have different types of soils but we will be measuring the same parameters and I thing that an interchange of experiences would be nice. The other thing is with the resistivity evaluation to seepage. In the DSIG project you have resistivity evaluation and in the SECURE we will improve further the temperature tools and also try to solve the problem with variations depending on the total dissolved solids and the temperature transport. Since the resistivity is depending on both theses thing we have to know in which cases we can ignore the combined effects and see the influence. This will be done within SECURE in a project with a PhD student working for Johan Claesson at the Chalmers Universtiy.

Gary Salmon:
And you would be a representative on SECURE so that the information could come back to this group?

Sam Johansson:
Yes.

Gary Salmon:
Another thing that Sam mentioned in the beginning was the idea that we should have some kind of standard model. Something like the 27 total cases that we have talked about earlier, and that we could evaluate the various methods against those. Something like what Peter Gaffran was talking about earlier when he tried to figure out the timing error and he the accuracy that they need in order to make the method work. If we had these various standard cases and we could say; which cases would seismic work on and what would you have to have and what kind of accuracy would you have to have. What cases would the ground penetrating radar work on, how far do you have to see and what would the surface condition have to be. Or for your cases with piping erosion; how close would you have to be with any kind of temperature measurements in order to

able to model your problem. So, maybe we could think of this as a long-term goal when we discuss the new ideas. Maybe I could call upon Jean-Jacques to say perhaps how your experience in France with geophysics might contribute with ideas on how we can peruse.

Jean-Jacque Fry:
Usually we first use geophysical methods for leakage detection. First we use SP with a simpler way than the one shown by Bob. Yesterday and this morning I understood that we can improve our way of using SP. During the rehabilitation survey that I made I was amazed of how cheap and efficient the SP was. And now, from this workshop, I come back with the idea that we can use SP not as investigation but as monitoring method with permanent installations. In my opinion, that is the idea that I would like to develop further. To further answer your question I can say that we use first SP and we use as well a very cheap electromagnetic method. We have a bar of 5-10 meters and we walk along the dam to see where is the great change in resistivity. That is the first survey that we can do and it is cheaper than SP, but also less efficient. So from my experience I prefer to use SP to detect leakage than we can use some more conventional way of investigations. I mean geotechnical ways of investigation such as boreholes, penetrometer and so on.

Gary Salmon:
What do you think that we should be developing further?

Jean-Jacque Fry:
In my opinion, I thing that the SP method with a permanent installation could be a good idea. I would like to convince my colleagues to do a test and to install one such device to check the behavior of a dike because we have old ones where internal erosion is the main problem and I would like to compare this installation with fiber optics.

Gary Salmon:
The SP installation compared with a fiber optic one measuring temperature?

Jean-Jacque Fry:
Yes.

Gary Salmon:
Those would be very interesting results. Thank you!

Dam safety engineers and geophysicists?

Gary Salmon:
Tai or Phong do you have any comment you would like to make? Phong, I think you said you would like to take a few minutes to talk about various things?

Phong Nguyen:

In the next twenty minutes I will present to you our experience at Hydro Québec in monitoring of dams and mostly with geophysical methods that we have experienced during the last ten years. I hope that this presentation will trigger a broad discussion on geophysical methods. And for you Sam, I have a short presentation on early warning system. So, my presentation will cover these topics; first I will talk about some basic rules on monitoring of dams-SP practice at HydroQuébec, and after that I will talk about the early warning system, fiber optic technology and finally I will talk about geophysical methods. I must say that my presentation represents the point of view of a practitioner, and I hope that I can trigger some technical exchange with guys like Sam who works with R&D-projects. This is the plan of my presentation.

(Phong presented a review of Hydro-Quebec experience of geophysical methods and monitoring of dams. See Appendix F.3 for overheads.)

Gary Salmon:
Phong, could I ask from your presentation how you see we should be aiming in term of improving our work that we are doing here?

Phong Nguyen:
Frankly I don't know, but I agree with Jean-Jacques Fry's position and I agree with Bob. For me the big thing that we can do is to expect geophysicist, geotechnical engineers and structural engineers to work together. I guess that right now we don't have a very useful conversation between engineers working with dam safety and geophysicists on geophysical methods. We don't have this type of collaboration. We don't speak the same language and I guess that this is the big thing to do.

Gary Salmon:
Who do the geophysical engineers work for?

Phong Nguyen:
I don't know. Really, I don't know. For sure in some projects they have worked for me. And in some cases they have been against me!

Gary Salmon:
I thing that Peter Gaffran made that point earlier that if you have them you need to know enough about what they are doing to control the quality of the information they give you. And if they are not really working for you, they are not doing you any good.

Phong Nguyen:
I guess so, but I can tell you for example in one of our projects I spent most of my time to make the trade off between my geotechnical engineer and the geophysicist. That is not very useful, not for me anyway. So I guess that many improvements must be there and for me a very important thing is the correct rule of interpretation and the physical limits. You must on the way have a sense of proportion. If you can do that, you can trust these methods.

Useful methods?

Gary Salmon:
To know the accuracy of the method like the time signal that Peter was talking about and the wave length versus the size of the target and that sort of things is important. You have to know the limits of the methods.

Phong Nguyen:
I think that we must make the correlation between these methods and their physical limits. We have many physical limits that we can not trespass with geophysical methods. For sure, right now at HydroQuébec we don't have any big project in dam safety that relies on geophysical results only. Mostly they rely on monitoring of dams and boreholes.

Gary Salmon:
I don't think that there is anyone that's proposing that you use geophysics to the exclusion of other methods. This is just using it to the extent you can to avoid intrusive methods or some other things. Does anybody else want to ask Phong a question?

Jean-Jacque Fry:
I have some comment related to sinkholes. We have two causes of sinkholes. The first one could be backward erosion and in that case temperature can give information. The second cause can be collapse during wetting process and collapse after pore compaction. In that case temperature can not give any information.

Phong Nguyen:
I guess that I agree with you. Temperature measurements make sense when you have big leakage and continuous flow. When you have only concentrated flows and very small discharge temperature measurements doesn't make sense.

Jean-Jacque Fry:
Six years ago while drinking a beer me and a friend from Germany we said that when you are in silt you have very little reduce of influence of a leak. So we need very close temperature points. How can we do that? We got the idea that when you put you electric cables under ground you have electric fiber optics to check that you have no cut off in the cable. We found that the fiber optic could be the solution to this problem. But it is quite difficult to install in old dams.

Urban Norstedt:
Phong, just to avoid misunderstanding; was your message that temperature is more reflecting permeability than flow?

Phong Nguyen:
Yes, that is our conclusion.

Urban Norstedt:
But, if there is no flow around the tube where you are measuring your temperature…

Phong Nguyen:
Then it doesn't make any sense. All you can tell is that the variation of temperature reflects the variation of the hydraulic conductivity at that point. That's all.

Urban Norstedt:
Will you have any change in temperature without any movement of flow?

Gary Salmon:
If you don't have flow do you have change in temperature?

Phong Nguyen:
Sorry, I can't make any conclusions about that. For me, when you want to detect leakage why don't you go directly to the discharge leakage? Why go with indirect measurements. This is against our basic rule of monitoring; if you want to obtain physical values, use direct measurements not other measurements.

Gary Salmon:
Sometimes that is not possible I guess because at Mica for instance any leakage would come out underneath the tail water so they had no other options. Anyway, are there any other questions?

Bob Ballard:
With regard to your sinkholes are they in the dam or are they in the reservoir?

Phong Nguyen:
We have only one case of sinkhole at the crest of one dam during the first impoundment. But mostly, our sinkholes are at the upstream or downstream part of dikes on pervious foundations. And we have many cases of that.

