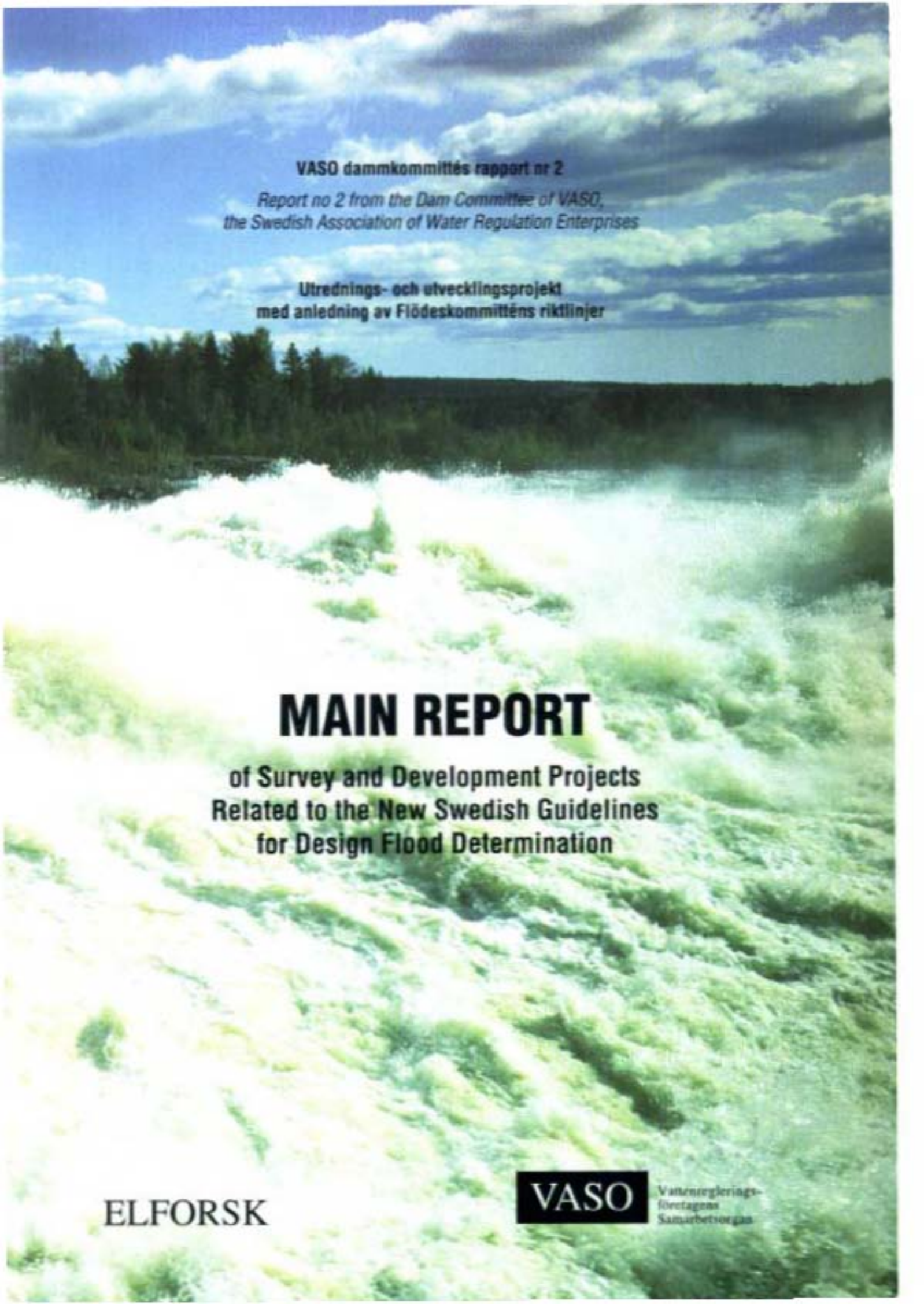




VASO dammkommittés rapport nr 2

*Report no 2 from the Dam Committee of VASO,
the Swedish Association of Water Regulation Enterprises*

**Utrednings- och utvecklingsprojekt
med anledning av Flödeskommitténs riktlinjer**

MAIN REPORT

**of Survey and Development Projects
Related to the New Swedish Guidelines
for Design Flood Determination**

ELFORSK

VASO

Vattenreglerings-
företagens
Samarbetsorgan

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SUMMARY

Most of the development of hydro power and construction of large dams in Sweden took place after World War II, reaching a peak during the 50s and 60s. The principles for the design and construction of dams during this period of intensive building are still largely valid.

As in many other countries, in Sweden we have re-evaluated the methods previously used for determining the design flows of dam facilities. The power industry and SMHI have, via the guidelines from the Committee for Design Flood Determination, agreed on new guidelines for this purpose, which in some respects has resulted in a new approach. The new guidelines mean that higher runoffs will have to be coped with than was previously the case, and consequently in several cases various kinds of improvements will need to be made to the dams.

In order to be able to modify the dams to meet the new requirements in a safe and cost-effective way, 24 of surveys and development projects have been carried out. These projects were completed at the request of the VASO Dam Committee, which is the power industry's joint organisation for dealing with questions of dam safety and, among other responsibilities, has the task of co-ordinating modifications of the dams to comply with the new guidelines. The steering committee that directed the work consisted of Harald Eriksson – Sydkraft AB, who was the Chairman, Sten Lasu – the Swedish Power Association, Lennart Markland – the Swedish Association of Water Regulation Enterprises, and Malte Cederström and Urban Norstedt – Vattenfall AB.

The goal of this Main Report is to provide an overview of the contents of the Committee's guidelines and routines for implementing them, and to present the background and contents of the studies carried out as well as to briefly summarise the more important conclusions and recommendations. In addition, this report presents the results of some minor studies that have not been previously presented as reports.

At present, there are more than 10 000 dams in Sweden, some 1 000 of which are used for generating hydro power. Approximately 200 of these dams are classified as high dams, i.e. higher than 15 metres. In general, it can be stated that there have been very few dam failures in Sweden.

The Committee's guidelines were published in 1990 and are to be used by the Swedish hydro power industry. The design flow specified in the guidelines is based on a consequence classification of the dams, i.e. the damage that would result from a possible dam failure, without considering the actual likelihood of a dam break occurring. The dams are divided into two "Consequence Classes", the design flows for which are calculated in different ways. There are, however, a large number of dams that do not belong to either category and are therefore not covered by the guidelines.

The routines for implementing the guidelines are quite complicated, especially since the goal is to find the most technically and economically optimal solution. This means that the dimensioning should be carried out for the entire river system. Dimensioning means that a calculation is made of the design flood and if this cannot be coped with without some sort of corrective measure or by temporary allowing higher water levels and flood mitigation,

additional reconstruction measures must be initiated in order to increase the discharge capacity, for example by building a new spillway. Alternatively, raising the height of the dam and thereby permitting increased temporary higher water levels; i.e. a flood surcharge above the normal water retention level can increase flood mitigation. The work involved in determining the optimal solution is begun by preliminary dimensioning the dam located furthest upstream and noting any corrective action that needs to be taken. Then the next dam is dimensioned, and this may affect the dimensioning of the upstream dam. In this manner the calculations are gradually performed for the entire river. In order to arrive at the technically/economically optimal solution, cost estimates of the various possible alternatives are made. These alternatives are also compared in terms of their benefits and drawbacks. An optimisation programme has been developed so that even with complicated river systems it will be possible to find the optimal solution. For each river, a dimensioning group is responsible for carrying out all dimensioning work.

During the dimensioning work for a river it is important not to pay attention solely to the spillways, but also to limiting sections in the watercourse, especially since experience has shown that there are often other "narrow" sections in the watercourse that can become limiting during a high flood situation and this may affect both the Consequence Class and the dimensioning. Temporary flood mitigation can be either passive or active. Passive flood mitigation implies keeping all the spillways fully open; while active flood mitigation involves actively seeking to increase the dampening by having the spillways partially opened or entirely closed. Active flood mitigation places particularly high demands on the technical systems and on personnel and organisation. The classification process means that the consequences of a dam failure are analysed, and in this context it may be necessary to calculate what happens in the area immediately below the dam, as well as how the flood wave will move down along the river. Other aspects to be taken into consideration during the dimensioning work for a river are the effects of landslides in river bluffs and of floating debris.

Each individual dam must be checked to see that it satisfies the requirements imposed as a result of river dimensioning. In the case of embankment dams, this means the ability to tolerate higher water levels than normal (a flood surcharge), which among other aspects involves issues such as the effects of waves, filters, internal erosion, leakage and erosion in the crest of the dam, as well as stability during increased leakage or waves overflowing the crest of the dam. In the case of concrete dams, this concerns, among other aspects, stability and in some cases the ability to tolerate overtopping. In general, methods for both monitoring and investigations are needed.

The spillway is of fundamental importance with respect to flow adaptation. It is particularly important that the assumed discharge capacity actually exists and that the spillway gates can really be opened when needed, or in other words that they have a sufficient level of functional safety. The dimensioning work is expected to result in the indication of a need for additional discharge capacity at a number of dam sites, which usually means choosing a conventional spillway with gates. A conceivable alternative could be some form of "fuse-plug", for example an erodible section of the dam. In the guidelines, it is assumed that the power plant will be shut down during a high flood situation and that the turbine water will no longer help to discharge the follow. Through the use of special measures, however, it may be possible in some cases to safely use the turbine waterways to discharge water.

In addition to the design flood, dam safety depends on a great many other factors. It is vital that all such factors should maintain the proper level of safety. A useful tool in this respect is a risk analysis.

In all the above areas, investigations have been carried out, which are included in the report series and are briefly described in this report.

An overall conclusion is that it is very important that the work of complying with the new guidelines is performed in a responsible and competent manner so that the increase in the level of dam safety, which was the aim of the work carried out by the Committee for Design Flood Determination, is actually attained. It is our hope that the surveys and development projects carried out will contribute to this end.

VASO Dam Committee

1. NEW SWEDISH GUIDELINES FOR DESIGN FLOOD

1.1. General

As in many other countries, in Sweden we have re-evaluated the methods previously used for determining the design flows of dam facilities. The power industry in Sweden and the Swedish Meteorological and Hydrological Institute, SMHI have, through the work in the Committee for Determination of Design Flood (the Committee), agreed on new guidelines for this purpose, which in some respects has resulted in a new approach.

The new guidelines mean that higher runoffs will have to be coped with than was previously the case, and consequently in several cases various kinds of improvements will need to be made to the dams. If these improvements and combinations of measures are not planned and executed in a careful and competent way, major economic resources can be wasted without having attained the desired increase in safety.

In order to cope with this complicated adaptation process, competence and knowledge are required within the following areas: hydrology (possible runoff), engineering (including actual discharge capacity, narrow sections, floating debris, technical capabilities for dealing with flood surcharge, safety of gate functions, and methods for examination and monitoring), reliable operation interaction, failure impact and preparedness, and risk analysis. Generally, it can be stated that an extreme flood situation results in problems that are difficult to predict since experience is, by the very nature of the event, difficult to come by.

For those facilities where, for example, additional discharge capacity must be created, it is important that the measures be designed with the greatest possible consideration to the above conditions. For those facilities deemed not to need reconstruction or conversion, it is of course necessary when making this determination to take into consideration the difficulties that may arise during an extreme flood situation.

After an analysis of requirements, the Dam Committee of VASO, the Swedish Association of Water Regulation Enterprises, initiated a number of survey and development projects in order to further clarify and increase know-how within certain areas. A working group for hydrological development work within VASO, called VASO/HUVA has conducted similar studies within the hydrological field.

In this Main Report, the contents of the Committee for Design Flood Determination's guidelines are briefly described, as is the compliance process, and a summary is given of the projects included as well as their background. The report has been divided into a general section, and a section covering the factors effecting the river dimensioning, and a section on the factors and requirements that are applicable for the individual dams. The report also addresses risk analysis, and briefly the research and development within the area of dam safety and organisational issues from a dam safety point of view. (Some of the reports included in the series are not only related to the adaptation of the Committee's guidelines, but are of a more general nature and have been deemed to be especially important for consideration in connection with pending increases in safety levels.)

1.2. Dams in Sweden

It is estimated that there are probably more than 10 000 dams of varying size and age in Sweden, some 1 000 of which are used for generating hydropower. Of these, after a recent survey, approximately 200 dams are classified as high dams, i.e. their height exceeds 15 metres, and three of them are almost 100 metres high. The larger dams belong almost exclusively to the category of hydropower or regulating dams. However, a few high dams with other owners also exist, such as mine tailings dams.

The high dams in Sweden are for the most part earth or rock-fill dams and most of the others are concrete dams, primarily buttress dams or gravity dams (some with masonry facing) as well as three arch dams.

The development of hydropower in Sweden began at the turn of the century, with the most intensive period of building taking place during the 50s, 60s, and 70s. The high dams are on average 35 years old, and all of them are more than 25 years old.

1.3. Causes of dam failure

In general, it can be said that Sweden has experienced very few dam failures, and when analysing the causes of dam failures we have had to use international statistics, as is the case with the analysis below.

A common cause of failure among embankment dams, i.e. earth and rock-fill dams, is overtopping, either as a result of extremely high flood levels causing an overflow or that the discharge functions failed in some way during, for example, a high flood. (The latter was the case when the Noppikoski dam collapsed in 1985. The dam was a 16-metre high earth-fill dam and this case is the only known failure of a high dam in Sweden.)

Another common cause of dam failures is flood erosion, such as erosion of the downstream toe of the dam, which has also occurred most often in connection with extremely high floods.

Leakage through the dam or foundation as a result of hydraulic fracturing, internal erosion or piping, are other common causes of dam failure. This category of failure is not necessarily linked directly with extremely high floods, even though a raised water level may have a contributory effect. Another common reason for dam failures has been the general instability of the dam.

In the case of concrete dams, it is possible that a failure will occur as a result of the tilting or sliding of both gravity and buttress dams. It is also possible for a local failure to occur in, for example, a buttress dam owing to leached concrete or as a result of reinforcement or anchorage failure. As regards arch dams, it could be possible for failures to occur at the springing or because of shearing near the foundation, but in general these dams have a very good capacity to withstand overloads.

International statistics indicate that the likelihood of a dam failure is in the order of 10^{-4} /yr.-dam. Similar statistical information gives an idea of the general likelihood of a dam failure

in terms of the various types of dams. But the safety of a specific dam cannot be based on this type of general data.

The majority of dam failures have occurred during the construction phase, in connection with the initial impoundment or during the first years immediately after, as indicated in

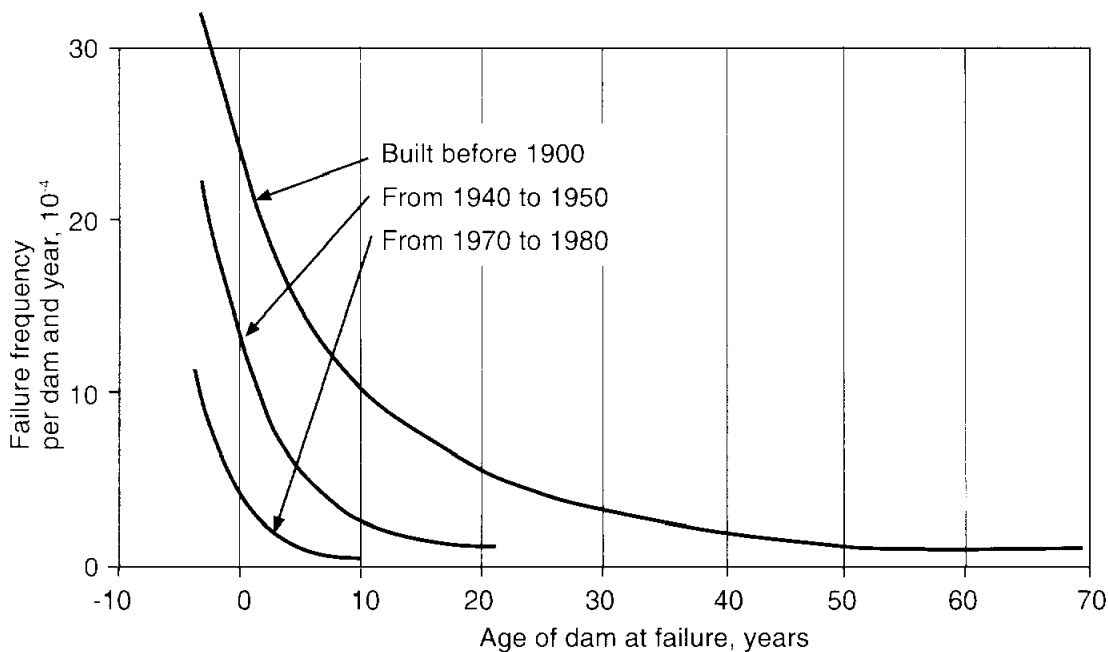


Figure 1.1. Dam failure frequency as a function of construction year and age.

fig.1.1. The figure also shows that the frequency of dam failures has decreased with time, which may be the result of an improvement in the level of know-how and technical expertise during this period.