Gary Salmon:
Have you used any water borne geophysical techniques? The acoustic impedance that I spoke of this morning might be available if there is a possibility of a sinkhole in the reservoir or in various pervious types of material it might be able to identify it.

Phong Nguyen:
When we want to discover leakage we use tracers as Elmo DiBiagio was talking about. Color tracers are very simple to use.

Basics for temperature measurements

Johan Claesson:
I had some difficulties to follow you when you talked about the hydraulic conductivity because when we have our equation on the thermal effects, the temperature effects and flowing water we never use any hydraulic conductivity. It is just water flow and the water flow distribution that determines the calculation of the heat conduction.

Phong Nguyen:
You use the physical law of flow?

Johan Claesson
Yes.

Phong Nguyen:
OK.

Sam Johansson:
That is usually a good starting point. What kind of physical laws do you have as motive for your conclusions?

Phong Nguyen:
I guess I have some trust in temperature measurements in pervious foundations. When you have large and continuos flow in a large area you can I some case make temperature measurements and I guess that they in this case make some sense. The experience of EDF in this type of measurements is very useful. But when we are talking about thin cores it is very difficult.

Gary Salmon:
We have one more question.

Johan Claesson:
It is more of a comment actually. The calculation we made of the flow in a pipe and how much flow we needed in order to see the variation. We did that exactly to see the limits of the temperature measurements. To me it is obvious that we have very clear limits, as you saw. Below certain limits you didn't see any signal at all.

Phong Nguyen:
Excuse me, but as a practitioner for me flow through a thin core is not flow through a pipe. It is not the same thing since it is a non continuous medium. This is a very big assumption and we must not force reality to our model.

Fibre optics

Gary Salmon:
Thank you very much Phong! Mahmoud, would you like to say a few words about how you see fiber optics is changing the way that we should approach our problems in the future?

Mahmoud Farhadiroushan:
From what I have discussed with Sam I think that temperature is one of the fundamental physical parameters that one has to know. If you want to make pressure measurements or other measurements you have to know temperature very accurately. I think that one thing that can be useful in these cases is to provide many sensing points along a very simple strain of fiber, which is the unique advantage of optical fiber, as I described in my presentation. It is the only technique that I know of that can make quantitative temperature measurements with high accuracy over many points continuously. But from the discussion we have had with various people I feel that there is one problem that needs to be solved and that is how we can actually install optical fibers effectively. They can cover a very wide range. You can go up to thirty kilometers and you can almost cover the entire dam with one cable and in one cable you can have say four or five or ten fibers so you can have redundant sensors very cheaply. So, the big question is how you can actually make some kind of installation since most of the dams in Europe have already been built. I guess that I would like to recommend to most of the people here to take the opportunity to install some fibers when you do any repair work in the dams if you want to monitor if it is effective or not.

Gary Salmon:
So you think that the implications of new techniques in fiber optics indicate that as we repair dams we should consider installing the fiber optics to give us more information of the behavior of that newly constructed section. Do you have any other inferences for the direction that our research should take us?

Mahmoud Farhadiroushan:
There is a new technique for strain measurement, which can be very useful. There is a lot that we can do with fiber optics like distributed sensing but we can also do very effective point sensing along the fiber with very high resolution. Those types of point sensing tend to be more expensive because you really have to modify the fiber. But I just have an idea and I don't know if it will be useful for these people here if they want to monitor their structures. What we do in optical fibers to make a component is that we create periodical structures. We expose fibers to UV-light to make a periodic pattern. Then, if you would stretch or heat the fiber you could actually change this periodicity. If you can measure that periodicity you can infer temperature or strain. This has also been used in civil engineering constructions where you for example may create a refractive pattern of concrete where some parts are refractive and some parts are not refractive. It is essentially like a bar code and then by reading the spacing you can actually see if the structure has been stretched or expanded or moved. So, there might

be some applications in dams, like when you build the dam you can install some layers of refractive and non-refractive material, I don't know.

Basic parameter studies

Gary Salmon:
Dale, would you tell us what the future holds for us in terms of this research and new ideas that we should be following?

Dale Morgan:
I don't know what the future will hold, but I wrote down four thing here that I want to through out. I should start with the last thing as I see as fundamental to everything that we are talking about here. I think that someone or some subgroup of this group or something needs really to look at the sensitivity of the various remote-measuring techniques to whatever happens in this pipe, in this seepage. To give you an example; say that you are looking for the change in porosity, which might be one of the things, that happens when you have leakage. We know quite well from rock physics that if you are looking at porosity, the lowest on the scale is the GPR. The next would be seismic. The next would be resistivity and the one with the most sensitivity is related to permeability or flow, which would be SP. But I think that someone needs to take a look at the sensitivity of the various parameters to what takes place in a leakage pipe and some of it is gonna be guess work. Really think before just running out and say "I love temperature, I must do temperature!" or "I love SP, I must do SP!". I think that one needs to step back in a really disfashionate way and look at the sensitivities. That is one thing I think we need to do from a fundamental level. The second thing is that there has been a lot of talk about SP and one of the things is that these leakages are coming from the upstream to the downstream side across the core of the dam. If you think of putting a little battery there or if you're thinking of your current, nearly all of the measures that we are taking on the crest of the dam is in the absolute wrong direction, because the electrical field is perpendicular to this. It is only because the whole dam structure is three dimensional that we measure anything. If the electrical field is one way and you go measure the other way you get no gradient. So I think that we need to concentrate on the SP in measuring down gradient somehow or if the dam crest of the dam is wide enough, perhaps even measuring across it. I think that you will see much greater sensitivities there. The third thing again sort of has to do with SP. The signal that Bob spoke about this morning; the telluric signal which is a noise and he has worked very hard to get rid of it, is actually a signal that is used quite a lot in geophysics. It is a time varying magnetic field that induces a time varying electric field in the earth and it has information about the conductivity and the resistivity structure. So, I say don't through it away at all!

Gary Salmon:
But you want to separate it…

Dale Morgan:
You want to separate it at the analysis stage. But, you can look at those spectra and you can look at the relative spectra across the array and it will give you the resistivity

structure not as good as you would do if you would send current through the ground as so forth. But don't throw this data away but use it! I get a sense that people are throwing it away. The last point that I want to make is that I think that the electrical people need to think some more about doing measurements from the reservoir to the downstream side across the dam. I believe that there is a lot in the future that could be done by trying to do the measurement through the dam.

Gary Salmon:
That is not often done because the front of the dam is frequently an inhospitable place and you have the big rock that you have trouble measuring the resistivity of. So, there is physical reasons why people are walking along the road of the top of the dam.

Gary Salmon:
Of course.

Bob Corwin:
That's actually the problem with doing the SP in that direction. The access tends to be along the dam covered with one-meter boulders. But, for the resistivity by putting electrodes in the water you solve that problem and I think that would be a very nice think to look at because it is really easy to get electrodes in the water.

Bob Ballard:
We shouldn't be blindsided either by the fact that this is a research need that you are proposing, and because we got a physical limitation we shouldn't through the idea away. I am in total agreement with you.

Dale Morgan:
I think that the limitation in the upstream is not really very large in the electrical thing because if you throw big electrodes over there and start running current through it, it doesn't matter more or less where it is. It is not going to make much difference because you have so much water there and it is a conductor. I think it is something to think about that we should think about shooting across the dam. Those were the only four comments I would like to make.

Gary Salmon:
Does anybody want to discuss anything about that or add something to any of these subjects?