1.4. The work of the Committee

The Committee for Design Flood Determination was formed in 1985 on the initiative of the Swedish hydropower industry. Its task was to develop proposed guidelines for determining the design flood at power station and regulating dams. In 1990, the Committee presented a final report with Guidelines for Determining Design Flood for Dams, which has been approved by the members of the Swedish Power Association. While bringing the dams into compliance with the new guidelines it became apparent that in some cases clarification of or additions to the guidelines were needed. Therefore, supplements to the guidelines have been produced, which are presented below.

The calculations are normally assumed to be carried out for one river at a time. Corrective measures for meeting the requirements of the guidelines may include an increase in the discharge capacity (e.g., by building a new spillway, converting existing spillways or in some cases by dredging the waterways) or by mitigating the flood in some way. A third possibility could be to make use of early and reliable precipitation forecasts to release water and thereby creating spare volume in the reservoir for flood mitigation. However, the methods of forecasting currently available are not considered to be sufficiently accurate to be able to use this method to meet the requirements of the guidelines.

In order to permit flood mitigation in the existing dams (Consequence Classes I and II), the Committee's guidelines allow departures to be made from the requirement, to be able to discharge a flood with a return time of at least 100 years at the normal retention level. Therefore, with respect to dam safety, a design flood may be discharged at a water level exceeding the retention water level, i.e. a surcharge occurs. On the initiative of the Committee, the Water Rights Act has been supplemented with the right to make the surcharge under certain circumstances and make the economic settlements for damages afterwards.

1.4.1. Consequence classification of dams

The Committee was of the opinion that the damage which can be caused by the failure of a dam should initially determine the consequence classification (which then was called the risk classification) and thus also the demands governing the design of the dam. The design flood according to the guidelines is therefore based on what is in the guidelines referred to as "risk classification" of the dams, but with the terminology that has subsequently been established, "consequence classification" would be a more accurate term and has been used in this report. The classification is based on the damage which a conceivable dam break at a certain dam would be able to cause, but does not on the other hand deal with the probability of a failure taking place in the dam. It is therefore not the probability of a dam break occurring at a certain dam that determines the class, but only the consequences that would occur if the dam did fail. The Committee has defined two Consequence Classes, but there are also a large number of dams which do not belong to either of these and which thus are not affected by the new guidelines.

During classification, it is important to note that the classification is based on the marginal effect of a dam failure, i.e. the increase in the damage to the surroundings which the collapse of the dam causes in addition to the damage that the exceptionally high water flow would anyway have caused, even if the dam had not collapsed.

Consequence Class I

- Non-negligible risk to human life or other bodily injury;
- or
- Considerable risk of serious damage to important traffic route, dam structure or other similar installation, or to an important feature of environmental value;
- or
- Clear risk of major economic damage.

Consequence Class II

Non-negligible risk of damage to major traffic route, dam structure or equivalent installation, feature of environmental value or property belonging to a party other than the dam owner in other cases than those specified for Consequence Class I.

The Committee maintains that the assessment of which Consequence Class a certain dam structure should belong to must be determined from case to case in the first instance by the dam owner but ultimately by examination in accordance with the Water Rights Act. Since it is the consequences of the damage that determine the consequence classification, it is

impossible to refer different types of dams (embankment dams, concrete dams etc.) to a particular consequence class.

1.4.2. Design flood

The guidelines of the Committee deal with both new and existing dams, between which there are certain differences. The present report deals in the first instance with existing dams. As regards the exact content of the guidelines, reference is made to the guidelines in question.

Design flood for Consequence Class I

The determination of a design flood for dams in Consequence Class I shall be simulated by applying an accepted hydrological model in the following summarised basic steps:

1. The model is calibrated against existing runoff series (at least 10 years).
2. By means of frequency analysis, snow storage with a return time of 30 years are calculated. This value is entered in the model on the last date on which the snow cover culminates during one of the years analysed.
3. The design 14-day precipitation according to the Committee's guidelines is adjusted for elevation, year and area.
4. Regulation strategies incorporating the Committee's guidelines, storage data discharge curves and water conservation regulations are entered in the model. In this context, consideration shall be given to the fact that only spillways that can be put into operation at short notice and with full safety are to be included. The storage is assumed to have reached the maximum water level by 1 August and is not assumed to decrease in level until the critical flow period is over. Any discharge possibilities through power station turbines may not be included from and including the 9th day of the precipitation sequence. The VASO Dam Committee recommend that in those cases where measures must anyway be carried out in order to cope with the design flood, the dam should be adapted to and be independent of whether turbine discharge is available or not.
5. The design flood shall be determined by simulation in the model for at least 10 years based on the latest available year's climatic data. In the simulation, the 14-day precipitation is advanced one day at a time from the date specified in item 2 above. The simulation that gives the highest water level in the year series according to the previous paragraph will be the design flood occasion.
6. The wind-impact is determined and added to the design water level in accordance with item 5 above.

In addition, for dams of Consequence Class I there are supplementary conditions which mean that the discharge capacity of the dam at the water retention level shall normally be such that a flow with a return time of at least 100 years can be discharged. Exceptions to this may be permitted after Water Rights Court determination, for example if a permit is granted for flood surcharge.

Design flood for Consequence Class II

For dams in Consequence Class II, the flow with a return time of at least 100 years is determined by means of frequency analysis by existing hydrological material (runoff, natural water flow or regulated water flow).

1.4.3. Supplements to the Committee's guidelines

During the course of the Committee's work, it was predicted that it might be necessary to supplement or adjust the guidelines, as well as instructions for the application of the guidelines in special cases. The power industry had already at this stage appointed a working group, the VASO Dam Committee, with the task of preparing and following the conversion works and flood mitigation measures that could be the consequence of the new guidelines for design.

The continued work on the adaptation of flows has warranted the provision of certain additions and changes to the guidelines, which have been made in consultation between the Swedish Meteorological and Hydrological Institute, SMHI and the Swedish power industry, represented by the VASO Dam Committee. The government has been notified of the consultation. The additions decided so far are:

Supplement 1:

The supplement concerns the consequence classification with respects to the consequences of high flows and establishes that the marginal effect (damage) of a possible dam slide is decisive for the classification.

Supplement 2:

The supplement concerns a change in connection with wind velocity for determining the required free board.

Supplement 3:

The supplement concerns a change in the instructions for calculating the flow for new dams in Consequence Class II and involves the deletion of points 2 and 3 in the guidelines.

1.4.4. Return time

When the probability of a certain year's maximum ($Q_{max.}$) being exceeded has been determined, the so-called return time for this value can be calculated:

$$T = \frac{1}{p}$$

where T = return time for $Q_{max.}$
 p = the probability of $Q_{max.}$ being exceeded

In design calculations reference is often made to 100-year flood, 1000-year flood etc. Return time may, however, be unsuitable to use since it is easy to be tempted to believe that if the 100-year flood occurred last year it will take some 100 years until the next time there is a similarly high flood. The probability of a 100-year flood during a certain pre-determined

year is of course according to the theory just as high irrespective of when it last occurred.

It is also possible to calculate the probability of a certain year max. Q_{max} being exceeded during a certain period, for example a 10, 50 or 100-year period.

$$p_n = 1 - (1 - 1/T)^n = 1 - (1 - p)^n$$

where p_n = probability that Q_{max} is exceeded during an n-year period.

Table 1.1 below gives the relationship between p_n , T and n . From this it is possible to see, for example, that the probability of a 100-year flood being exceeded over a 200-year period is 87%.

Tabell 1.1. The probability of exceeding a T-year flood over a n-year period in %.

Return times interval T	Length of period					
	10	50	100	200	500	1 000
10	65	99	100	100	100	100
50	18	64	87	98	100	100
100	10	40	63	87	99	100
200	5	22	39	63	92	99
500	2	10	18	33	63	86
1 000	1	5	10	18	39	63

1.4.5. Methods for calculation of return times

As previously mentioned, different choices of distribution functions give different values for probabilities and return times. Those parameters used in the analysis are, among others, the mean value of the series and standard deviation. Determination of these depends on the length of the time series – the longer the series, the better the estimation. With the observation series generally available in Sweden, two-parameter distribution functions should be used.

2. APPROACH FOR IMPLEMENTATION OF THE COMMITTEE'S GUIDELINES

2.1. General

The Committee's guidelines involve a relatively complicated approach to design work, especially when the goal is to discover the optimal technical solution. The approach is described below.

In order for the work in connection with adapting the dams to the requirements of the new guidelines to take place in an optimal way with respect both to safety and to economy, the design work must be carried out jointly for all installations on a river. This means that it is possible to find a more optimal solution than without further analysis increasing the discharge capacity in all facilities, where it is insufficient to allow the water to continue downstream, which would involve both high costs as well as serious damage as a result of flooding and erosion etc. An optimal solution of this kind may mean that larger water reservoirs are used to mitigate the flows, which can be done either by not fully utilising the existing total discharge capacity (active flood mitigation) or by deciding not to increase the discharge capacity. This does not only mean an optimisation on the part of the power industry but the flood mitigation may also be desirable for the sake of society since construction carried out on behalf of society often takes place in such a way that extensive damage has already occurred for flows that are considerably lower than those for which the dam spillways are currently dimensioned. This in turn depends on shortcomings in community planning but also on the fact that society in general is designed for considerably lower flows than the dams. At the same time it should be pointed out that active flood mitigation should not be carried out for any purpose other than for securing dam safety and then in accordance with a plan prepared for the river, since otherwise (e.g. if active flood mitigation took place to avoid downstream flooding) there would be an encroachment on the capacity of the dam to cope with high flows. The margins would in such case already have been utilised (at least partly) if the extreme case occurred.

If the design flood cannot be coped with by surcharge and flood mitigation, reconstruction measures must be taken to convert the structure in order to increase the discharge capacity, for example the construction of new spillways. Alternatively, the dam can be raised, which gives a certain increase in discharge capacity in the existing spillway and at the same time may lead to increased flood mitigation.

The discharge capacity of a dam referred to in the guidelines does not merely mean the release capacity of the spillways; consideration shall also be given to the effect of other limiting sections and other possible obstacles to water runoff.

In certain cases converting existing spillways, often by lowering the spillway thresholds can create an increase in discharge capacity. By replacing older shut-off devices that are difficult to operate and maintain by modern, easily operated gates it is possible at the same time to increase the functional reliability and permit a quicker increase in discharge. Sometimes, dredging or enlargement of the waterways below a dam may be a sufficient measure to increase the discharge capacity. Finally, new spillways can be constructed in or alongside the existing dam, for example in the form of a free overflow weir, surface spillways closed by gates, erodible dam sections, labyrinth weirs or siphons. A previous investigation on these issues is presented in the report, "Increased discharge capacity in existing dams" [5].

2.2. River-oriented design groups

In order to carry out the work, river-oriented design groups have been formed with competence in hydrology, hydraulic engineering, operation and water rights legislation. It is the task of these working groups to determine whether the dams and their spillways can cope with the design runoff or whether, and to what extent, the discharge capacity of the waterways needs to be increased or the dam crest raised. The aim is to find the most suitable technical and economic combination for the entire river system of extended discharge capacity and various forms of flood mitigation.

2.3. Design methodology

In a first stage, a design runoff to all the dams on the river is calculated on the basis of the so-called zero alternative, which means that each dam and spillway is assumed to be able to cope with the design runoff. In a second stage it is decided which dams have to be modified in order to cope with the design flood (raising of the dam, increasing the discharge capacity, or a combination of both), starting upstream in the river. After each modification a new calculation is carried out for the river. In cases where the required flood mitigation cannot be achieved, active flood mitigation may be attempted in one of the upstream reservoirs. Active flood mitigation in this context means that an installation under a high flow situation does not use its maximum discharge capacity. However, in order to find the

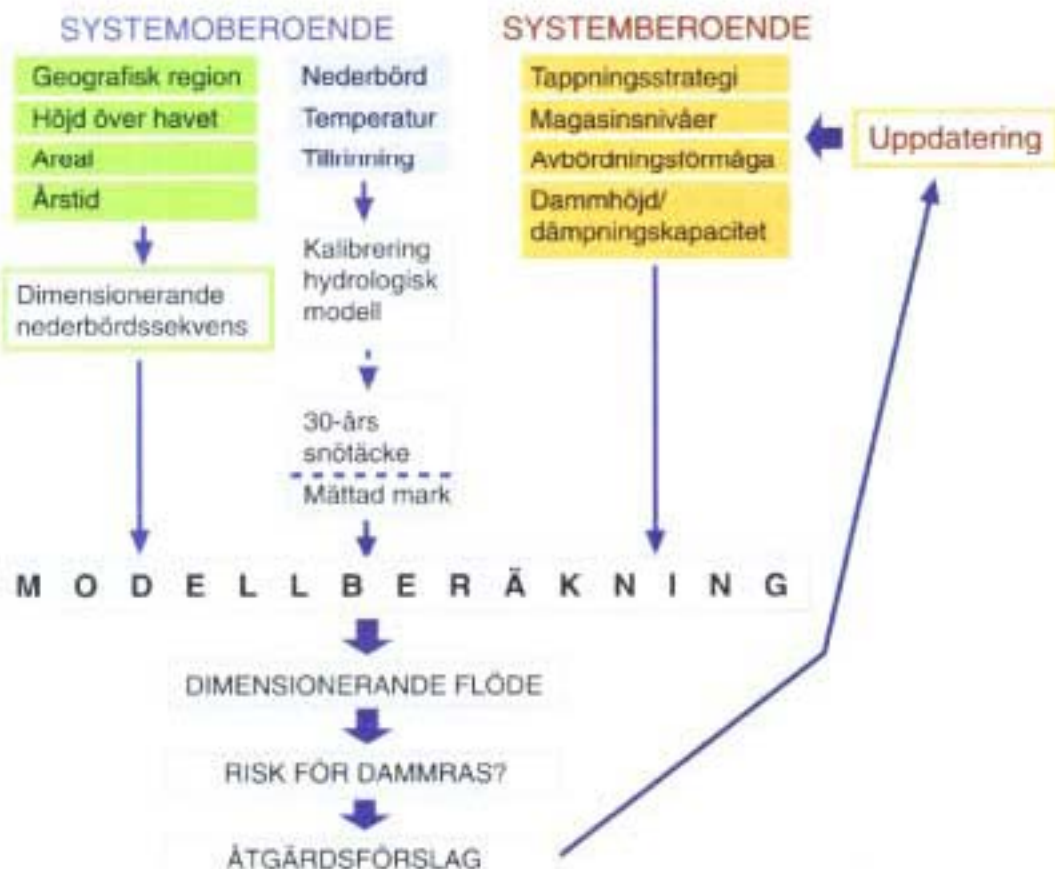


Figure 2.1. Overall description of approach to flood dimensioning.

optimal solution, a comparison should be made between alternative solutions, on the basis of which the most suitable technical/economic measures for the entire river can be finally based.

2.4. Strategy model QS

Active flood mitigation should only be necessary in more complicated watercourses, in which case the performance of the calculations will be much more complicated and a simulation method will be needed. An optimising program/a strategy model referred to as QS has therefore been developed which can be used as an aid in finding a technical/economical solution.