Ken Lum:
I think through a lot of discussions including Dale's we have focused on the field procedures, how we might go about doing it, collecting the data. From my own personal perspective I am at a point where collecting more data is not going to help me. I think we certainly need to move more on the interpretation and particularly the verification side before we start continuing to keep on collecting data. I can see that in even the projects that I am involved with I am asking myself "Should I go out there and collect

any more or have I now enough?". So, we need to now start to focus on the interpretation/verification side.

Gary Salmon:
I guess Ken that you don't feel that the geophysicists are working against you?

Ken Lum:
No, for sure they are not. But, I agree with other comments that have been out there and that is that we do speak a different language. There seems to be always this slight tension there because the geotechnical engineer thinks about it from a geotechnical perspective and they have that kind of thinking and the geophysicist has a different perspective and sometimes there is just that lack of communication. That is something that we have to work on. It seems almost like each one is protecting their territory and we just need to overcome some of that.

Gary Salmon:
Bob, do you have something that you would like to say?

Bob Ballard:
I agree with Ken totally. One of the things I think we need to concentrate on though is when we have a question and we do more and more interpretation with the data we've got. The question we must ask ourselves is "Did we take that data correctly?".

Dale Morgan:
It is truly an iterative process. I do feel that at this point we need to think about the physics and chemistry of things and what is the meaning with respect to the data we have collected or should collect.
I think that two points were made; your first point Dale about sensitivity and Ken's point about being comfortable with the analysis and the verification. We're touched downed at noon by Sam who was proposing that we should do something like the nuclear industry. To have a standard set of conditions that we can apply the theories on and see how each one of them would…maybe Sam you could explain it better than I do.

Sam Johansson:
Well, I was thinking if you remember were we have identified three different damage types that can occur at different points with different seepage. We can of course extend it to sinkhole formations etc and find out different features that we wish to localize and quantify for dam safety impact. If we could define some cases and work on them from our own experience hand with our own method which we are used to and see what we can evaluate, what can we find, what can we not find at all with this method etc. Then we could compare all results and perhaps learn when a certain method is useful and when it is not. I think that it should be useful if we could define something like we tried to do in our parameter study. Then we can come back next year and see that we have made some improvements concerning monitoring, evaluation tool and see that we can handle this problem. We could also identify where we need more research to get a better understanding, which might be in the basic physics or in the evaluation part.

Gary Salmon:
So essentially what Sam is proposing is a structure for which we can evaluate sensitivity, for which we can look at verification and we can look at the different methods that will work under what conditions. He is suggesting that if such a structure were developed for what each of us could relate our experiences and give our comments on that we might collectively have a lot more understanding about what works and what doesn't work. It is going to be a very difficult thing to develop this structure because that it should be something that almost anything can be tested against; the seismic, the electrical stuff, acoustic whatever. So, when will you have the first draft of it ready to be circulated?

Sam Johansson:
I think we will have learned something when we have finished our parameter report. I think that we will meet at different places and at different occasions and perhaps we will solve the problem during the study tout to Sädva. There are short nights and long days up there…We have these three cases and I think that we can identify some other cases that would be interesting from dam safety point of view.

Gary Salmon:
Maybe we should all think about it a little bit. We'll get a copy of Sam's report which will have the cases that are in it now which are essentially just a little hole, a thin layer and a thick layer and different depth in the dam and with different levels of erosion. We can think about that and of other cases that need to be considered in order to evaluate all the tools that might be available to us. Maybe I could ask Paulo if you can comment on anisotropy and whether or not you think we should start considering it in our models for analyzing SP and resistivity and so forth. Do you have any comments on that?

Paulo Morabito:
Not really, but I have some experimental data that confirm this anisotropic behavior.

Modeling and anisotropy

Gary Salmon:
What do you think Dale? Do you think that we should be looking at our models to account for that?

Dale Morgan:
Well, I think that the rock physics is ahead if the game here and I mean the state of the practice in terms of the things we are talking about measuring in most cases we can't get anisotropy unless you do bore hole to bore hole. For very short distances you might have enough accuracy to be able to see that change. But I think that a lot of things we are doing with resistivity and SP is just…it is nice to know there is anisotropy but I don't think we can really resolve it in the field.

Gary Salmon:

The results that Paulo presented were from the electrical conductivity standpoint where frequently the horizontal conductivity was 50 % greater than the vertical conductivity. If this is true should we not at least test it in our models to see if it makes any difference?

Bing Zhou:
We can model the change in anisotropy over the potential along the dam. That is not a problem for the numerical modeling. I think that we can test how an anisotropy of 10 or 20 % effect our model, but I have never done it before.

Phong Nguyen:
Anisotropy in a thin core is not 25% it is 9 to 25 times between the horizontal and vertical. It is not 25%.

Gary Salmon:
Are you talking about electrical or hydraulic conductivity?

Phong Nguyen:
Hydraulic conductivity. We can show you the information how to measure the anisotropy in a thin core. One problem is when you draw the flow net in the classical way and you talk about anisotropy of 9 to 25 times between the horizontal and vertical hydraulic conductivity you must draw your flow net on the modified section to take into account this anisotropy. When you talk about resistivity temperature is to determine flow. If you don't take into account this anisotropy what about the accuracy of your results. It doesn't make sense.

Gary Salmon:
Did you say you had some information you could provide on determining anisotropy?

Phong Nguyen:
We have experimental results showing that the anisotropic coefficient in thin cores is somewhere between 9 and 25.

Gary Salmon:
Are you willing to provide that to Sam?

Phong Nguyen:
It is no problem.

Gary Salmon:
You'll send it to Sam?

Phong Nguyen:
Yes.

Gary Salmon:

Thank you very much! Anyone else have anything to comment on anisotropy before we go on?

Bob Ballard:
I made the observation that we have noticed it in conducting down-hole tests versus cross-hole tests. So, we know it exists in the seismic world and as Dale points out it should be expected. We are trying to pursue the question as to how we can relate the to together to come up with the parameters that are causing it to happen. And we would be happy to share that if we ever solve the problem.

Inversion of resistivity

Gary Salmon:
Thank you! On to another subject. Yesterday or maybe the day before Bing Zhou presented an equation, which he said he used for inversion and it seemed to me that he felt it was fairly important. Dale, I think that you have reviewed it a little bit. Could you comment on the application of that formula and what it might do for us?

Dale Morgan:
Yes, we spent quite a bit of time trying to understand what that equation does. It is really a transformation of the pseudo-section data, which even though we plot it up as though we have depth and we make a nice color figure, where we put in depth is totally artificial. What he does with the formula is to take that figure that has artificial depth and to map it over to a model that has true depth. But, is an approximate mapping so it is like the second law of thermodynamics; you get nothing for free. It is approximate and it is very fast and that is the trade off. I think that it is probably so fast in a computer that you cannot even measure it on a PC. To do a good two-dimensional inversion today on a fast PC takes something like half an hour so it is a question of if you want something that is very rapid and approximate or if you want to spend half an hour doing it more accurately. It is not as accurate as an inversion but it is fast, so if you are out in the field and you just collect the data I would say that it would be a good thing to use there because it is better than the pseudo-section. I think that you should never look at the pseudo-section at all, I think it is very bad and I think this transformation is good to look at. But when you have the time back in the lab you should do the inversions.

Gary Salmon:
And because of the assumptions, this transformation can never be made refined or be made to be accurate?

Dale Morgan:
No, the refinement would actually make you do an inversion. That would be the refinement. It is fast and I think it has a place in the order of things.

Bing Zhou:

I have seen that sometimes when you do the inversion you have to get more information to control your solution. As I know, if you make an inversion without constrains you cannot get a solution. I agree that the sensitivity is very important because a small change in variation makes it hard to fit your data and find the only solution.