During the design work, sensitivity analyses should be carried out so that a solution is not chosen that does not function satisfactorily if, for example, the spillway capacity for the spillways in a dam is in actual fact somewhat greater than assumed and for the downstream dam somewhat lower.

QS model

The model is a pure flow regulation model that is fed with local runoff values based on measurements or hydrological model calculations. The basic concept is that the model shall, in each step in time, use information available on the river to select the best flow-flood mitigation measure. In those cases where flood mitigation is not possible, the model can be equated with the regulation section of, for example, the Swedish "HBV-model". However, in QS a sub-area can have two outlets with different addresses.

In the strategy model, critical water levels are specified for each dam, which should not be exceeded. Before a critical water level is achieved at any of the dams, release is controlled completely in a predetermined way with required production releases and current discharge capacity at the various installations. After each step in time, the model studies, starting furthest downstream in the river, whether a critical water level has been reached and thus whether flood mitigation needs to be carried out before the next stage. If so, the model calculates, on the basis of the runoff forecast for the next stage, the maximum releases that are allowed from installations situated further upstream. In the first instance, the model attempts to mitigate the flow in the reservoir situated immediately upstream. If the critical water level has also been reached here, the flood mitigation requirement is moved one stage further upstream etc.

The model not only provides the possibility to analyse suitable flood mitigation reservoirs in connection with flow design calculations but may also be a planning aid in acute flow situations.

The model and manual have been produced within the framework of the report series and are therefore available to the Swedish hydropower industry. They have been prepared jointly by Vattenfall Utveckling AB and Vattenfall Hydropower AB.

2.5. Legal and economic aspects

Once the working group for a river has completed its work and the power and regulation companies concerned have accepted the solution, it shall normally be presented and, if required by the solution, be established in some form by the Water Rights Court. Depending on the nature of the solution, this is judged to be able to take place on a common basis for the entire river or for one individual dam at a time, in which context, however, the overall situation should be presented in a suitable way. Certain measures, for example raising the height of the impervious core without the dam otherwise being changed, may involve a simplified approach.

The texts that have been added to the Water Rights Act in connection with the right in certain cases to surcharge the dam with the aim of protecting a downstream dam or dams and to compensate for the damage after the event support the idea that there is no other party concerned.

In certain cases, it may be considered rational to implement measures for a dam in order to protect some other party from a flow, which the latter cannot cope with. Here, of course it is the responsibility of the owners of the dams to reach an agreement on a solution of this type and the financial compensation for both the reconstruction measures and for operation and maintenance costs as well as production losses connected with it.

The revised liability situation that new legislation concerning "strict liability" (i.e. the dam owner has the full responsibility, irrespective of whether he was negligent or not) involves may need to be considered in connection with design.

The VASO Legal Committee handles legal matters in connection with adaptation to the Committee's guidelines.



Figure 3.1. The photograph shows head losses upstream from Stugun Power Plant in high flow conditions. The losses are experienced at both the bridge and further upstream (lower part of picture).

3. INVESTIGATIONS CONCERNING THE DESIGN FLOOD DETERMINATION FOR A RIVER SYSTEM

3.1. General

When designing a river system, consideration must be given both to factors that are dependent on the river as well as to the preconditions for each existing dam in the river system. A presentation is given below of studies that primarily concern the river.

During design work, and particularly when selecting the optimal solution, it is of course important that the basic assumptions are correct, for example that dams which are assumed to be surcharged can actually withstand this and that the spillways actually have the capacity assumed. This means that once a preliminary design has been made a careful check must be made for each dam to ensure that it meets the requirements imposed on it by the solution, or that modifications to meet the requirements imposed are possible and their costs acceptable. Alternatively, the design work shall be repeated, i.e. a different or modified solution should be developed.

The design flood according to the Committee has been judged to have a return time of at least 10 000 years, and during check calculations for a flood of this magnitude there is not the same need for safety factors concerning, for example, loads as with a more common load case. Besides this design flood, a flow with a return time of 100 years shall be combined with a higher wind velocity than the Committee's design flood and it is not necessarily clear which case will be the decisive load case, so for example, for an upstream slope, a check must be made for both cases. Also cases with a sudden shutdown of the turbines, whereby the turbine water flow is to be discharged through the spillway, may be possible and the discharge capacity must in such case be sufficient and, depending on the rate at which the water rises in the reservoir, perhaps rapidly available. In such cases it shall normally be possible to cope with this by only using one of the gate systems, i.e. AC or DC-operated gates. An analysis should also be made of the consequences of incorrect operation of gates in upstream dams. If a critical situation could occur from such gate operation, measures should perhaps be taken to prevent an unintentional opening of this kind.

A description is given below of certain factors that have proved to be of particular interest in connection with design work and the studies on these subjects.

3.2. Limiting sections in watercourses

Experience shows that there are often other sections in a watercourse apart from the dams that serve as hydraulic control structures for flows generated in a high-flood situation. This affects both flow design and consequence classification of the dams.

3.2.1. Influence on Consequence Class

A naturally narrow section (or limiting section, i.e. a section with steep hydraulic gradient, for instance a critical section) upstream of a certain dam may, for example, restrict the volume of water released in connection with a dam failure (see fig.3.2) and which continues

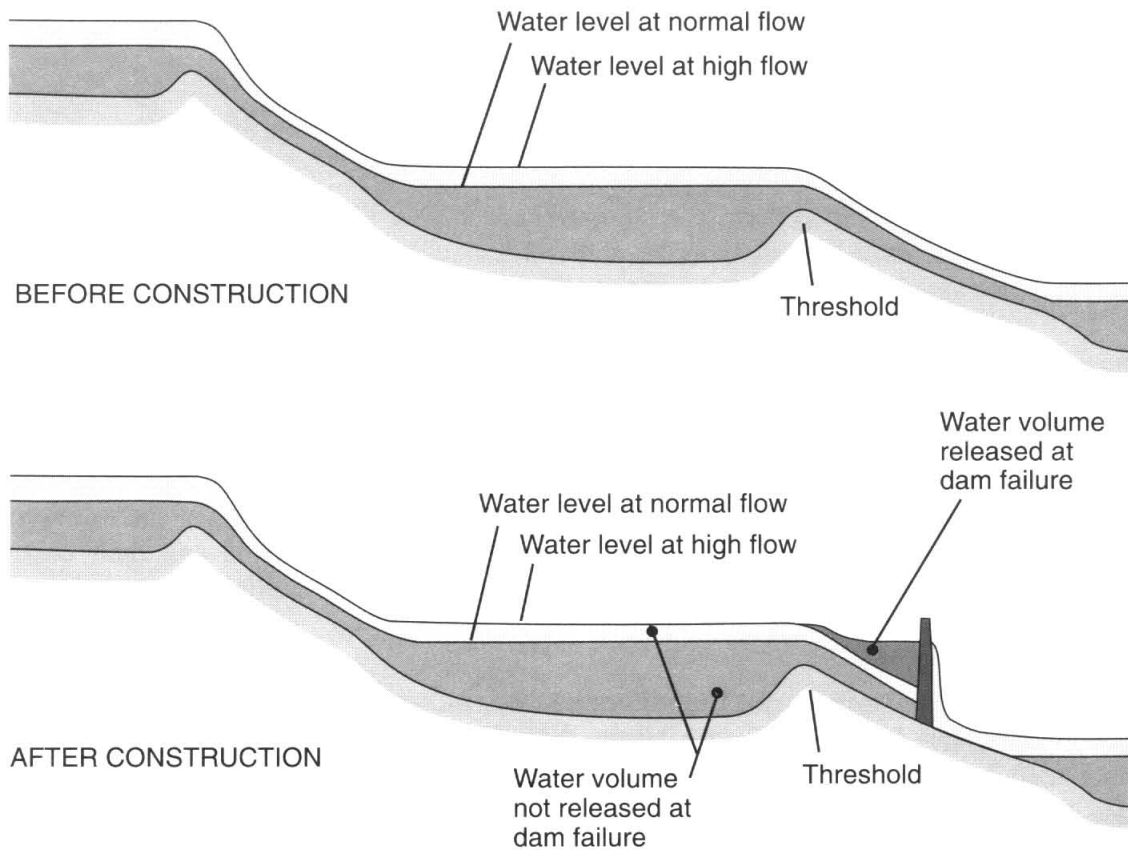


Figure 3.2. Example. The figure illustrates how a threshold, if it is a critical section at high flow, can restrict the water volume released in case of a dam failure.

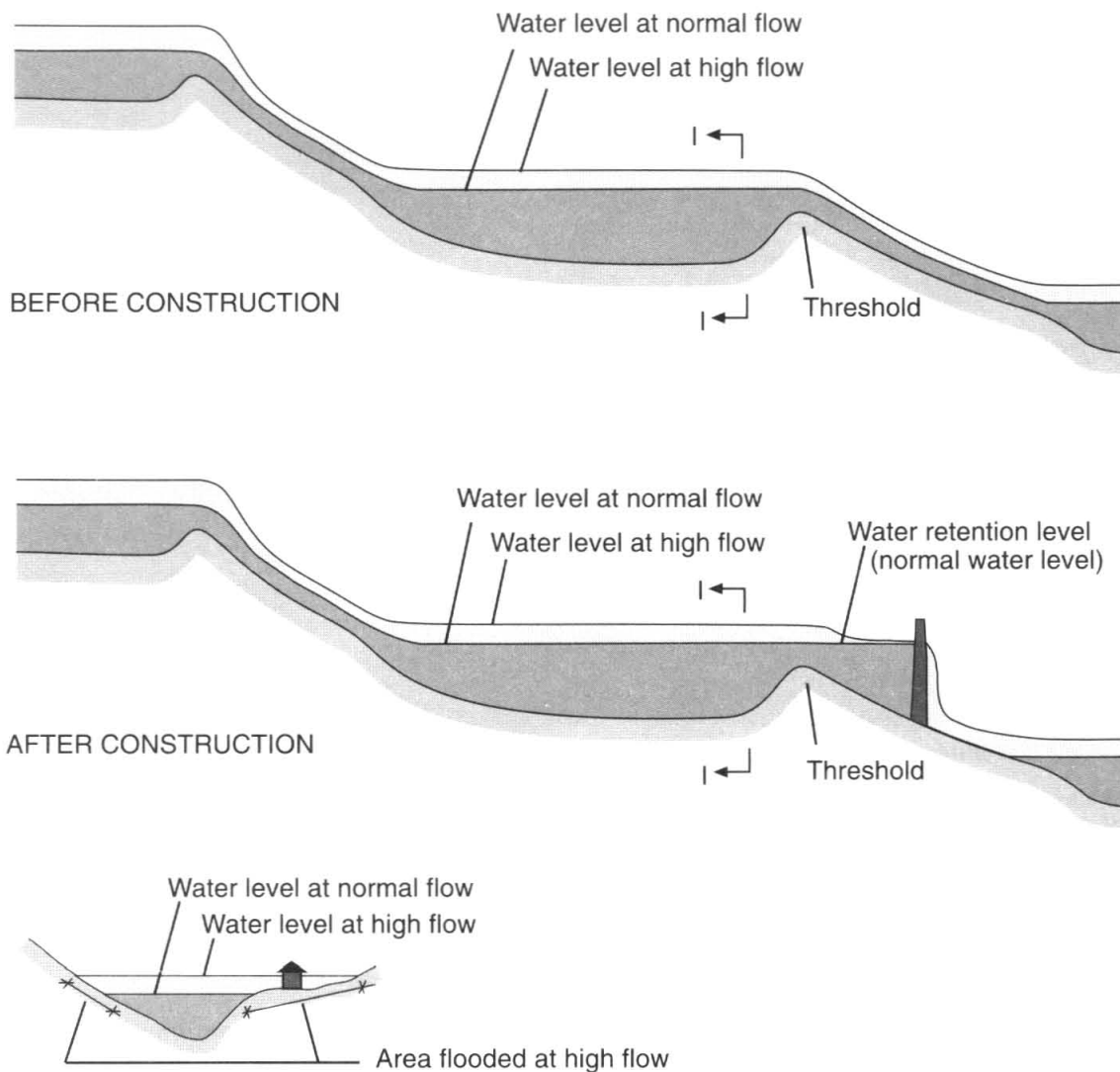
to the next downstream dam so much that the latter dam can cope with the situation without collapsing.

3.2.2. Effect on the design

A natural narrow section upstream of the spillway in the vicinity of a dam means that the water level will rise more than it would have done if this section had not existed before the balance is achieved between runoff from upstream of the narrow section and the discharge through the spillway. This means that flooding may occur upstream of the limiting section (see fig. 3.2) and it is of course necessary for this to be known when calculating the water levels that would occur during the design flood. Subsequently, a check must be made that the system can withstand these water levels (particularly upstream of the narrow section).

A limiting section downstream from the spillway can in certain cases reduce the discharge capacity by backwater effects, which means that the calculated discharge will not occur until a higher reservoir level is reached than otherwise.

It is worth noting in this context that flooding upstream of a naturally narrow section does not normally have any connection with the existence of the dams downstream but depends on the high flow as such.



SECTION I-I

Figure 3.3. Example. Flooding when a threshold is a critical section at high flow. Section I-I shows how a house by the river can be affected by flooding irrespective of the existence of the dam.

Which section is the limiting depends on the flow. In other words it may be the case that a certain natural section does not become the limiting section until a high flow is reached, which of course makes it more difficult to identify (see fig. 3.1 and 3.4). A study has therefore been made on the importance of narrow sections and how they can be found. The study is presented in report 3, "Limiting sections in watercourses":

The new Swedish guidelines on design flood determination provide ample reason for analysing the flood conditions along the watercourses. This should start with a compilation of maps, existing hydraulic data, investigations and other experience from different dams. The material may be analysed in a mathematical river model. Especially sensitive reaches should be identified and the accuracy of the predictions, e.g. regarding water levels, should be compared to existing margins and acceptable deviations.



Figure 3.4. The photograph shows head losses under high flow conditions at the outlet of Gesunden. During normal flow, it is the same water level as far as Krångede Power Plant 1 km downstream.

Sensitive reaches are those that comprise:

- Dams and spillways with discharge canals and energy dissipation arrangements.
- Lakes, water reservoirs and other flat reaches where significant damping effects could be achieved.
- Reaches with small safety margins regarding significant flooding or other damage affecting bridges, roads, industries, water works, other infrastructure or nature, as well as points where the water could breach the river banks and create a new watercourse.

Field investigations to improve the geometric or the hydraulic information should at first be concentrated to such sensitive reaches and to the identification of reaches with steep hydraulic gradients, for instance critical sections. Available field methods comprise aerial mapping, echo soundings or sonar surveying of cross sections and registration of water levels and stream flow. Spillways and turbines with known discharge capacity should in the first instance be used for flow measurements. The results may conveniently be analysed in a mathematical river model.

To summarise, it may be stated that the study describes how to find the limiting sections in a watercourse and the importance of identifying them, partly in order to be able to make an accurate consequence classification and partly to be able to calculate the discharge capacity of the spillway at different reservoir levels.

3.3. Landslides in river bluffs

In general, it can be stated that landslides may incur considerable risks to society. Normally, the problem is not specifically related to hydropower but may in certain cases be of importance to dam safety. If a landslide in a river bluff were to occur in connection with a design flood (e.g. triggered by erosion caused by the high flood) it could lead to an impoundment of the river upstream from the slide and if this were to occur near a spillway section in the dam it could lead to clogging or impair the runoff to one or several spillways. In the event of a major landslide near a dam, a large surge wave could occur and be so powerful that it broke over the crest of the dam. Against this background, a study has been made concerning landslides in river bluffs. The study on these issues is presented in report 4, "Landslides in river bluffs":

River bluffs are steep slopes formed by erosion in silty and sandy river deposits. They occur along river valleys in the middle of Sweden in areas below the highest shoreline formed during the post-glacial period. Due to the ongoing land elevation the rivers have eroded terraces formed by their earlier depositions. The formation of high river bluffs has thus been enabled at the riversides, at some places up to 50 m high and with an average inclination of 45° . According to a traditional slope stability analysis they are too steep to be stable. The fact that they remain standing can mainly be explained by the occurrence of negative pore pressures and cementation effects.