Gary Salmon:
I think that what we agree upon that it has been a development here that needs to be looked at further. I am not sure that this further discussion today will be fruitful for very many of us. Perhaps you could develop it further and also develop some examples both using the equation and using inversion and the advantages and disadvantages. I thing that would be a contribution.

Torleif Dahlin:
I have a comment here on this discussion when it comes to the inversion of the resistivity data or any geophysical data. I think that the point that Dale brought up yesterday about acquiring a lot more data when you go into the field and developing the data acquisition technique so that we can get much more data. It is important to get a better control over the inversion process but also to look into ways of putting in different kinds of constrains to the inversion to stabilize the results and reduce some of the inherent uncertainties. I think those are important steps to improve results.

Peter Gaffran:
I was wondering if you could use this quick result as the initial guess when you do the full inversion?

Dale Morgan:
Yes, absolutely. I think that's a very good use of it.

Peter Gaffran:
I have always looked at the pseudo-section as a way to check the data set globally for bad data. Could you use this quick inversion for a data quality check?

Dale Morgan:
Probably not because it is just based directly on the numbers you have in the pseudo-section. It is just a straight calculation.

Peter Gaffran:
But if you contour something up and you get a super hot red zone that you don't think should be there, would that be an indication that you have a bad data in there?

Dale Morgan:
You would probably have seen it in the pseudo-section.

Torleif Dahlin:

One method that can be used is to do a fast preliminary inversion and look at your model residuals and those data points that give very high values could be trimmed of and then do another final inversion with that.

Acoustic methods

Gary Salmon:
Maybe if we have finished with our inversions we can talk about acoustic methods and where we can go from here in terms of research? Do you have any comments Bob?

Bob Ballard:
I think I heard some comment with regard to the acoustics when in fact we were talking about the possibility of developing fiber optic sensors. If it would be possible to device a way to insert these sensors into an existing dam without having to get Peter upset by putting too many bore holes down to the centerline of the dam, it may be well worth while to think about acoustics from the passive standpoint. But not only from the passive standpoint, maybe we could actually initiate some kind of a pulse that we can use to monitor from the frequency content, the velocity content and the amplitude content on a relative basis.

Gary Salmon:
What is it you'd learn from that?

Bob Ballard:
Well, I think that you might be able to map anomalies…sorry that's a word that you don't like…I mean zones of different velocities, different densities all of which could relate to some kind of a degrading condition within a dam, which should be of uniform content.

Gary Salmon:
Would you do that before you think you have a problem or when you think you have a problem?

Bob Ballard:
I think that I would do it before. I am a strong believer in establishing some kind of base line because no matter how careful you have been in constructing a dam you gonna get different features built into it. Especially around buried pipes and things of this type. So, I think that you need to establish some kind of a base line and then go from there on a periodical basis recognizing, as Peter has already established, the fact that reservoir elevation, temperature and various climatic changes can cause changes within your data. So, recognizing all of these factors and accounting for them as best you can. I believe that if you move from that baseline and establish that you see something that appears to be degrading more than one time, then you need to take a much closer look at it.

Gary Salmon:

Would you put this in the crest of the dam just like you put a TV-cable to a house?

Bob Ballard:
Yes, you could. You might be able to put down some kind of a slurry-trench but I think that you want to do it so that you can look at it in 3D. You want to use some kind of geometry and placing it both vertically in a few selected spots in boreholes as well as horizontally. This gives you the best of all worlds in trying to look at the entire picture of a dam.

Gary Salmon:
And you want to go vertically not just down the back face?

Bob Ballard:
I wouldn't exclude anything at this point because I am thinking of the top of my head. I believe that you could plan an installation that would take advantage of the construction zones of the dam. I think that you would like to look at the different types of zones; the core, the downstream and upstream shell etc. and possibly you'd want to go vertically and horizontally in all of these different aspects to collect as much data as you could.

Long term monitoring aspects

Gary Salmon:
Phong, if you had a cable across the top of the dam and down the back and it acted a certain way for ten years and then it started to change, would that cause you to investigate the dam?

Phong Nguyen:
For myself, I will use this as a detection measure for displacement of my dam and this is very useful to me. Don't forget, more and more we make monitoring of dams not to detect design criteria but to detect potential failure mechanisms. So, I don't want to monitor parameters that cannot be potential failure mechanisms. This is our point of view.

Gary Salmon:
So, if I can summarize that to see if I got it right the philosophy for monitoring a dam is to find out how the dam could fail and then to find out what those failure mechanisms would be and how you could detect them before they progress very far.

Phong Nguyen:
Exactly.

Gary Salmon:
And you feel that a global look at the dam isn't likely to be of any help.

Phong Nguyen:

The direct measures of leakage etc are useful, but you must prove to me that this indirect measure quantifies the leakage correctly. If it is not, it's not useful to me.

Seismic methods

Gary Salmon:
Peter, do you have anything you think we should be doing with regard to seismic in terms of research?

Peter Gaffran:
Well, I will say that on the basis of our new understanding of the potential influence of saturation, we are going to do another round of P-waves at the Bennett dam to help us understand if this drawdown cone is influencing our results.

Gary Salmon:
Are you sure they are going to be P-waves? I thought you didn't know what kind of waves they were.

Peter Gaffran:
No, we are going to go back to the original method of energy generation with Buffalo gun and that makes fantastic P-waves.

Gary Salmon:
And it doesn't have any shear waves to accompanying it?

Peter Gaffran:
I am sure that it does, but you can't ascertain where they are and where they come in on the wave train. Actually, that's a very good point. A question that has come up again and again as we have discusses seismic with other seismic people is how to identify shear waves in a complicated wave train. I think there could be fancy work done at the numerical and analytical level to improve that. That would be a valid research topic

Gary Salmon:
Do you have a P-wave detector that separates out compression waves from any other motion?

Peter Gaffran:
No, the sensor is just an accelerometer; a little thing that vibrates in whatever direction it is oriented in. We have three of them and we record these three components and then we get all of these lines for each of the three units and then you scratch you head and say; "Where is the shear wave?" But, I think that work can be done here. We've got a hint of that by talking to Rick Miller and he is doing some pretty sophisticated signal processing that we are not very familiar with in the civil engineering world and it looks like it might be valid research to be done in there. I guess, in a more general level I was trying to things about things from sort of first principals. What do we really worry about in my business to access the performance of a dam and what are the things that

we want to measure? No, forget about *<u>measuring</u>*...*that we want to* *<u>know</u>* *about. And it is pretty simple things; we want to know the seepage quantity and we want to know where the seepage is coming from. We'd also like to know the water content inside the dam, we'd like to know the density of the material in the dam, we'd like to know what the hydraulic pressure in the dam is and if we really get fancy we'd like to know the stress inside the dam. If one uses a loose definition, all of these five things are mechanical properties, very simple mechanical properties. Typically water content in a core of a dam with the tills that we make dams out of is in the order of 10%. A 3% change in water content has huge significance to us and it might have a very, very dramatic impact on the performance of the structure and on how much the dam is going to leak and what the pressure regime inside the dam is going to be. It's a very simple thing. In my limited experience from the Bennett Dam we tried all these techniques and I've heard someone else echo the sentiment; the seismic methods worked the best. And why is that? It's because it measures a mechanical property. We have kind of convinced ourselves that shear wave velocity is an excellent surrogate for density. We need to develop these kinds of confident correlations for the electrical techniques. I think it is very imperative. I think that it is much more complicated than some of these equations lead us to believe. I give radar velocity as an example. The theory tells us that radar velocity responds mostly to water content and water content is an indication of saturation. But, I am convinced or I'd suspect rather that it might be a function of more than just that. Based on our experience with electrical techniques, if we could develop better and reliable correlations of these electrical properties, be they electromagnetic or radar propagation or resistivity, to mechanical soil properties I think that's when we could start to make progress with some of these techniques. I still think that the degree of correlation is not well understood*

Dale Morgan:
I don't think that statement is true. I think there is vast knowledge out there on it. You don't know about it but there it is out there but it comes back to the question of communication. You can not go measure resistivity and try to learn something about mechanical properties. It would be a foolish thing to set out to do.

Peter Gaffran:
You must communicate this to all of the geophysicists that are practicing out there, because that is how they are selling it.

Dale Morgan:
That's what I meant by understanding the physical properties that relates to the dam problem. I think that you said it very well in terms of fluid flow, the density and the mechanical, but no one should tell you that you are going to do radar and get density or something like that. It just doesn't exist.

Peter Gaffran:
Well, what they tell us is that radar is going to give us water content and our experience is that the correlation between radar velocity and water content does not exist. When you plot it up you get the classic shotgun blast and I tell you, that was for us a $400 000

shotgun blast. That was one third of our budget for all the geophysics that we did for one year and we just wasted it because we didn't talk to you first to tell us there is no correlation.

Dale Morgan:
No, there is correlation and there is a lot of evidence that you really can get that so I have no idea why…I'll have to look at this, you know.

Gary Salmon:
Peter, with seismic stuff you don't go out and run a seismic line to bedrock and assume that you can get the depth without putting s couple of holes down. Would you use the electrical methods to give you mechanical properties without putting a couple of "truth tests" in?

Ken Lum:
I am not even sure what those truth tests might be.

Peter Gaffran:
But when we tried to do the truth test it was untruthful! Anyway, we are going to roll up our sleeves and start a wrestling match here. I have stated my opinion as a practitioner based on my experience and it is on the record and we'll leave it with that.

Communication between engineers and geophysicists

Gary Salmon:
Ken, could you elaborate just a little bit in what you mean when you say that you don't know what the truth test is. If you are interested in porosity and you do an electrical test that is supposed to help you determine porosity, can't you take a soil sample and measure it?

Ken Lum:
That helps to a certain extent but I think that you compare a point comparison to a bigger problem.

Gary Salmon:
But, that is what you do with the seismic measurement.

Ken Lum:
Yes, you do. I don't have enough experience as much as Peter has but I guess it is like when we try to extract seepage from SP as an example. When we have no means of measure seepage flow, how do we actually verify it?

Gary Salmon:
And this is in a case like Mica when the seepage comes out below tail water and you have no method of checking it

Ken Lum:
Yes, and another example is even if you have weirs downstream there is no guarantee that what you see as a SP anomaly would be captured in the weirs.

Gary Salmon:
It could be going under ground?

Ken Lum:
Yes. So, how does one do that verification or truth test in the field?

Gary Salmon:
Does anybody have an answer to that? Does anybody have any suggestions to how you could get corroboration of your geophysical results?

Dale Morgan:
A lot of it is communication. The answers to many of these things are already out there, you know. I listen to the blood sweat and tears that Peter went through and many of those things already exist out there. If you had asked the geophysical community if you could go out anywhere in the field and map the porosity, what would be the correct answer? The answer is that in the zone above the water table there is no method that can map it. Plain and simple, we don't know how to do it. Beneath the water table you will have a reasonable chance with seismic and radar. With resistivity you can get the porosity if you have a borehole and you get the solution conductivity. People are clearly selling kind of crazy things. I listen to the seismic stuff and I hear that there seems to be a correlation between the horizontal geophones and shear waves. And somebody must have said that at some point, that these are the geophones that measure shear waves. But they measure any movement in that direction! What we probably need is some type of very simple calibration procedure. I was thinking of this thing that Sam was talking about. If you make a little hole and put a garden hose down two meters in the ground and you turn it on and then you challenge these guys. You tell them to find the leakage for you.

Peter Gaffran:
They will probably say; "Well, if you tell us where it is first, it will be much easier for us to do."

Gary Salmon:
It is clear that this is about communication. Dale, you spoke about this homogenous geophysical community. Where do we meet them?

Dale Morgan:
Well, there are two societies and one of them has actually a lot of civil engineers belonging to it, which is called the Society of Environmental and Engineering Geophysics. A good proportion of that are civil engineers. That is where you go to learn what is really truthful because I think that people here has been told a lot of untruth.

Toleif Dahlin:
I want to comment on this truth or verification for evaluating geophysics. To my experience, it can be quite difficult in some cases to match geotechnical information with geophysical information and it is not always because there is something fishy with the geophysics. Very often it is the geotechnical information that is fishy. They use drilling and sounding methods that can give quite misleading results depending on various factors. For example, they say that they hit rock when it is actually a big stone or a block instead. If you sit down and look at some classification of soils you see that you can have a big variation in resistivity in what is classified as more or less the same soil and you don't have any correlation at all. But, if you really go into detail and look at cone fraction diagram and things like that you can see that there is actually 40% clay in the soil in the low resistivity zone and only 10% in the slightly higher zone. So, you may have to go into detail in the reference data and really scrutinize both the quality and the type of information you have in the reference data. When it comes to taking

samples of loose material such as in the core of a dam there can be great errors. It is very easy to loose the fine fractions of the material when you take the sample, which makes it misleading. If you try to match that with geophysical results you will have a difficulty to get a match but it also means that your samples and the conclusions that you make from them could be misleading. I think that we have to be critical not only to the geophysical techniques, but also to the other investigation techniques because there may be quite a lot of traps and errors in them if we don't know exactly what we are doing.

Gary Salmon:
I think one of your mayor messages is that you can not do it simply on a global basis, you have to look at it in detail.

Torleif Dahlin:
Yes, you have to do that in each individual case until you really understand what you are doing.

Dale Morgan:
It sounds like you need the answer first…

Torleif Dahlin:
Well, when you go out and investigate something you don't know the answer from the start but when you have done the investigation you may know how you should have done the investigation and that is a step forward.

Developments in seismic methods

Gary Salmon:
Peter, do you have anything on seismic that you could add to your comments so far? Especially as it relates to future research and development in seismic methods.

Peter Gaffran:
Perhaps just a repeat of that we are doing a little bit more P-wave work in the through dam seismic. We are also going to continue investigating the use of a shear wave source to have a reliable, reproducible, high amplitude, high frequency shear wave. I think that would be a benefit not only for through dam seismic, but also for other applications. The other think that I mentioned was the work in the signal-processing field. We want to see if we can better discern components of the wave train, whether they are shear or Reilegh or all these other waves that are all mixed up and that we record, as you mentioned, on whatever orientation it comes in on.

Gary Salmon:
Can't you develop some instruments that are preferential toward measuring only P-waves or only shear waves?

Dale Morgan:

Just to make a general comment, everything that Peter is asking for is there. Within the petroleum industry they have a highly sophisticated level. There are shear wave down-hole sources that are being tested now. They all exist but someone has the time to go learn this.

Gary Salmon:
He doesn't want a shear wave down-hole source he wants a source of shear waves that will work on rip-rap at the water's edge.

Dale Morgan:
I know, but again there are vibrators and signal processing like that. You don't have to redo all that.

Gary Salmon:
Do they drive down a thirty-degree slope on rock?

Dale Morgan:
It is probably worse than that where the petroleum industry guys work. One think I would like to add in terms of the acoustics and the seismic is that a lot of US government money was put into developing, at the San Alamos national lab a very small instrument system that can go down boreholes of just one centimeter or so. You can put geophones down in holes that small and it might be something to look in to because the smaller you can make the hole, the better of you are.

Bob Ballard:
With regard to that there is a commercially available geophone that is made by the Geospace Cooporation and that is the model GS14. It is only six tenth of an inch tall and about a half inch in diameter. They market it and it costs $35 a piece.