Landslides occur occasionally due to river erosion as well as other causes. The slides are shallow and insignificant compared to clay slides. The slide surfaces are plane and the action quite slow (see fig. 3.5 and 3.6).

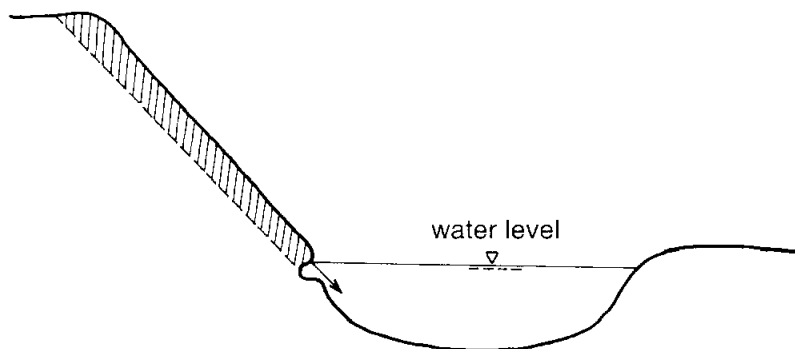


Figure 3.5. Landslide on a river bluff caused by undermining of the slope. Landslides often take form of several slides in that the slip surface gradually works its way upwards. After the landslide, the slope will have the same gradient as before.

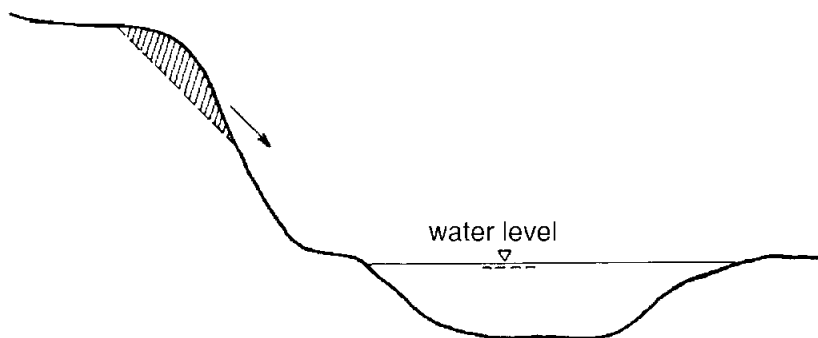


Figure 3.6. Landslide in the upper, often steeper part of a bluff. The slide may, for example, have been initiated by a fracture above the crest.

The consequences of slides in river bluffs are relatively uninvestigated. No case is known where masses from a slide have dammed up a river and it is not likely that even a large slide could reduce the cross-section in a large river (*in Sweden*) by more than 10–15%. The waves generated during such a slide are said to be relatively small. Trees that fall down with the slide masses and caught by the stream are a greater risk, because they might jam in narrow sections or under bridges, causing a rise in water level and horizontal forces on structures. Risks to residents and buildings have to be investigated for each river bluff, suitably by inventories of the same kind as those already made for a number of municipalities along the river Dalälven at the request of the Swedish Rescue Agency.

Further studies within this field are desirable. The mechanical behaviour and cementation of silt as well as failure mechanisms of river bluffs and their sensitivity to external disturbance should be investigated. Development of slope preservation programmes for various vegetation types should be considered. A list of slide occurrences might increase the knowledge of slides and make it possible to estimate the probability and economic consequences of different course of events. All bridges and narrow sections downstream from river bluffs ought to be examined in order to identify places where trees might jam and cause damage to structures or a rise in water level upstream. Inventories of risk zones in inhabited areas are recommended.

The effects of slides in river bluffs should be considered during design work in connection with the effect on watercourses and the occurrence of floating debris. As regards slides in more general terms, they are incidents for which society or the individual is responsible for providing protection – not the hydropower industry. This applies in particular where buildings have been constructed close to a bluff where a slide is bound to happen sooner or later.

3.4. Flood mitigation

A consequence of exploiting rivers for lumber floating, water mills etc. and more recently for power purposes is that new, limiting reaches are introduced and that the flow as a consequence is damped in the reservoirs. The previous, often annual, inundations thereby cease. In the case of very high flows inundations similar to those that occurred in the past may occur since the flood mitigation capacity of the reservoir then may be insufficient. The natural flood mitigation is obstructed by ditch excavation and deforestation as well as by the construction of permanent or temporary dykes against flooding, which during recent years have caused problems in several European rivers. Such dykes provide local protection but may lead to worse problems downstream. It is of course important in connection with community planning to give due consideration to all these factors so that the floodings during a situation of this kind do not come as a surprise. In certain cases, camping sites have been allowed to be established in areas which in the past were flooded almost annually and for which the preconditions have not existed to grant building permits for more permanent buildings. Many years later, when a flood has occurred, these circumstances have often been forgotten.

As has been described above, one way to handle the new design flood according to the new guidelines may be a combination of increased spillway capacity at some dams and flood mitigation by allowing a flood surcharge at others. For society, this solution has the

advantage that cities at river-mouth will have to endure a much lower flow than if only the spillway capacity was increased.

The study of possibilities, difficulties and risks associated with flood mitigation is presented in report 9, "Flood mitigation in Swedish dams":

The study deals with the possibility of flood mitigation as a means of improving dam safety at existing high-hazard dams in Sweden. The investigation method employed is a simplified probabilistic safety analysis, which aims at identifying and controlling dominating risk factors.

The investigation reveals that many Swedish dams will require construction measures in order to permit safe flood surcharges above the present upper retention levels. Thus, thorough safety evaluations will be required for those existing dams, which are considered for flood surcharge. These studies should define technically safe surcharge levels and also acceptable levels for planned surcharges with regard to proposed usage frequency and required safety margins. Operational shortcomings due to technical problems, human errors and external climatic impact are to be considered. The risk of losses in discharge capacity due to blockage by floating debris, mostly uprooted trees, is found to be of singular importance.

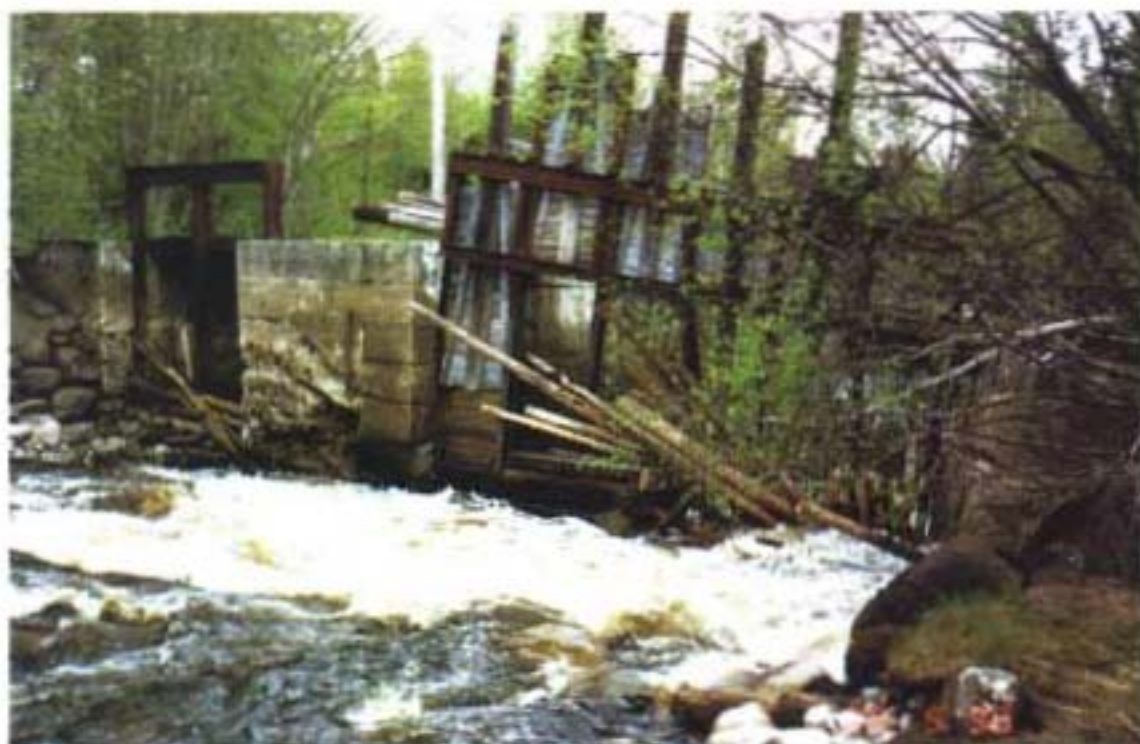


Figure 3.7. An old spillway blocked by logs, etc. that have become jammed against the beams of the lever gates.

It is further noted that the most developed form of active flood mitigation, based on current hydraulic information from different parts of a flood system, will put extreme demands on the system, as well as on the organisation and planning for dam operation. The conclusion is that such practices should be considered only where the potential benefits are substantial and the flow development is slow, i.e. in very large drainage areas.

The study was originally intended only to deal with active flood mitigation, but was subsequently extended to cover mitigation in general – both active and passive.

A risk inventory of this type may easily give a negative impression. It is nevertheless necessary as far as possible to list conceivable risks in order later to evaluate them. Considerable progress has been made in this context, which does not mean, however, that there are no other risk elements to be considered – reality sometimes surpasses the imagination.

When it comes to the evaluation of individual risks, this must often be based on assessments, which of course can be made in different ways. As regards the recommendations that an inventory and evaluation of this kind may give rise to, the scope for various evaluations is even greater. The recommendations in this study have been given the form of the preconditions that are considered necessary in order for flood mitigation of various types to be considered satisfactory from the safety point of view.

It is concluded in the study that the difficulties associated with **active flow mitigation** may be so great that this type of flow management strategy should as far as possible be avoided and that **system-controlled active flood mitigation**, a method that requires accurate information transmission, as well as requested operations (e.g. opening and closing of spillway gates) to be carried out, through the entire sequence of events, should be avoided. This conclusion is in accordance with the recommendations by the International Commission on Large Dams – ICOLD.



Figure 3.8. The equipment must withstand the sometimes hard climatic conditions in the northern Scandinavia. The photo shows a communication link tower.

3.5. Flood mitigation during the compliance stage

During the period up until when the dams have been entirely adapted to the new guidelines, it may however, be necessary (and suitable) to use a flood mitigation approach if a flow were to occur which is greater than the installations are currently designed to withstand. It is therefore important to have sufficient knowledge of each river in order to be able to judge the possibilities of mitigating the flood during a period of this type. The legal conditions and division of responsibility for such flood mitigation measures should also have been clarified.

There may also be good reason when the design work is carried out on the river to analyse situations that may arise if the turbine water flow in a station does not stop (i.e. the station does not trip) at the same time as the stations further downstream have been tripped. This case means that a higher flow than expected will continue to the next dam. There is of course the opportunity to shut off the turbine water flow or not fully open a spillway, but this should in such case be planned and agreed, especially if the rate at which the water level is rising is high. Preparedness for such actions could be especially important during the compliance stage.

3.6. Dam break and impact calculations

The process of adapting to the Committee's guidelines is one reason for studying the consequences of a dam break. The consequence classification for a dam is based on the marginal impacts of a dam break, i.e. damage over and above the damage, which the extremely high flood causes in itself. In some cases this may be easy to judge, but in many cases a more accurate calculation may be necessary of what the consequences would be both with and without a dam break in connection with successively increasing flow. In this context it is a question of calculating how the body of the dam is successively eroded in an initial stage and the flow thereby increases, and partly how the water masses continue downstream along the river. The study on these issues is presented in report 18, "Methods for dam break and impact calculations".

3.6.1. Dam break sequence

The question of how a dam break is developed varies, of course, from case to case, but there are often a number of common characteristics. If an embankment dam begins to be overtopped, this often takes place along a certain limited section of the dam whereby the dam starts to be eroded in this section so that the depth increases and erosion of the sides takes place. The knowledge available concerning dam breaks that have occurred in embankment dams indicates that the dam break is developed relatively rapidly down towards the foundation level of the dam and will later spread more slowly to the sides. A dam break is often developed with surprisingly steep sides and even though major variations exist depending on the size of the reservoir etc., in the final stage the width of the opening at the toe is often one to two times the height. A study on this subject was presented at HydroPower '97 in Trondheim [9].

As regards the actual sequence of the dam break, i.e. how the opening widens in the vertical and horizontal axes with time, several established computer programs are available, for

example BREACH. A careful calculation of this development may sometimes be necessary, for example, for objects at risk in the vicinity of the dam. It is deemed possible to develop a more physically correct description of the development time, size and form of a dam break. A careful evaluation of the program would be of interest. However, these questions have not been studied in any greater detail within the framework of this report series. Continued work is planned to be carried out jointly by the Swedish hydropower industry via Elforsk AB.

3.6.2. Flood wave calculations

When it comes to the impact of a particular dam break, in the past investigations of an advanced and less advanced nature have been performed for a number of dams. However, the potential for advanced calculations has rapidly improved with time as a result, among other things, of advances in computer technology. The consequences of extreme floods in a river valley have in the past not normally been studied. One of the activities of this report series has been to look at existing methods to calculate how the water released by a dambreak will propagate down by the river valley and also to analyse the consequences along a river in which the extreme runoff is assumed to flow unmitigated past the dams.

In general, it can be stated that for reservoirs with a large area and volume, the development time for a dam break is of little importance to the flood wave. On the other hand, the size of the failure opening is of great importance. In the case of high dams with small reservoirs, as regards both area and volume, the development time of the dam failure is of great importance. The importance of the various dam break parameters decreases, however, with increasing distance from the dam.

3.6.3. Impact calculations

When analysing the impact of a dam break, the break sequence and the hydrograph, which is a consequence of the dam break sequence are used as input values for the continued calculation of how the flood wave will propagate down the river. When calculating the impact, a physically correct mathematical model is needed in order to describe the unsteady flow condition in a dam break wave. A study has been made on this subject, which is presented in report 18, "Methods for dam break calculations":

A limiting factor for accuracy when calculating the impact of a dam failure is the topographic maps available, usually with a 5 m contour interval. The accuracy could be improved by a systematic collection of calibration data during high floods and by improved and more accurate maps with a 1 m contour interval in narrow river reaches. Improving maps along a whole river is prohibitively expensive. Mainly one-dimensional mathematical models for flood wave calculations are used, for example DAMBRK and Mike 11. Two-dimensional dam break models or hydraulic model studies could be useful in very restricted areas, for example downstream from a dam and where detailed and accurate results are needed.

The mathematical models utilising dynamic routing methods used today all suffer more or less from stability problems when calculating flow conditions near critical flow. The elimination of such problems would lead to lower dam break calculation costs in the future. A substantial part of the total cost of dam break calculations



Figure 3.9. During the rainy autumn of 1985, the groundwater level in Dalarna had risen to above the normal level. When this was later followed by a particularly heavy and long-lasting rainstorm, and at the same time one of the spillways in the Noppikoski Dam failed to open, the earthfill dam was overtopped with a resulting dam failure. This caused the 1 Mm³ reservoir to be emptied in less than an hour. The flood wave caused damage over an area along 20–30 km of the river.

consists of problems to get the mathematical model to work in difficult reaches, and in evaluating the correctness of the results. A dynamic routing model with numerical stability also for near critical flow calculations will make an interactive simulation model possible, which the average PC user could utilise in making new dam break calculations as well as simulations of extreme floods.

There are a number of methods available for calculating how dam breaks develop and for determining how the released flood wave propagates downstream from the dam. The report describes the various methods and their advantages and disadvantages. A correctly performed calculation with realistic assumptions for the dam failure is invaluable when planning for emergency preparedness and during emergency training, etc. but may also be of value in connection with the consequence classification of the dam.