Dale Morgan:
That is the same thing. The idea was just to put it in the ground and leave it there.

Research directions?

Peter Gaffran:
I would like to clarify this issue of research. For instance, BChydro is sponsoring research I SP, which you or anyone else involved in SP would not call research. But it is research for us because we are learning. So, I kind of include the whole learning of geophysics under the umbrella of research. Finding out about the fact that it might exist in some lab in Houston is part of what include as research. You have to keep in mind that we didn't realize naïvely that we had to become geophysics experts to use geophysics.

Gary Salmon:
You mean to have people provide geophysics services?

Peter Gaffran:
Exactly, we have learned that you have to be pretty well as knowledgeable as the guy doing the work is. We didn't know that

Bob Ballard:
That is true in almost anything that you get in to.

Peter Gaffran:
Well, when I go in for appendicitis I don't know everything the surgeon does.

Bob Ballard:
You know where it hurts though…

Peter Gaffran:
When I go in for a court case, I don't know the legal business the same way the lawyer does. When I take my car in for service, there is no way I know as much as the mechanic. That is a false statement.

Gary Salmon:
So, you are relay complaining that the geophysics community provides inferior service to unqualified purchasers.

Peter Gaffran:
Well, that is an inflammatory statement and that is not the comment I wanted to make. The comment I wanted to make was that in our beginning baby steps into the geophysical world, finding out about what the oil and nuclear industry are doing, and all these other fancy things that are going on at MIT and elsewhere, is part of what we constitutes as research. We can't just dismiss the fact that "It has been done already, don't you know" because we don't know anything, and after three days that should be quite apparent to you.

Gary Salmon:
It does seem, as there should be some kind of guide into the geophysical community that makes it a less painful route to travel.

Dale Morgan:
I'll make a direct suggestion to Peter. You keep hearing about lustrous civil engineers on your advisory board. Do you have any lustrous geophysicists there?

Peter Gaffran:
That is a very good point and we have look for them. And because we are not plugged into that network they are difficult to find. Especially with a practical and result oriented mindset. I must say again, and this is a subjective statement that is a prejudice, that I got the feeling that these geophysics guys were conducting work and overstating their capabilities on purpose. I really have the sense that a lot of geophysicians are so enthusiastic and they love to do their work, their are excited about the neat stuff that

they do and going out collecting data and reducing it with their fancy program for them is enough. They kind of view the whole thing as an experiment. They don't care about whether or not the data makes any sense or the results are useful or not.

Dale Morgan:
Peter, you are right. What can I tell you…

Peter Gaffran:
It is like they are going out to play and they play at my expense.

Gary Salmon:
If anyone in here has a suggestion for K en or Peter with regard to who would make a good geophysical board member. A geophysicist who has a result-oriented mind and experience in all sorts of things.

Peter Gaffran:
We have two in the room, Bob Ballard and Bob Corwin, who we have used but truthfully the stuff is too complicated. If you go to a dam like Bennett and use fourteen different techniques you are going to need fourteen experts. You can not be a super expert in every single technique.

Gary Salmon:
If you get someone like Ralph Peck who is an expert in certain aspects of it and has such a big, broad general knowledge in the rest of it you'll get good advises. Isn't it someone like that in geophysics?

Peter Gaffran:
I don't know if there is a Ralph Peck in geophysics, he is pretty rare.

Ground Penetrating Radar

Gary Salmon:
OK, I have just about gotten to the end. Johan, is there any development on radar that we need to have, or anything that we need to know or think about for the future in terms of ground penetrating radar?

Johan Friborg:
As I said, what I believe is important is multi-channel acquisition. That is something that is going to be important in the future. More sophisticated imaging software are being developed by several parties around the world. The imaging is still on a research level and I think that the development of instruments is probably best done at the companies that make the things. What is important as a user is to communicate what features are important. I am still not convinced to what extent radar is the right tool to use on a dam. It has its merits and I think it has its place within the other methods that we apply to the problems of dams. As it looks to me, the most promising work has been

done in cross borehole methods. I understand that people don't want to put holes in their dams so it is obviously to prefer if we could use some other way first.

Torleif Dahlin:
I have just a question with regard to putting things in the dam and Bob Ballard's point about putting different sensors into the dam. You don't want to drill open holes and put in sensors. Would it be possible to use something similar to cone penetration test equipment to push some sensors into the dam without drilling an open hole?

Installations in dam?

Peter Gaffran:
Not unless you have a dam with some defect because typically the level of compaction applied to the soil when it is placed in the dam is so high that it is so dense that you can't push anything into it. In fact, even drilling is tough.

Ken Lum:
Let me just make one point and that is as Gary said; we don't want to put holes in our dams if we can help it. But, we do it for the purpose to install piezometers and we do it for the investigation. From a geotechnical perspective we feel that we can rely on the information that we obtain. If geophysics was developed to that level than perhaps using it in a down-hole application could be great, but I think that we are a long way from that yet.

Torleif Dahlin:
If you installed fiber optics for temperature and strain measurements, geophone elements, integrated electrodes and maybe pressure transducers etc at regular intervals from the top of the dam to the bottom, you would have fantastic possibilities of measuring and cross-correlating various parameters.

Gary Salmon:
What about using existing piezometer holes?

Bob Ballard:
That is what I was about to mention to you. I think that it could be an excellent idea. Peter, didn't you mention the use of existing piezometer holes to run down-hole seismic tests at Bennett Dam?

Peter Gaffran:
Yes, we used all existing standpipes for down-hole seismic and temperature profiling etc and we even used some of those for cross-hole seismic where we had a nearby drill hole. So, it does have potential.

Torleif Dahlin:

A problem when it comes to the electrical measurements is that if you have a metal casing you would have to remove that in some way because it interferes with the measurement.

Gary Salmon:
I don't know much about drilling but I understand that there are some ways of perforating the casing. Can you not only pierce it but also push a probe out into the soil away from the casing?

Peter Gaffran:
The piercing is a compressed air driven event that drives spikes through the casing and presumably those spikes goes some distance into the soil. If one thought about shooting a sensor it would have to be very robust. If one tried to push it in slowly there has to be some kind of clever mechanical device to do that, bearing in mind that you have a very confined space.

Gary Salmon:
We are getting fairly close to the time when we are going to have to leave. We have just gone through these various topics that I thought might contribute. We'll have a little time no for a open discussion for anybody who wants to talk about any topic that would lead toward future research in the geophysical field.

Dale Morgan:
Maybe the question is money. When you look at geophysics in the petroleum industry you are looking at tens of millions of dollars. I think if some individual out there felt that this dam operation monitoring for seepage had some money in it, maybe something could be developed. Like if someone came up with an acoustic method that could be used on every dam in the world or something like that. I don't know if there is a way of making that work. In a free market environment the development will be very slow here. The community has to build something and show its potentials.

Gary Salmon:
We are all banded together during research cooperatively because there is a shortage of money. In the oil industry the investigation leads to more money. In the dam industry the dams are built, the money is made from using the water and they don't want to spend any money on the dams. It is only fear that drives them because if they let their dam break they will be put in jail.

Jane Salmon:
Are you not suggesting that perhaps some of these things can be demonstrated for some of the commercial manufacturers who are building the equipment for the petroleum industry to show that there is a market here? They might invest the money and they don't have to start from scratch. They can just modify their equipment to fit to the dam industry. Let them spend the money.

Urban Norstedt:

Our business is to keep the dams safe and it is the fact that we are not successful that bring out the money. I would like to say something about why the Swedish power companies are investing in this field. The background is that the Swedish dams are quite old and I must admit that the amount of monitoring of Swedish dams is very low. Probably depending on that people thought for good reasons that they built watertight and stable dams. They would stand without any monitoring. There was a lot of monitoring during and just after construction to confirm that the water was pressed down. But after that many of the instruments and the standpipes have been abandoned. So, compared with your experiences at HydroQuébec, BC Hydro, Corps of Engineers and Bureau of Reclamation I would say that we are half way to your degree of instrumentation. Also, because people were convinced that the dams were tight there was not enough emphasize placed on the filters. After some time we constructed dams with filters that didn't meet the criteria. With filters that don't meet the criteria you always have the potential of internal erosion and if you don't have any filters you have a problem. We have had a lot of sinkholes and some have been linked to internal erosion. We have to know better than we know today what is going on inside the dam. I agree that the global thing to do is to measure the leakage. But, even if you measure the leakage very properly you can't find all the leakage and perhaps it is to late when the leakage is coming out. It could be. There are different interpretation methods in order to have an early warning but internal erosion is one of the main failure mechanisms so we have to be able to predict as far as possible whether or not internal erosion is going on. There is another method of course, you could strengthen the dam so that you cold accommodate all credible seepage through the dam. In that case you may not need any measurement at all. If you are sure that any possible leakage through the core couldn't jeopardize the stability of the dam. With this background of too low level of instrumentation and our experiences from internal erosion, we think that we need to know what is going on inside the dam. This should be possible in these times when we can put a man on the moon. It is not cheap to use the ordinary geotechnical methods like drill holes and so on so we hope that it would be possible to standardize methods to keep a grip on if internal erosion is coming up or not. To start with we thought that there is no more practical thing than a good theory. We were also happy to have Sam Johansson who is a civil engineer but also well skilled in geophysical methods and he has a good grip on where are the professionals in Sweden. He has created a group that we can support in order to find out if it is possible or not to come up with a standardized method to assist us in understanding what is going on inside our dams. We will ask them after this meeting to tell us what they think will be reachable and feasible in this field in the nearest five or ten years. I am happy that you have assisted Sam and his friends with your opinion and knowledge in this field. We have good hope of being successful in this and we are also happy that the Dam Safety Interest Group was working in this field so that we could cooperate to make the best use of our money.

Conclusions of the meeting

Gary Salmon:

Thank you Urban. I think that we should try to come to the conclusions of the meeting. What conclusions can we make? What future actions should be taken? And then maybe *a little bit of prioritization. What can conclusions can we come to with regard to the general physics and mathematics of the geophysical methods we have been talking about?*

Torleif Dahlin:
I think we have seen that geophysics can give significant and useful contributions in many cases but we are only on our way to learning how to use it in the most efficient way.

Gary Salmon:
What you are talking about is the overall thing including the field, data gathering, the analysis etc. But what about the basic physics on which this is all based? Are we okay there?

Torleif Dahlin:
I think, as Dale pointed out, in rock physics they have worked quite a lot with some of these detailed questions and I think we have things to learn from them. There are also things that we need to look into more in detail. These parameter studies may be a step in that direction and we need to continue that work.

Gary Salmon:
Bob, what do you think of our basic situation with regard of the physics of geophysics?

Bob Ballard:
I think Dale pointed it out a while ago. Most of it is very well understood and it is a matter of communicating the theory and modeling experiences. Much of it does exist, and that is not to say that everything exists by any means, but I wouldn't know what to say would be the proper emphasis to be placed.

Gary Salmon:
Dale, what do you think? Do we have a good physics background?

Dale Morgan:
I think that Bob used all the right words for it. The physics does exist and the chemistry does exist but nobody has talked enough about how it interfaces with the dam seepage problem.

Gary Salmon:
I think that is a very, very good conclusion. What about the mathematics of the thing we need to do? Johan, what do you think?

Johan Claesson:
I'd say that there are minor thins that you should elaborate on but the basic mathematics are of course there. You could find different situation where you can get nice formulas to assess things in advance. I think you can do more there but it is also a question of communication.

Gary Salmon:
Does everybody agree with that conclusion? Anybody who disagree with it? What about the electrical methods? Is there any conclusion we can come to with regard to SP and its applications? Are we on the right track in trying to develop a field manual for collection of data?

Dale Morgan:
I would say that of all the geophysical methods, SP may have the best chance of being you method of choice for monitoring but it is also the method of geophysics that is in the dark ages compared to for example the seismic methods, which are very well developed. I think that SP is very important for the dam problem but o lot of work needs to be done there.

Gary Salmon:
So, I think that may also be an important conclusion that although SP has the greatest potential it is the least developed geophysical method, which has the implication that we should do some developing. Bob?

Bob Corwin:
As part of this ongoing DSIG project, that is what we intend to do. We are trying to this sort of development of SP for this application and that is ongoing. That is what professor Morgan is involved in and we expect to make progress in that area. We could always use more, but at least we have started.

Gary Salmon:
Are the resistivity methods better developed?

Torleif Dahlin:
They are probably more developed than SP but we have still more to learn when it comes to improving the resolution and finding the responses and the right ways of using it for this particular application. There is definitely more work to do.

Gary Salmon:
Would that be in collecting the field data, the correct electrodes or is it in the analysis of the data once you have it?

Torleif Dahlin:
I think it is all of it really. Acquiring good quality data in an efficient way at a reasonable cost and how to process and analyze the data in an efficient and repeatable way. I think it is really the whole process.

Gary Salmon:
As Bob pointed out the Dam Safety Interest Group has funded research and electrical resistivity methods are part of that project.

Ken Lum:
Could I just make a comment Gary? When we first started we felt that the field collection methods were all ready in place. As a result of Dale's talk over the last few days we may want to rethink that or at least assemble how we should be collecting data.

Bob Corwin:
I think the idea is that the equipment we developed for doing resistivity as oppose to SP, the techniques for doing the measurements and obtaining data and checking reproducibility are far more developed than for SP for example. So, what we need to put our emphasis on is what sort of geometry, what sort of arrays should we be using for our problem. That is one thing we should be looking at and the second is what we are measuring. What are the physical parameters that we are looking for? That is what we will try to deal with within our program.

Peter Gaffran:
Is it included in your research that we take soils that we use to build cores of dams and get them into a lab under very controlled conditions and place them at a range of densities and a range of saturation conditions and all the rest? We measure the resistivity in every which way from Sunday so we get a better idea of which resistivity go with what types of soils at what density and at what moisture content and so on.

Bob Corwin:
We are in the process of trying to set up a program to do this type of thing.

Peter Gaffran:
I have heard several times that electrode contact is important. Does anybody want to comment on that?

Bob Corwin:
I think it is just field practice really. Somebody who knows what they are doing should understand how to obtain contact.

Peter Gaffran:
Another thing that I wonder about is if it is worth thinking of getting a super charged system that puts more energy into the ground?

Torleif Dahlin:
It is quite possible but that more power could do it but you must still get the right grounding of the electrodes. That is the very first step to take. I learned after my presentation yesterday that some of the problems I have at the right dam crest of this dam is probably due to the fact that there is an insulating layer on top of the dam core, which has not been known before. Of course, if you have a layer of plastic, insulating material on top of your dam core it is very difficult to get any current into it. That is something that should be considered before planning a field survey.

Gary Salmon:

Okay, with regard to temperature, are there any conclusions that we can make that we should carry forth from this meeting?

Sam Johansson:
My feeling is that we will continue to develop good evaluation tools because it is necessary to have good understanding of when you can apply the method and when you should interpret your results. I hope that we can give some guidance to when people should use temperature measurements and when they should not.

Gary Salmon:
Thank you. Are there any conclusions as far as this meeting is concerned about how we should proceed with future research in seismic method? Has it all been done?