3.6.4 Floating debris in dams

The Committee specifies that only spillway arrangements that can be used with full safety can be included in the discharge capacity. Floating debris could block a spillway or reduce the flow, and a study on this subject has therefore been carried out, which is presented in report 6, "Floating debris in dams":

In Sweden floating debris has not been considered to be a threat to dam safety under the usual annual high flood conditions. But under extreme high flow conditions we



Figure 3.10. Where the slopes are very steep, debris may be formed during highwater flows or heavy rains (Canada).

have to consider floating debris in the rivers, such as trees. The experience from Norway and other countries and also from local high floods in smaller watersheds in Sweden indicates that floating debris could be a danger to dam safety.

In the major rivers in Sweden, gated overflow spillways are the most common type of outlet structures. Hydraulic model tests with respect to floating debris have been performed with this type of outlet. The model tests have been performed in two hydraulic models originally built for other purposes.



Figure 3.11. Test with floating debris (Canada).

Model I has three dams separated by two islands. One of the dams has six gated spillways. Tests have been performed for this dam both with only one spillway open and with all six spillways open. The inflows to the spillways are straight and the water is shallow upstream of the dam. The second dam has eight gated spillways. The inflows to the spillways are not straight and the water upstream of the dam is deeper than in the dam first mentioned. Tests have only been performed with one spillway open, the spillway located furthest downstream which has the most inclined inflow conditions.

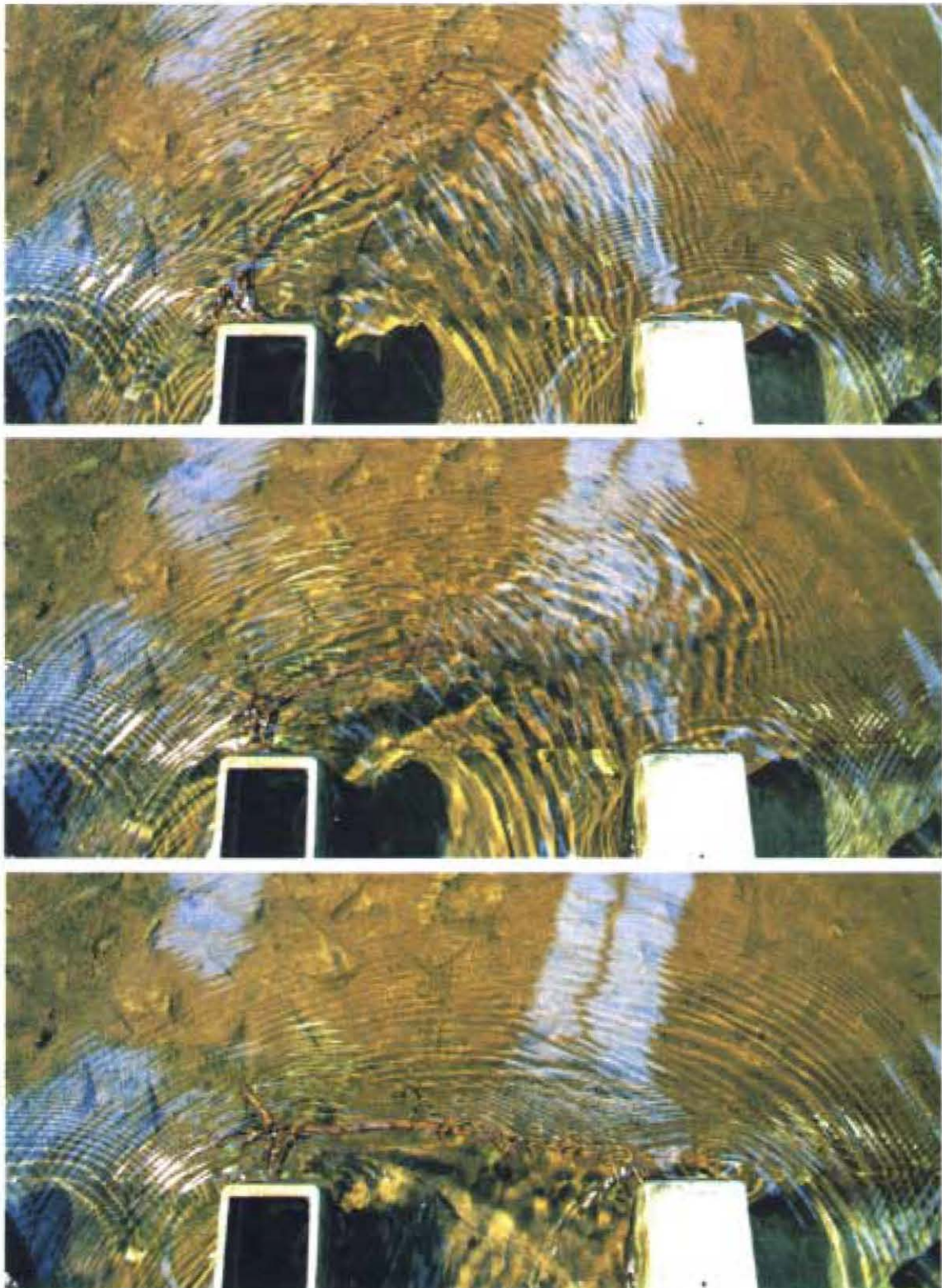


Figure 3.12, Behaviour of floating debris in front of a group of open spillways. A long tree immediately in front of a column continues towards the column, pivots at the point of contact and becomes jammed across the spillway.

Model II has one gated spillway. The inflow to the spillway is straight and the water deeper compared to the other dams.

Small pine and spruce plants were used as model trees. The root diameter is about 16% of the trees' length, a measure found in the Norwegian study. Pine and spruce are the most common trees in Sweden. To describe the flow conditions and the length of the tree in relation to the spillway the dimensionless parameters H/B and L/B are used.

The results from the model tests have increased the understanding of the behaviour of floating debris and pointed out important factors for allowing debris to pass through a spillway opening in a dam. The tests show that one such spillway usually will allow a single tree to pass with a length twice the width of the gate – the tree will turn to the direction of the flow and pass the spillway without any problems. When two trees entangled with one another approach the same spillway opening they do not pass so easily. One tree can turn in the direction of the flow but on account of the other tree being turned across the pillars. The model tests also showed that with many spillways next to each other, the water flow would not turn the single tree along the flow direction as well as with only one spillway (see fig. 3.12). The tests also revealed the importance of a good spillway design; small details can improve the capacity for floating debris.

In the smaller rivers and especially in plants constructed long ago, the dimensions of the spillways are small. Usually there are lever gates with support beams at a distance of 1 m in these plants and it is here that the problems with floating debris have occurred in Sweden and also can be expected in future. At high-hazard dams, the spillway gates are seldom of this kind.

Steps against debris in order to avoid problems can vary:

1. Make an inventory of the area upstream in order to find possible sources of debris.



Figure 3.13. Collecting or retaining floating debris with the aid of log booms in Canada.

2. A management plan for the area is determined where e.g. trees higher than 1.5 times the spillway opening are taken down, erosion protection is performed etc.
3. Log booms to retain or lead the debris to a suitable spillway. (See fig. 3.13)
4. New spillways with an improved design in order to minimise the risk for debris jam.
5. Preparations for clearing the spillways from debris jams by using machines, blasting etc.
6. Improve the design of old spillways to increase the probability of trouble-free passage of debris.

A combination of these steps could be the best solution. One must look upon the whole river system and be aware that a solution of debris problems at one dam may affect a dam downstream.

An example of problems in connection with floating debris, which it was possible to solve by active measures, is the event that took place during heavy flooding at Whitsun 1995 in the river Vrångsälven. It is normally a fairly unremarkable watercourse with a flow of approximately 8 m³/s, which rises somewhere inside Norway. Bengt-Olof Sundell of Gullspång Kraft AB has described the event:

On the Norwegian side, close to the river Vrångsälven, lies Lake Vingersjön, which normally drains into the river Glomma, and then there are no problems. On the other hand, we can sometimes be faced with fairly difficult situations when the water is running high because when the water level in Glomma rises to a certain level, the water flows into Vingersjön, which in turn rises and drains into the river Vrångsälven, that is towards the Swedish side.



Figure 3.14. Floating debris of a smaller size during a high flood.



Figure 3.15. After several days of high floods, trees remain standing along the banks of the river despite the high water level.

On this occasion, when we realised an extremely high flood was to be expected we started to make protective dykes at critical points along the watercourse. The river was also checked upstream all the way up to the town Kongsvinger in Norway. During this check it was discovered that a lot of floating debris was being carried down by the river and it was decided that steps should be taken to clear the river channel where it was

becoming clogged by trees and other debris that was being swept downstream. Particularly sensitive objects were spillways, bridges and other structures on and in the river. In order to acquire flexibility and capacity in this work, a mobile crane with a grab claw was leased and put to work. The results were good and it proved to be a rational way of keeping spillways and other critical passages clear. The clearing operations were probably decisive in being able to cope with and master the powerful flow, which at its peak was running at 80 m³/s.

There are also examples of how large trees and islands of floating peat have been removed by boat or helicopter in heavy flooding situations.

The report describes the problem of floating debris and a number of possible solutions. It states that in normally high flood conditions (with a return time of 40 or 50 years) floating debris has not posed a safety problem for dams of Consequence Class I or II, but at the same time it is emphasised that the spillways must function as planned even at higher floods (from a 50 year return time up to the design flood as per the Committee's guidelines) without being blocked by floating debris. It should be noted that even if the questions related to floating debris are very important for Consequence Class I dams according to the Committee's definition, they should also be considered for Consequence Class II dams, partly because the safety of these dams shall be able to withstand a 100-year flood and partly because the collapse of a Class II dam could lead to the concentrated release of a large quantity of floating debris which can often constitute an additional risk to downstream dams. The report also recommends continued development work within the area.

Questions related to floating debris are important and should be given special consideration in the continued work involved in adapting dams to the Committee's guidelines and in the work on common guidelines for dam safety. Inventories should also be made of sources of floating debris.

4. INVESTIGATIONS CONCERNING EMBANKMENT DAMS

4.1. General

River dimensioning is usually based on existing data concerning the power stations or regulation dams, and includes information on the level of the impervious core and discharge capacities of the spillways. It is, of course, very important for this information to be correct and that the dams meet the requirements for dimensioning in other respects. Checks must therefore be carried out by carefully analysing each dam. This checking should also cover the dam foundations. It should be carried out before the selected solution is finally determined since it would otherwise be possible at a later stage, once the measures have been carried out, to find that the preconditions are not met and that the solution adopted cannot be implemented or can only be implemented at a significantly higher cost. In addition, sensitivity analyses should be performed so that information is available on what factors have a particularly strong impact on the course of events.

Checks of the kind outlined above should be made not only in connection with the new design flood but also concerning dam safety requirements in general. This applies in particular, of course, to embankment dams of Consequence Class I but also to dams of Consequence Class II.

A review is given below of factors that should be given particular attention.

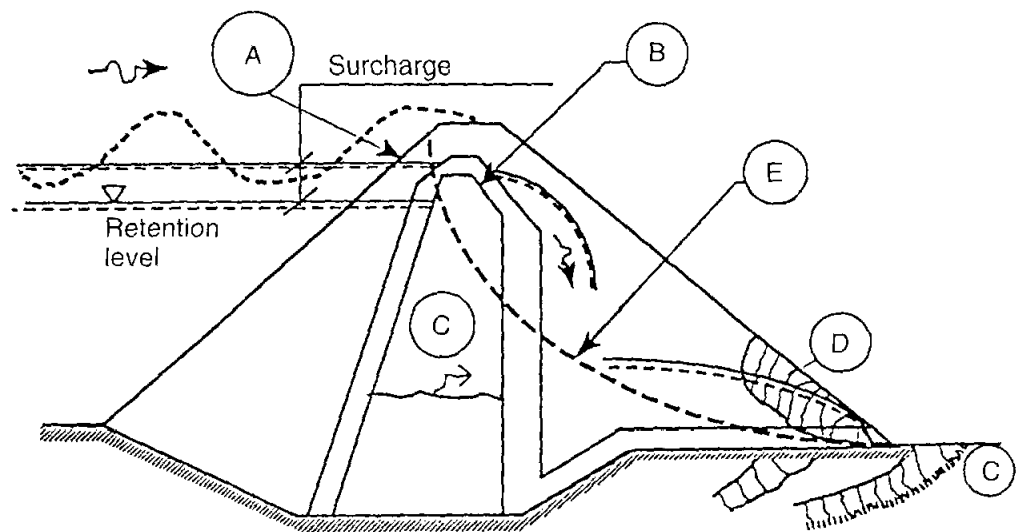
4.2. Flood surcharge capacity of embankment dams

In those cases where the discharge capacity at the retention water level is lower than the design flood, the Committee's guidelines permit that temporary flood surcharge, i.e. filling to a water level higher than the prescribed retention water level, may be employed in extreme cases in order to prevent dam failures in downstream dams. However, such flood surcharge may not be carried out so that the safety of the operator's own dam is jeopardised. A survey has been carried out to clarify under which conditions a flood surcharge may be employed. The study is presented in report I5, "Flood surcharge capacity of embankment dams":

The following critical points, common to most of the plants, may determine the maximum allowable water level (see fig. 4.1):

- The effect of waves.
- Internal erosion in the body of the dam or the foundation.
- Seepage/leakage and erosion in the crest of the dam.
- Erosion at the toe of the dam.
- The stability of the downstream slope.

The report deals with each of the above points in turn. Examples regarding estimations of erosion resistance at the dam toe are also presented. Finally, the report presents examples of reinforcement measures, which may be necessary in order to secure the dam for a flood surcharge – a water level above the normal retention level.



- A) Surface erosion in the upstream slope of the dam and the crest
- B) Leakage and internal erosion in the crest of the dam
- C) Internal erosion in the body of the dam or its foundation
- D) Erosion at the toe of the dam
- E) Stability of the downstream slope

Figure 4.1.

Experience from studying existing dams shows that in many cases there are other factors which also have an influence on the required freeboard and the possibilities to allow a flood surcharge. These critical points and loading conditions are unique for each individual plant and depend on the design and condition of the dam in question. The following are examples of such factors:

- The erosion protection, the level of the crest of the dam and/or the zoning of the dam may not have been constructed as shown on the construction drawings, and in many cases “as built”-drawings are not available.
- The design wind at the retention water level may require a larger freeboard than the wind at the flood surcharge level according to the new Swedish guidelines.
- Existing weaknesses, e.g. unexpected high seepage already at the normal retention level, may require investigation and possibly remedial measures before additional loads from water levels above the normal retention water level can be considered.

The above experience shows that an in-depth knowledge of the dam is required before the maximum allowable water level for flood surcharge can be determined. This may result in an extensive search in archives. Field investigations will also be necessary in many cases to determine how the dam really was constructed and the characteristics of the different materials in the crest of the dam. As further help, the approach described has been applied at two specific dams.

4.3. The effect of waves

When designing new dams, as well as during review of the design of existing ones, consideration must be given to wave effects. The effect of waves on the upstream slopes of a dam depends on their size, direction and duration as well as on the capacity of the dam to withstand them. Whether or not overflowing occurs depends on the size of the waves and on the level of the water, as well as on the freeboard of the dam. The effect that overtopping waves have on the dam depends on the resistance and size of the dam, and the number of waves that wash over the dam crest. An accurate calculation of the wave size is therefore an important stage in the work to make the dams comply with the guidelines.

Waves are calculated as a significant wave height, on the basis of which a design wave height can be determined. This differs in the determination of erosion protection and of wash-up height. During calculation, consideration must be given to the wind set-up of the reservoir. The Committee's guidelines specify which wind is to be used in combination with the design flood. In addition, the dam shall also be designed for the case of water at the retention water level combined with a higher wind (a wind with a longer return time).

A number of methods are available for determining the significant wave height, and a study has been carried out to decide which one is most suitable for Swedish conditions. Furthermore, a study has been made of how the upstream slopes of embankment dams should be designed and a study of the capacity of embankment dams to withstand overflow.

These reports are presented below.

4.4. Waves in hydropower reservoirs

The studies concerning methods of calculating effective strike length and significant wave height are presented in report 10, "Waves in hydropower reservoirs":

The calculation of wave heights in reservoirs with limited width and length is often made according to a method stated by Saville (1962) which, for example, is used in Sweden. An alternative method recommended by the United States Bureau of Reclamation, USBR (1992) results in 20 – 30% higher waves at wind velocities and fetches of practical interest in Sweden than what is obtained with Saville's method. A background investigation shows that Saville's method is based on wave and wind measurements in reservoirs with approximately the same dimensions (length = 5–15 km and width = 1–3 km) as many Swedish hydropower reservoirs. However, the method recommended by USBR is based on measurements in larger reservoirs. Therefore, it is suggested that wave heights in reservoirs with dimensions as above be calculated according to Saville's method. In larger reservoirs it is possible that this method underestimates the wave height.

The selection of design wind is often based on wind records from other sites. A transformation of these data to the reservoir in question can be performed by using a statistical model, if there are registered wind measurements covering at least a few storms.

Accurate calculation of wave height is important from the point of view of dam safety since it is often a controlling factor in dimensioning the dam's freeboard.

4.5. Erosion protection of upstream shoulders of embankment dams

An important factor in connection with dam safety is the stability of erosion protection used in earth or rockfill dams. A study on this subject is presented in report 11, “Erosion protection of upstream shoulders of embankment dams”:

All of the 1980s and the first part of the 1990s has been characterised by efforts to improve dam safety. The stability of the erosion protection layer on the upstream slope of an embankment dam is an important factor for this safety.

In 1988, Vattenfall published a manual called “Earth and rockfill embankment dams” [3] containing guidelines for the design of erosion protection at embankment dams. Before that the design followed guidelines used in coastal and harbour engineering.

If adjustments have been required and performed according to the new Swedish guidelines on design flood [1] the need may arise to allow the water level in the reservoir to rise above the retention level. As a consequence the erosion protection layer on the upstream slope has to be increased and reinforced (see fig. 4.3, 4.4, 4.5).

The report describes how to design stable protection layers while taking into account the design values for wave height and wave run-up. The design values for wave height and wave run-up are derived from values for wind velocity, effective fetch and significant wave height. When dimensioning, different values are suggested regarding wind velocity depending partly on the geographical location of the dam and partly on the purpose of the calculations, i.e. whether it is the size of the stones or boulders in the protection layer or the freeboard of the dam that is to be decided.

The methodology used for calculating the effective fetch and significant wave height has been dealt with separately by the Royal Institute of Technology in Stockholm in report 10 in this report series.

A comparison shows that the guidelines for design of erosion protection layers according to Vattenfall’s manual “Earth and rockfill embankment dams” concur with the guidelines in the Norwegian “Regulations for dams”.

A design with two layers of long and narrow stones with the longest axis perpendicular to the upstream surface and with the rockfill arranged in a stable fitting of stones is an example of an excellent type of erosion protection layer. This method has especially been used on dams in Norway.

There is a great deal of experience in Norway of embankment dams located on a high level, which are extremely exposed to high wave forces. Furthermore Norwegian dams are constructed with steep slopes, often 1 vertical to 1.5 horizontal, which increases the risk of damage by erosion. Since 1 January 1981 “Regulations for dams” is valid in Norway for the design and construction of erosion protection on embankment dams. In Norway erosion protection layers on dams have successfully been constructed, reconstructed and reconditioned according to the regulations over a period of 20 years.

Experience shows that a review needs to be made of the erosion protection on existing dams. Consequently, a review of this type is recommended regarding both design and current status. In addition, there could be a need for continued development work, for example the development of methods to strengthen existing erosion protection at dams where suitable stone blocks, which includes their durability, are not available.



Figure 4.2. Damaged erosion protection on the upstream shoulder.



Figure 4.3. Laying boulders with an excavator for the upstream erosion protection at a rock-fill dam.

4.6. The capacity of embankment dams to resist overtopping waves

The capacity of an embankment dam to withstand design waves depends on the freeboard as well as on how the dam can cope with individual waves that wash over the crest of the dam. As can be seen from above, calculations relating to compliance with the Committee's



Figure 4.4. Provision of erosion protection with a surface layer of carefully arranged narrow and flat-sided boulders.



Figure 4.5. Erosion protection with a surface layer of randomly-laid boulders.

guidelines for dams of Consequence Class I are carried out both with the water level at the retention water level and at possible flood surcharge level. In both cases, the level increases with a possible wind set-up of the reservoir water level. The study is presented in report 12, “The capacity of embankment dams to resist overtopping waves”:

This study has been made in order to clarify what is required of the fill in the crest and also in the downstream slope and toe of zoned earth fill dams in order to resist erosion due to overtopping waves. Consequently, the purpose of the study is also to give an indication of how the fill material in the crest and shoulders affects the need for freeboard.

A basis for the assessment of necessary minimum freeboard is obtained by calculating the water flow over the dam crest due to overtopping waves, the ability of the dam crest to resist wave erosion and also the stability of the downstream slope and toe against the pressure of overtopping waves.

A review of theoretical methods for the calculation of flow over the crest of earthfill dams due to overtopping waves shows that the unreliability of the results from such calculations is significant. The method that is proposed for such calculations is assumed to provide information about the magnitude of the flow. The flow increases rapidly with the size of the attacking waves. Therefore, the accuracy of the results depends on correct estimations of the wave size.

The method mentioned in the report regarding stone design in dam crests in order to resist erosion by overtopping waves can be used for rough estimates. However, the results of the calculations are unreliable.

If the dam shoulder fill is permeable, there will be a gradual reduction of the surface flow on the downstream slope of the dam due to overtopping waves. This should mean that with the same fill material, the crest or the downstream toe will erode before the surface material in the downstream shoulder. However, if the shoulder is made up of more fine-grained material, e.g. sand or sandy gravel, pore pressures may develop in the downstream slope, which will result in insufficient stability with regard to slides. Repeated overtopping of the crest can therefore not be permitted if the shoulder fill is constructed of such material.

If the shoulder fill is permeable, the water which has flowed over and through the crest and core of a dam will be led into the fill and then flow out at some low part of the dam toe, thus forming a water spring. Here, the flow rate depends on how the topography of the terrain leads the water. A mathematical relation is proposed for the assessment of necessary stone size in order to prevent erosion of the downstream toe.

With the purpose of demonstrating how much water can be conveyed due to overtopping waves, and the consequential demand for proper stone size, numerical examples based on the characteristics of a typical zoned earth or rockfill dam are included in the report. The freeboard of the dam has been assumed to be 2.0 m and 3.0 m, respectively. For the wave predictions an effective fetch of 5 km has been assumed.

The results of the numerical examples indicate that there may be margins in the freeboard of existing zoned fill dams, provided that the crest and downstream shoulder have been constructed from erosion-resistant materials.

Further investigations comprising the verification of numerical computer aided simulations are proposed to be carried out with the purpose of preparing guidelines for freeboard design of dams made of various materials.

In the case of dams that have a poor capacity to withstand even individual overtopping waves and inadequate freeboard, reinforcement measures may be needed or some form of protection (for example a concrete barrier) may have to be constructed against wave overtopping (see fig. 4.6).



Figure 4.6. Wave protection (parapet) to avoid overtopping of the dam crest.

4.7. Effects of a flood surcharge

A flood surcharge is a way of mitigating a flow and also to increase the discharge capacity of the spillway. A surcharge may also be the result of the faulty function of, for example, spillway gates. It is therefore important to know the level to which a surcharge can be allowed without erosion starting at the top of the impervious core or in the overlying filter material. Studies have thus been carried out concerning the function of the filter in connection with overflowing of the core and of the stability of rockfill dams during overtopping of the dam.

4.8. Erosion in the crest of the impervious core

The initial intention of this study was to describe the risks of erosion in the crest of the impervious core if the water level were to rise so high that there was a flow of water in the filter above the core (overflowing of the core). The study was subsequently extended to include a more general overview, analysis and review of established criteria for reliable filter function with respect to broadly graded base material such as moraine for flow parallel with but also at right angles to the interface between base material and filter. The study is presented in report 14, "Geomechanical filters and erosion in the crest of impervious core".

The report contains a selected review of theoretical and experimental investigations in the field of granular or geomechanical filters and filtration phenomena. Part of the purpose has been to distinguish between and provide appropriate design criteria for different types of filter situations with regard to degree of stability, type of hydraulic load, gradation and effects of cohesion. Consequently, a distinction is made between flow parallel and normal to the contact surface between the base (the erodible soil) and filter material, cohesive and friction material, horizontal and vertical filter surfaces and geometrical and hydraulic filter criteria.

A geometrical filter criterion ensures that the base material is stable after an initial, small amount of volume loss irrespective of the hydraulic load applied on the filter cake. Sherard (1984) found that the equality $D_{15}/d_{85} = 9$ corresponds to the geometrical filter criterion if the flow is perpendicular to the base/filter interface. For cohesive base soils, the critical grain size ratio can be as high as 60. On the other hand, if the flow is parallel to the base/filter interface, erosion is not prevented to the same extent by mechanical clogging. Hence, for friction materials the grain size ratio appears to be somewhere in the range of 6 to 8.

For economical or practical reasons, hydraulic filter design may be utilised. This method implies that the geometrical filter criterion is not satisfied and, as compensation for this simplification, the choice of base and filter material is related to the design hydraulic load. Since the base material in such a case is subjected to a small but finite erosion rate, the destabilising effect should be considered in the whole life span of the structure. However, successive clogging of transported base grains, in variable degree, leads to a decay in erosion with time which is a significant factor to the capability of the hydraulic filter. Accordingly, the current investigation includes laboratory experiments on filter development of widely graded base soils with flow parallel to a horizontal interface. This problem is concurrent with the erosion process induced by flow over the moraine core in a rockfill dam and erosion in canal bottoms provided with hydraulic filter material.

On the basis of a known grain size distribution curve for the base soil, the surface area of the base soil that is exposed to flow and available to erosion can be described as a function of the filter development and indirectly to the erosion depth in the base soil. The available area declines with continuing erosion and thereby with continuing filter development. In the evaluation of the experimental results, the statistical relationship between a dimensionless parameter representing the transport rate, the available area and another dimensionless parameter representing the hydraulic load was determined from multiple linear regression. Both dimensionless parameters were derived from

physical principles. The transport relationship is verified by the experimental results within the ranges:

$$1.11 < d_{100}/d_{85} < 4.43 ; \quad 0 < x/d_{85} < 30; \quad 0 < J < 40$$

and

$$d_{85}/D_{15}=0.084$$

The proposed relationship can be used to describe the erosion process induced by water overtopping the core in an earthfill dam as was done by Wörman & Skoglund (1992).

One conclusion that can be drawn is that a filter can function even if the filter criteria are not entirely met, but the fact cannot be ignored that material migration will take place in the long term. It should, however, be noted that the study primarily concerns flows parallel to the base material. During a high flood situation, a short-term overflowing of the core is more likely to occur and the report indicates that in certain circumstances this may be accepted.

4.9. The stability of rockfill dams during overflowing of the core

An investigation has been made of the behaviour of rockfill dams during increased leakage and during overflowing of the core, the filter, the transitional layer or the rockfill. The study is presented in report 17, “The stability of rockfill dams during overflowing of the core”:

Rock-fill dams in Norway and Sweden are generally of similar design – a core of moraine, protected against erosion by surrounding sand filters downstream as well as upstream. Outside the sand filter there is a transitional layer with somewhat coarser materials and then rockfill, usually consisting of stone without any special demands on assortment. In principle, each layer should function as a filter to the next layer.

A certain amount of water always seeps through the core. A sudden increase in this seepage (without any connection to variations in the reservoir level) may be a sign of an unstable core. If the seepage water is muddy it contains suspended material which probably originates from the core. This indicates a possible on-going material transportation from the core, which has to be carefully monitored by those responsible for the dam. In this situation, among others, it is very useful to know what seepage the dam can withstand from a stability point of view with regard to damage to the dam toe and in the rockfill downstream.

Another situation, of particular interest in connection with the reviewing of dams brought about by the new Swedish guidelines on design flood, is when water flows over the core and into the downstream fill. Hypothetically, this can occur at very high flows, if the spillways are blocked or after a dam failure upstream. The report discusses different scenarios due to water flowing over the top of the core, the filter, the transitional layer or the rockfill, and also shows how calculations can be performed. Furthermore, the report shows how to calculate the stability of the crest, the stones at the dam toe as well as the rockfill and also to what level the water in the reservoir can rise before causing a dam failure.

Important factors for the ability of a rock fill dam to withstand water flowing through as well as over its structure are the size of stones at the toe of the dam and in the rock fill, and also the water level downstream. During an overflow, the flow of water in the filter is usually considered to be insignificant, and it is therefore important to carefully establish the true level of the filter along the dam. During analysis, consideration must be given to all the conditions affecting the dam in question, such as how the water flows sideways.

One way of improving the stability of a dam in connection with water flowing over and through the structure is to construct a retaining embankment with large stones at the toe of the dam and in the lower section of the supporting fill.

There is a need for continued development work in connection with the simulation of the flow in the downstream fill, whereby the opportunity also exists to make comparisons with the experiments being carried out by BC Hydro in Canada in connection with the drainage capacity of rockfill.

It should be mentioned that, with respect to rockfill dams founded directly on bedrock, there are no known cases of a dam failure occurring as a result of internal erosion.

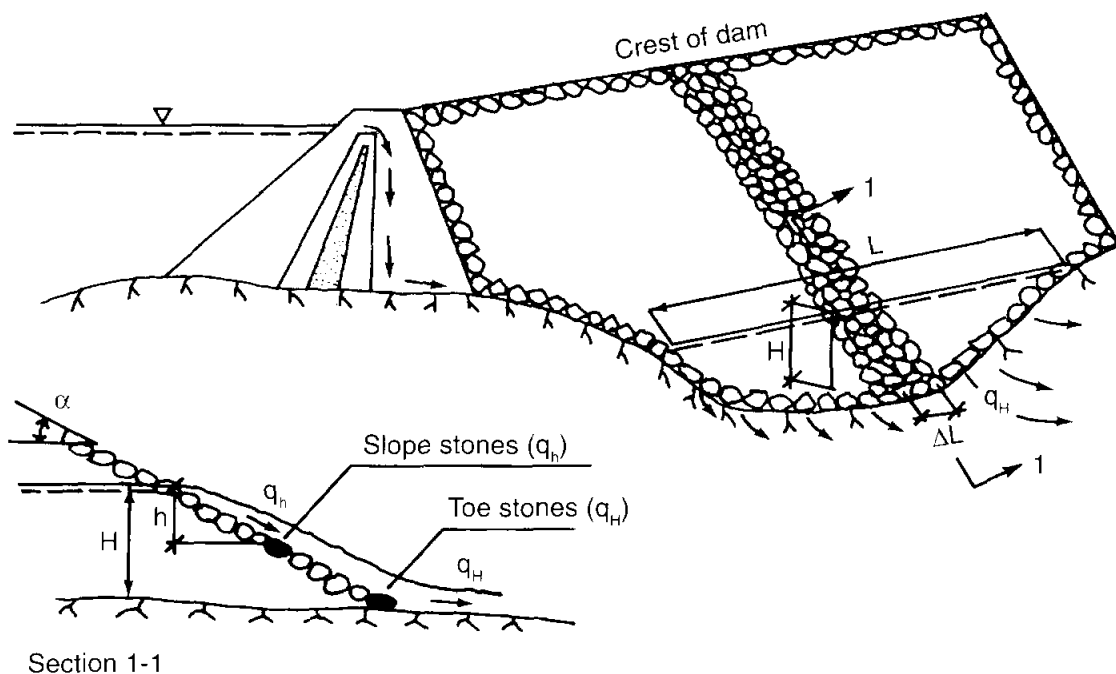


Figure 4.7. Rockfill dam during overflowing of the core.

4.10. Filters in embankment dams

During a flood surcharge, an embankment dam is subjected to greater loads than under normal conditions, and it is therefore important for the dam to have adequate safety margins to withstand this additional load without failing. One advantage in this context is the fact that a flood surcharge can only continue for a limited period of time. The velocity at which the surcharge takes place is also important in the assessment since a slow rise in the water level is more advantageous than a rapid rise.