Mahmoud Farhadiroushan:
There was a point made earlier about passive acoustic measurements, just to listen to the dam and hear what is happening. I think you can hear a lot in there. I am not sure, but for example the oil industry is using this technique to find very small leaks. Acoustic methods are widely used and I think that you don't need very expensive sources or sensors in this case. You can permanently monitor the sounds and if you have a leak you can listen to it. I think it would be possible to hear it specially if it is a slow leak producing very low frequency energy.

Gary Salmon:
Perhaps we could say as a conclusion that we should consider the use of passive, or otherwise, acoustic methods using fiber optic cables for our dams prior to have any problems so that we can have a signature of it, and that we can consider that part of future research. Is that satisfactory to everybody? Do you agree with that statement? Okay, what about the seismic methods themselves? Do we need further development of sources, Peter?

Peter Gaffran:
Yes, we do and maybe it is a matter of getting connected to the industries that have done this first. We sort of need to get the source from the source…

Mahmoud Farhadiroushan:
I think there is also a lot of development at different acoustic research sites where they try to recognize different signatures of the sound. This is widely used in the music industry as well as sound recognition, in communication and so on.

Gary Salmon:
So, a start of this acoustic monitoring would be a literature search…

Bob Ballard:
A lot of these things do exist because acoustic emissions have been around for 20-30 years, but I think that the application to dams is relatively new. For unstable slopes along river and things like this, passive acoustics have been used in times in the past.

Let us not reinvent the wheel because a lot of work has been done. Where we can advance the state of the art now though is in terms of rapid read out and triangulation maybe on the source of the noise itself.

Dale Morgan:
In power plants the turbines are good sources and if you just monitored them from the surface and kept on doing it to get the changes over time, it is probably not a bad way at all.
Bob, do you have any comments on future research for seismic?

Bob Ballard:
One of the things that I would like to see might be the use of Reilegh waves through the dam or on the dam or somehow associated with the dam. One could use it as a non-intrusive technique hat would simulate and further complement shear waves. I'd like to see something like that considered.

Gary Salmon:
If we were to take a future direction or propose some actions, what should it be?

Dale Morgan:
I really feel that if you would do a monitoring SP you should use the telluric signal. You could use that signal to get a resistivity map and I think that it should really be done. It takes nothing more than an afternoon of computing to get it done.

Bob Corwin:
I might just add that when we do measurements we do record some of the parameters that Dale is talking about. I actually have some of that data we just haven't had a chance to use it. I agree that we have seen some very interesting things in the telluric signal that we have removed from the SP.

Gary Salmon:
I think that we not only have an action item; we have an actor.

Bob Corwin:
Well, it is very preliminary result but I am just agreeing that there is some interesting content there. I would like to throw something else in on monitoring, just a sort of a different philosophical approach. We are talking about understanding what we are doing in modeling but there is another way of looking at this, which is to throw out a whole bunch of SP monitoring systems on dams, get them going and get some background information to see how the instrumentation perform. Even if you don't understand now what it is telling you it is going to take a few years to get baselines of data to see how the monitoring itself works without you knowing what it means. Something people might think about is putting in these prototype monitoring systems and getting some experience with the equipment while we're developing the interpretation techniques.

Gary Salmon:
So, if HydroQuébec felt like there was a dam that might fail by internal piping and if they couldn't make direct measurements of seepage, they might want to institute some SP monitoring today with the belief that in five years they will be able to interpret the data very well?

Bob Corwin:
Right, I mean you wouldn't suddenly call out the legions if you saw that SP change but at least you are establishing the background and you are saving a few years.

Gary Salmon:
Is there anything else that we should do in terms of future actions or research to put ourselves in a better position?

Peter Gaffran:
Dr Morgan said that we are in the dark ages and I think that you were referring to the analytical or predictive side. Bing was talking to me at coffee about possibilities to make another numerical model that can predict the surface manifestation of SP, given the resistivity structure and the current conductivity structure plus the anisotropy and other factors. Maybe that should be on the list.

Gary Salmon:
Nobody wants anything big done?

Bob Corwin:
Let's go for another order of magnitude of funding. As Dale was saying, the level of funding for research in geophysics is so tiny compared to the return by saving one dam from failure. It is sort of sad to see what that ratio is.

Peter Gaffran:
Ray is always encouraging us to think big and he is talking about the possibility to make a test embankment. Thinking big and mobilizing all these experiments on this test embankment.

Gary Salmon:
This could be the same one that Sam thinks of as the ideal one for all tests. You can test the dam on his conceptual one and Ray will build the true embankment…
Does anybody else have a big idea?

Urban Norstedt:
I just wonder if we are talking money in the magnitude that would make it possible to drill all necessary wholes in the dam instead of any geophysics.

Gary Salmon:
So, instead of doing the geophysics we just dig up the dams to make them bullet proof?

Bob Ballard:
Let me ask a question with regard to maybe a smaller approach. Piezometers have been around for a long time. Is there a way that they can be improved such that it would help out the civil engineering profession like automatic read outs or something like that?

Gary Salmon:
I think that they have done a lot. Ken, would you like to describe what has been done?

Ken Lum:
As far as automatic read out, I think there is a lot of experience in the world. But along those lines, what I was thinking of was some type of instrument that goes down a hole with enough power source to provide readings for a finite length of time and then still transmit data and information to us. You've done the hole, you send it down there, you grout up the rest and then you at least get some information. That would be very useful.

Gary Salmon:
How about the priorities? Is there anyone of these, that have been suggested, that you say is number one priority?

Peter Gaffran:
Everybody seems to have mentioned SP as the first thing that they do, and it seems to be the most promising and it is the one with the most potential but it is also the one that needs the most work. It seems like the SP is kind of the top area anyway.

Gary Salmon:
Does everybody agree with that? If nobody disagree with it Peter, you carry the day.

Ken Lum:
Before we go Gary, could I have the floor for just one minute? I just want to thank again the organizers for this wonderful meeting. We've learned a lot during these last few days and it has been very, very enjoyable. I know that there has been a lot of effort in the organization and I certainly thank Anders and Sam and the other organizing people for arranging it, and certainly Elforsk for helping in some of the financial aspects.

Sam Johansson:
Thank you very much. It has been both a privilege and a pleasure to work with this conference and I would like to thank you all for coming, for sharing you lectures, for sharing in discussions and presentation and everything. I have learned that as a geophysicist you are always allowed to make new interpretations and I would like to make a new interpretation of the cross-coupling coefficient. I have seen that we have come together, we have cross-coupled ideas in very different ways and I have a feeling that this workshop, because of you has had a very high cross-coupling coefficient, which will be useful in the future. Each parameter must also have a unit and I think that it is more towards Volt as in potential than Ohm as in resistivity. I think that we have a potential in the future to develop this cross-coupling coefficient further. Thank you.

9 References

[1] Johansson, S., Barmen, G., Bartsch, M, Dahlin, T, Landin, O., och P. Ulriksen, (1995). *Nyare metoder för tillståndskontroll av dammar,* VASO Dammkommitté rapport nr 21, Stockholm, ISSN 1400-7827, 71p.

[2] Johansson, S., Claesson, J., Torleif Dahlin, Friborg, J., Hellström, G and Zhou, B. (2001). *A parameters study for internal erosion monitoring Elforsk/DSIG (in press)*

Appendix

Appendix A – Presentations from Session A – Monitoring of dams

Appendix B – Presentations from Session B - Temperature

Appendix C – Presentations from Session C - Resistivity

Appendix D – Presentations from Session D – Streaming potential

Appendix E – Presentations from Session E - Acoustic methods – Seismic /Cross-hole seismic

Appendix F – Presentations from Session F - Electromagnetic methods and miscellaneous

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