The impervious core is naturally of decisive importance to the function of the dam, but impervious cores are in turn dependent on there being sufficiently effective filters. The upstream filter can be said to have the function of preventing material from being transported out from the impervious core into the reservoir and, when necessary, providing the impervious core with replacement material, for example if fines for some reason have moved from the impervious core. The principal task of the downstream filter is to prevent the transportation of fines from the impervious core.

The downstream filter can therefore be extremely important to the function of the dam during a surcharge. A poor quality downstream filter may involve a risk of the impervious core having already lost fines, and therefore having an impaired function, and a risk that the increased water pressure during a flood surcharge will initiate the washing out of fines.

In view of what is stated above, an inventory has been made of the downstream filters in Swedish embankment dams as well as an analysis of how much importance can be attributed to the results of the inventory with regard to the function of the dam. The inventory of the grain size distribution in the downstream filters of embankment dams and the analysis are presented report 13, "Filters – inventory and functional analysis":

An inventory of grain size distribution of the downstream filters in earth and rockfill dams constructed after 1950 has been produced through studies of the VBB Anläggning and Vattenfall archives. Most of the data has been collected when testing filters in connection with construction, but in some cases there is also data from subsequent tests carried out in connection with investigations of observed deterioration.

Changes in the filter regulations since the first specifications were introduced, following Terzaghi's studies in the 1940s, have been reviewed. The regulations described in Vattenfall's "Earth Dam Manual" of 1958 (*in Swedish*) were applied during the principal construction period of Swedish dams. However, there were some uncertainties in the regulations and no instructions on the maximum grain size for the filter materials were included. This led to significant variations in the particle size distribution of the filters and in many cases the filters were allowed to have an unspecified, relatively large, content of cobbles.

The current specifications for the design of filters are presented in the handbook "Earth and Rockfill Dams", Vattenfall 1988 [3]. In general, impermeable cores of moraine now require finer filters than specified in the previous regulations. A limit for the maximum grain size of the filter material is also specified in order to avoid large accumulations of cobbles in connection with construction.

The inventory comprises data on the particle size distribution of downstream filters in a total of 44 earth and rockfill dams. The results show that at most of the plants the particle size distribution D_{15} does not comply with the current filter criteria. At some of the dams it can also be observed that the maximum grain size for the filter material exceeds 60 mm, which is the upper limit in the current specifications. However, many dams have records that do not contain any data on maximum grain size.

This study has not included any systematic review of which dams have experienced problems such as seepage or sink holes. However, the inventory does indicate that



Figure 4.8. Erosion channel at toe of sheet piling (above) and sinkhole in crest of dam (below).

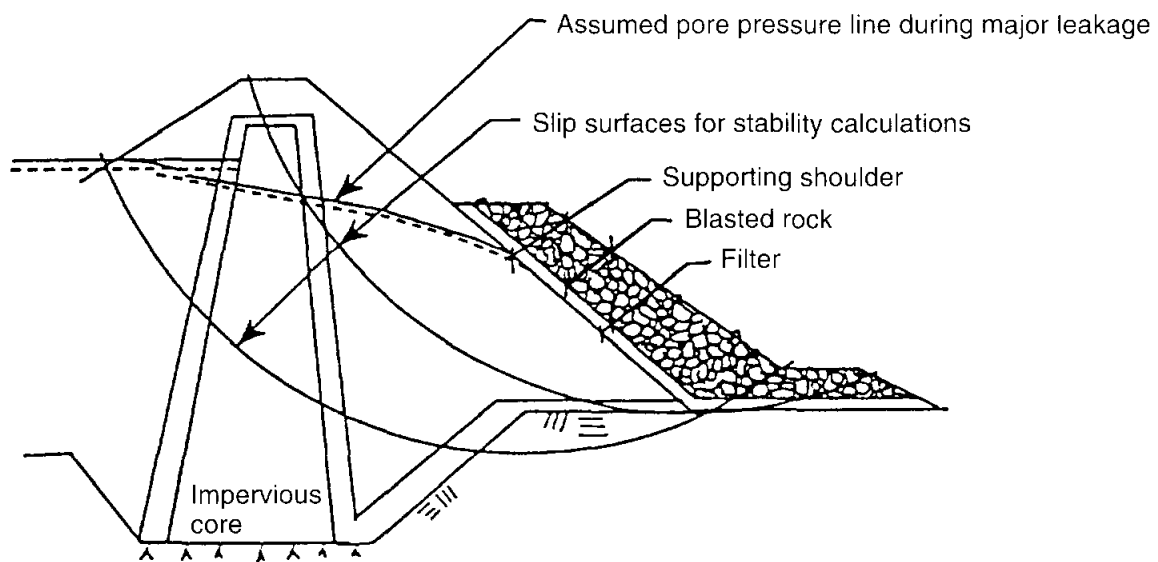


Figure 4.9. Reinforcement of downstream shoulder and toe with a retaining bank.

dams where such damage has occurred have downstream filters, which are among the coarsest of those listed (see fig. 4.8). There is also information from the examination of some dams with such damage, that the filters had both a generally coarse level of large D_{15} and a large content of cobbles, leading to separation with accumulations of cobbles.

In those cases where the requirements made in the new filter regulations are not met, greater attention should be given during scheduled and routine inspections to detecting the onset of internal erosion or seepage at an early stage. In addition, increased instrumentation can in many cases be recommended – in the first instance for seepage measurement. For embankment dams in which the stability is not secured in connection with major seepage, reinforcement of the dam toe or the construction of a retaining bank of riprap on the downstream side of the dam may be considered in order to increase stability. (See fig. 4.9)

It should be pointed out that the quality of the filter is very important also at normal water levels.

Experience also shows that restrictions should be applied in addition to those specified in Vattenfall's manual from 1988.

4.11. Ageing of embankment dams

When analysing the capacity of embankment dams to withstand new loads, it is of course important to consider the changes that may have taken place since the dam was built which may be attributable to age. This applies to the dam as a whole, but since changes in the shoulders are easier to discover during inspections, etc. it is largely changes in the impervious core and filters that are of particular interest since changes here are difficult to detect. Ageing is defined as the kind of changes that have a negative effect on dam safety and which occur more than 5 years after the dam was completed.

Consequently, these questions have been investigated in a study by means of an inventory, which was carried out by sending a questionnaire to those people responsible for the safety of dams higher than 15 m and to those who are members of the Swedish Power Association. Subsequently, a compilation was made of all the answers received, which were then analysed. An inventory and analysis of changes due to age are presented in report 16, "Ageing of embankment dams":

The effects of ageing on Swedish earth and rockfill dams have been studied by compiling the answers to an inquiry sent to owners of dams higher than 15 m.

In Sweden there are 119 earth and rockfill dams higher than 15 m. However, if deterioration was observed in lower dams, this information was also collected and included in the result.

The result of the inventory show that a total of 84 earth and rockfill dams, of which 68 were higher than 15 m, had experienced some kind of ageing. The degree of deterioration varied to a great extent. In some cases erosion had been observed in riprap protection on the upstream slope of the dam. These types of deterioration have little, if any, influence upon the safety of the dam.

The ageing cases were grouped into 13 different types. Surface erosion was found to be the most common type of deterioration. After that came sinkholes at the crest or shoulders of the dam. Sinkholes were in many cases reported to occur in combination with other types of ageing, e.g. seepage in the foundation or in the dam body.

Internal erosion is, according to statistics reported by ICOLD, the cause of a large portion of the total number of failures in earth and rock-fill dams. Internal erosion is linked to the cases of sinkholes and seepage reported in the inventory. Attention should be drawn to these types of deterioration, since these in some cases could seriously affect the safety of the dams in question. The amount of seepage and the erosion resistance of the materials involved are factors that affect the development of a possible failure.

The deterioration cases were almost all detected by "direct observations" in connection with planned inspections by operators or engineers. Thus, the surveillance of the dams is very important from a dam safety point of view. However, additional instrumentation should be considered in order to discover the ageing at an earlier stage. As a first step more dams should have a system installed for continuous seepage measurements.

Finally, the necessity of research regarding the ageing of embankment dams is discussed. It is proposed that the ageing phenomenon, which is difficult to detect, should be studied in order to reach a better understanding as well as obtaining appropriate methods for detection. Details from where the problems have occurred, e.g. the quality of the downstream filters in existing dams, especially in the vicinity of concrete structures, should be studied.

The report confirms that with time, certain changes take place that may be of importance to dam safety, which means that in general it is important to consider changes in embankment dams and in particular in connection with investigations into the capacity of a dam to withstand a flood surcharge. It is also stated that the inspections by operators and engineers are important for the detection of damage and that increased instrumentation can in many cases be recommended.

5. INVESTIGATIONS CONCERNING CONCRETE DAMS

5.1. General

Concrete dams, like embankment dams, shall be checked to ensure that they can withstand the loads that are imposed on them with the particular river dimensioning solution chosen. To begin with, it is often assumed in the dimensioning work that concrete dams will be able to cope with both a flood surcharge and overtopping, and that new spillways are therefore unnecessary. The calculations are often intended to determine the water level that may occur. This is often true, but not always, so a check calculation and status assessment must naturally be made in each individual case, and in some cases it may also be important to check the function of these dams under normal condition. Consideration may in particular need to be given to the ageing phenomenon, e.g. with respect to the corrosion of anchorings, both prestressed and not prestressed. There is also good reason to make a review of the original calculation and assumptions. The dam foundations should also be checked.

5.2. The capacity of concrete dams to withstand overtopping

A study has been made to determine if, and under what conditions, it is possible to handle design floods according to the Committee's guidelines by allowing temporary flood surcharge or even overflowing of concrete dams. The study on these issues is presented in report 19, "The capacity of concrete dams to withstand overtopping":

The study shows that it is impossible to give a simple general answer. It is necessary to perform new and more thorough examinations before it can be decided whether it is advantageous to overtop the concrete dam or to build more spillways.

Some of the examinations concern the connection to the existing embankment dam. This very sensitive area must be given particular attention, since it easily erodes without the necessary precautions.

Questions regarding what happens to an embankment dam when the water level reaches above maximum retention water level are reported in a separate project (report 15).

In the report, stability calculations for the new loads are described. The general status of the concrete structures should also be checked with regard to new loads and the risk of cavitation in spillways.

The report also shows that it may be necessary to perform geological investigations downstream from the concrete dam as well as along the new waterway. For instance, there may be a number of cracks in the bedrock downstream and close to the dam. If some of this rock is torn up when overtopped, it could jeopardise the stability of the dam. Therefore the bedrock may need to be strengthened with concrete, which is anchored and drained.

The geological investigation of the soil also gives the answer to the question of whether there are some parts along the new waterway that are more sensitive to

erosion than others. If these parts start to erode it may result in various degrees of damage. Therefore, areas likely to jeopardise dam safety if exposed to erosion must be protected from such action.

The report shows that also in the case of concrete dams it is necessary to make a careful review of both calculations and the condition of the dam. The report also deals with related design questions etc. concerning concrete dams.

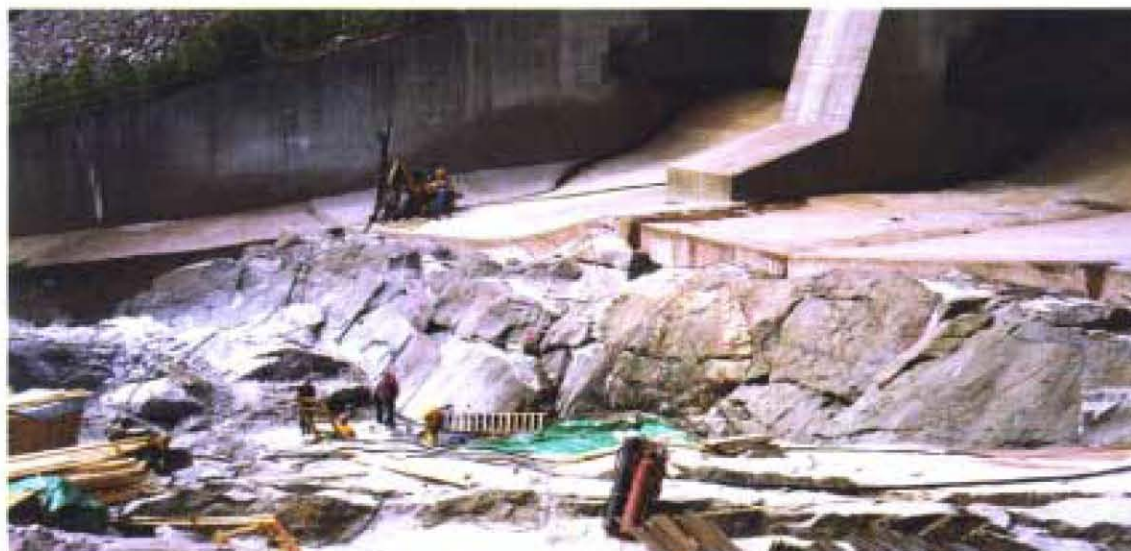


Figure 5.1. Repair and reinforcement downstream from the spillway owing to dislodged rock.



Figure 5.2. Damaged concrete in a spillway.

6. INVESTIGATIONS CONCERNING THE SPILLWAY SYSTEM

6.1. General

In high floods, it shall be possible to conduct the water further down the river without serious damage being caused to any of the dams (in Consequence Class I). Alternatively, as described above, use can be made of flood mitigation measures by storing the water in larger reservoirs. For the purpose of dam safety, it is a basic requirement that the discharge facilities should function in the way intended. This applies both to the previous design floods, for which the facilities were designed, and to the flows specified in the Committee's guidelines. In addition, as before, in the event of the power station being tripped, turbine drive water may not cause damage to the dam installation.

Water can be released, for example, by means of special discharge devices (spillways) which are normally kept closed by some form of shutting device or by the dam in a certain section being designed to withstand overflowing. For example, concrete dams with a rock foundation can often withstand overtopping. A further possibility is to design part of the dam so that it is eroded away by the action of a certain predetermined high flood (or rather at the water level that is caused by the flood) which means that discharge can take place without the dam being otherwise damaged. A dam section of this type is called a fuse-plug. Another example of a fuse-plug is a part of a concrete dam that is intended to be blasted away in the event of a flood that exceeds the normal capacity of the spillway.

The closing devices normally consist of gates made of steel or, in the case of smaller facilities, timber, for example lever gates (sliding gates operated with a lever). The spillways and gates that are used in connection with high water flows exist in a number of forms. In



Figure 6.1. Spillway columns with stones that have disappeared.

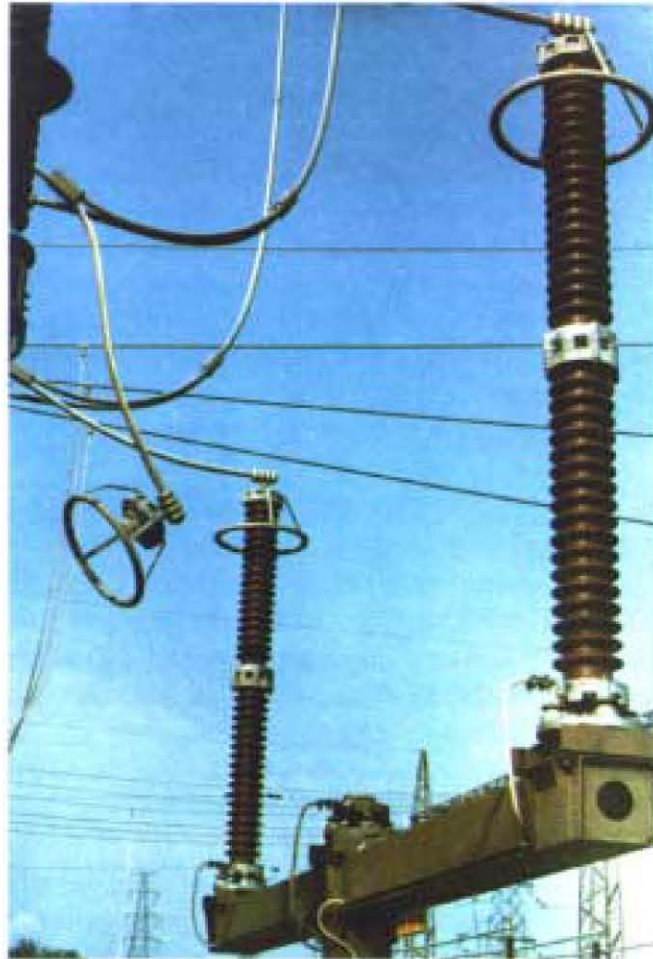


Figure 6.2. A L2-phase surge arrester has exploded when struck by lightning. The photograph is intended to point out the risk of lightning causing power station outage, which means that the turbine water has to be released through the spillways. It is, of course, necessary in this context to make sure that the spillway function will not also be damaged on the same occasion, or in other words that the power supply and control equipment are fitted with a good lightning protection system.

this context, gates also exist for other purposes, e.g. bottom outlet gates for releasing the last water remaining in the reservoir, but which are not intended to be opened at full water pressure and for this reason cannot be used during a high flood. There are also skimmer gates, i.e. log floating gates, which are (or were) used for logging operations, but which have a limited discharge capacity.

Waterways downstream from spillways must of course also be able to withstand the effects of the flowing water throughout the period in question.

The Committee's guidelines specify that only discharge from spillway devices, which can be used with full reliability and at short notice may be included in the discharge capacity. They shall of course also have the capacity assumed in the dimensioning work.

The expression "with full reliability and at short notice" has been discussed, and the interpretation that has been made can, with respect to dams in Consequence Class I, be summarised to mean that there should be redundancy with respect to for example power supply in order to open the gates and that "short notice" should be seen in relation to the rate at which the water level in the reservoir rises and the capacity of the dam to withstand a temporary surcharge. The requirements will be formulated in guidelines that are worked out jointly within the power industry.

The rate of water rise is normally (during river dimensioning) calculated on the basis of the design sequence. If the rate is low, there is a chance for certain measures to be taken for example the connection of mobile power supply. It should be noted that according to the Committee, the design flood has a certain charging period and that there is therefore a chance to take certain action, such as increased manning of the stations. At the same time, there are restrictions in the resources with respect, among other aspects, to personnel, since a design flood concerns several or sometimes all the power stations and regulation storages in the river in question.

Furthermore, in certain cases redundant power supply (or some other system) is required in order to open gates which can cope with discharging turbine drive water when a station is suddenly switched off. In this case the rate of water rise, of course, is the important factor. The redundancy requirement has often been solved by installing two separate power supply systems – one based on direct current and the other on alternating current – which normally operate on different gates.

As regards the demands for availability of the gates, there are also differences as a result of geographical location and thus associated temperature conditions. The probability of a high flood concurrent with conditions, which mean that gates may be frozen in place, requires analysis from case to case. This type of event may be more likely to occur in the southern parts of the country.

In connection with work on spillways and waterways, it is important to take dam safety into consideration by making a careful analysis before the work is started. Examples of such measures could be not to work on several spillways at the same time, to have a standby power unit available at the gate, to have extra personnel on duty for the event of an emergency, etc. Carefully considered planning could also significantly reduce the risks. For example, when replacing the wires on a gate, the new ones should be on the site and checked



Figure 6.3. The machinery of spillway gates often has a connection for a crank in order to make it possible to open the gate if both the power and back-up power have failed. It is recommended to replace the handle with an electric motor, which can be powered from the electric system of a car or an equivalent system.

before the old ones are removed, and also only one wire should be removed and the new one installed before the next one is removed, etc. (The design of the gate has as a rule been made such, that one wire is enough to open it).

It is not the intention of this report series to determine demands in connection with redundancy, for example, for dams in different consequence classes. This will be done as part of a second project, RIDAS [10], which is in progress within the power industry and for which the reports of this project serve as input.

The report series includes reports on how the actual discharge capacity of spillways is determined, on the functional safety of the spillway gates and on the preconditions, etc. for the use of fuse-plugs to increase the discharge capacity. The Department of Hydraulic Engineering at the Royal Institute of Technology in Stockholm has, with support from the power industry, studied the possibility of using siphon spillways for the same purpose, which also could be of interest [11].

A summary is given below of the reports written on the subject and also a study of the technical potential for discharging through turbines, which has been carried out within this investigation work.



Figure 6.4. Spillway test at Motala Power Plant (no damage).

6.2. Real spillway discharge capacity

In connection with the work on adapting the dams to new design floods in accordance with the Committee's guidelines, it is important to use the correct values for the discharge capacity of spillways. Discharge will normally take place at a higher water level (and higher flow) than was originally assumed. This normally means that the existing discharge curve has to be extrapolated. Review of the spillway capacity calculations have in many cases shown it to have been overestimated and spillway tests with high discharges have often revealed design and construction mistakes. A study has therefore been made on how the actual discharge capacity should be determined, which is presented in report 5, "Real spillway discharge capacity":

The report defines two kinds of spillway discharge capacities. The **hydraulic spillway capacity** is in this report defined as the theoretical discharge capacity of the structure with no regard to restrictions imposed by erosion, inundation, vibrations etc. on the spillway or its surroundings. The **technical spillway capacity** is here defined as the discharge capacity with regard to such restricting factors.



Figure 6.5. The spillway of Motala Power Plant is examined using a ROV (remote operated vehicle) before, after a certain amount of discharge and then again after discharge at the full capacity.

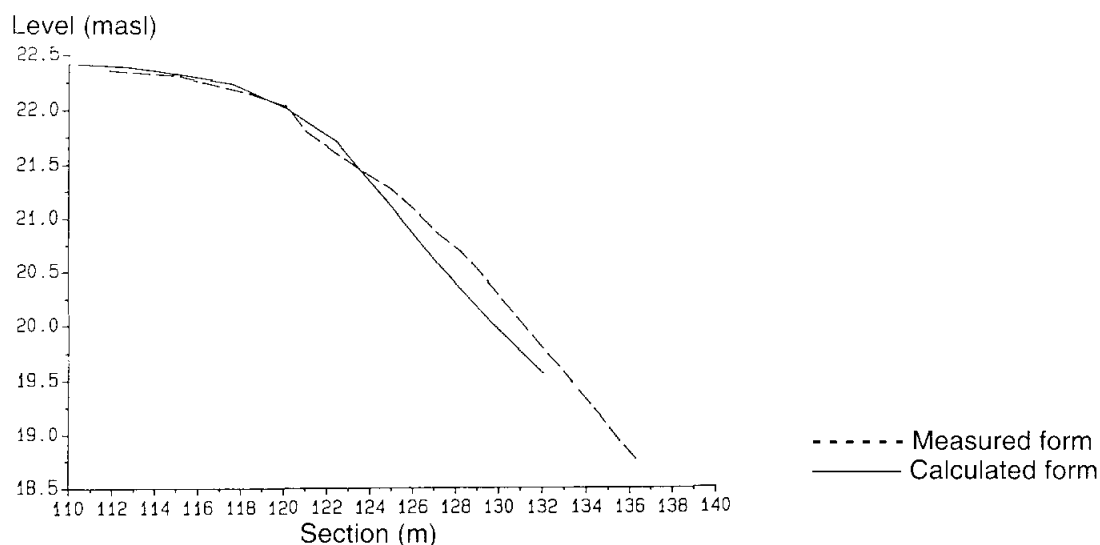


Figure 6.6. A spillway at Älvkarleby Power Plant. The form of the water surface through the middle of the spillway.

With the aim of developing an alternative to physical modelling for determination of hydraulic spillway capacity and to some extent also technical spillway capacity, mathematical models have been made of surface spillways in the hydropower plants Trängslet and Älvkarleby. Moreover, a mathematical model of a bottom outlet at the Holmen power plant is presented. Mathematical modelling is a technique with considerable potential but the initial difficulties should not be underestimated. It will be some time before sufficient experience has been gained for an accurate and reliable engineering tool.

The available experience from prototype discharge tests indicates that such tests are of great value for the determination of technical spillway capacities. On several occasions such tests have initiated reconstruction and strengthening of spillways and adjacent structures.

Flow measurements have proved to be difficult during prototype discharge tests and the traditional method, using current meters, has given inaccurate results. New acoustic techniques are recommended. However, where the conditions are favourable, nearby hydro turbines can be used for flow measurements.

The documentation of performed prototype discharge tests has in several cases been insufficient. A designated test leader should be responsible for the provision of an adequate documentation.

It is sometimes difficult to perform prototype discharge tests because of the risk of causing damage along the river downstream. In such cases, other methods are required to determine discharge capacity. Physical modelling is the most accurate (and expensive) method available, followed by mathematical modelling and theoretical calculations.

In the first instance those spillways should be investigated where a mistake in the determination of the discharge capacity can lead to serious repercussions or where the discharge capacity is unusually difficult to estimate. Spillways meeting both these criteria are of course especially important to check.



Figur 6.7. Spillway where the rock was damaged during a test.

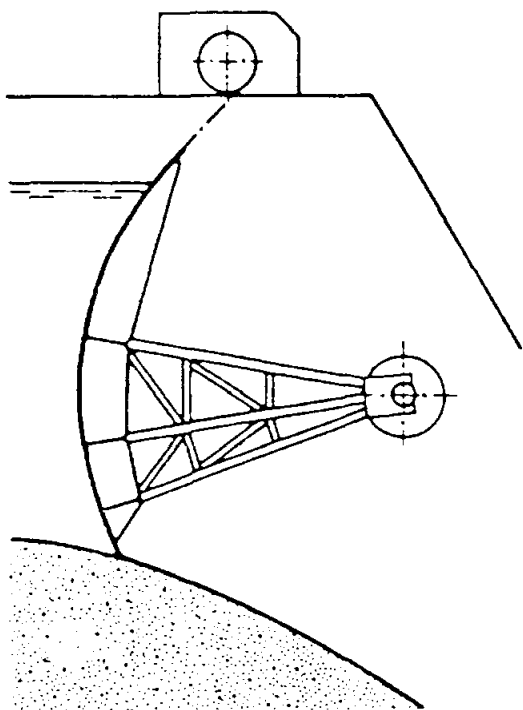
The investigation shows that, if it has not already been made, a review should be carried out of the discharge capacity of the spillways. In this context, consideration should be given to those factors that are specified in the report. This applies also to dams of Consequence Class II, although dams of Consequence Class I should be given priority, especially those that are difficult to assess correctly.

6.3. Functional reliability of spillway gates

The Committee's guidelines presuppose, as specified above, that only those discharge devices which can be used with full reliability and at short notice may be included in calculations of discharge capacity. A study has therefore been made regarding the functional reliability of gates, which is presented in report 7, "Functional reliability of spillway gates":

The first stage of the investigation consisted of collecting information on fault frequency, the most common faults and also possible breakdowns of existing spillway gates by an inquiry covering major hydropower and water regulation enterprises in Sweden. The inquiry was followed by personal visits and telephone interviews to ensure a more detailed compilation of facts. The investigation was subsequently extended into a second stage which proposed measures, and later also included some event trees and safety analysis.

The inventories of faults and problems showed that more serious incidents or breakdowns due to the lack of gate functions are very rare. The power industry works constantly at maintaining and improving a high level of discharge safety. Stated below are a few areas of special importance or where problems have proved to be comparatively usual and thus should be given special attention.



Figur 6.8. Radial gate.

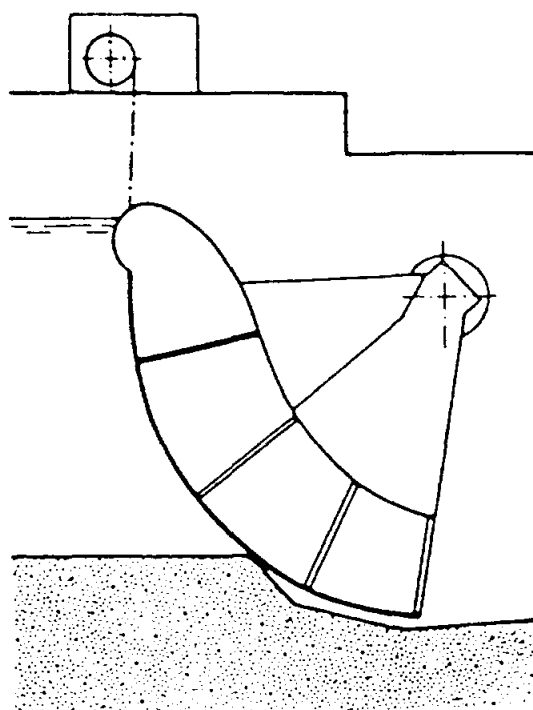


Figure 6.9. Sector gate (oscillating gate).

Shortfalls in the function of limit switches are a common problem, which can cause serious disturbances, perhaps even a breakdown of a gate or the machinery. Problems with the lubrication of bearings in segment and sector gates wire fracture, freezing and loss of communication links can also cause disturbance or absence of a function. Other, not unessential, causes of disturbances are shortfalls in the organisation and the division of responsibility.

Attention should be drawn to limit switch functions and system design, and especially to back-up power, monitoring and the “KAS-system”, a protection system, which automatically opens gates if the water level becomes too high. Recommendations for the entire hydropower industry (in Sweden) should be established.

Designs and methods for effective bearing lubrication on new as well as existing gates should be developed. Equipment for heating and anti-icing should be monitored in order to discover faults as early as possible and to avoid being surprised by a malfunctional gate. Joint design guidelines on gates and lifting devices should be established for the hydropower industry.

A homogeneous marking of spillway gates within a plant should be introduced to ensure manoeuvring of the correct gates. A schedule outlining the main data for the entire discharge apparatus (gauges, gates etc.) should be available at every plant.

Similar instructions regarding inspections, condition control and monitoring of gates and lifting devices should be followed by the entire Swedish hydropower industry.

The frequency of training should be increased for extreme situations such as long-term power failures and large floods acting simultaneously on several power stations along a river. Improved routines regarding the reporting of incidents should be established within the power industry.

The aim of the work has been to provide basic input for analysing the safety and reliability of common types of gate system. The report provides reliability assessments and proposals for technical designs and equipment, and points out the importance of detailed operation and maintenance procedures as well as training, practice and preparedness for extreme situations. The report also discusses requirements for the organisation needed to maintain a high level of discharge reliability. The views may be of value in more general terms, but there may also be other acceptable solutions.

On the basis of questionnaires and interviews held with operational staff at a number of power stations as part of the project, fault tree analyses have been performed for different types of gates. These are presented briefly in an appendix to the report. Fault tree analyses have been carried out for the spillway gates in Yngeredfors Power Plant by Sydkraft and earlier by Vattenfall for Stadsforsen Power Plant.

The report will also be used as a basis for the joint work that is being carried out within the power industry in Sweden concerning common guidelines for dam safety among power companies, which also includes a common incident reporting system.

6.4. Fuse-plug as auxiliary spillway

The new guidelines for design floods are expected to involve the need for increased discharge capacity at a number of dams and some form of fuse-plug could then be a good solution. A study has therefore been made of when this type of spillway can be suitable and how the design can be effected.

The Committee's guidelines indicating that only those discharge devices which can be used with full reliability and at short notice may be included in calculations of discharge capacity can, depending on the conditions at the dam in question, be solved with various technical systems or by a high level of preparedness. One alternative could be to have an emergency spillway that opens if the normal spillway fails to open as intended. This spillway could be of the fuse-plug type, the activation of which could be either automatic or manual.

A study on the question of fuse-plugs is presented in report 8, "Fuse-plug as auxiliary spillway at existing Swedish dams":

The study consists of a general analysis of the fuse-plug spillway and of its potential as an auxiliary spillway at existing Swedish dams in connection with the application of the new Swedish guidelines regarding design floods. Erodible dams as a particular type of fuse-plug have been considered as being most appropriate for use under Swedish conditions and are therefore described in more detail in the report.

The report gives recommendations on the design of fuse-plugs that are to be built at existing dams. The report also shows how to conduct the analysis and the choice of which type of spillway is most appropriate for use as an auxiliary spillway. Problems



Figure 6.10. An erodible section of dam (fuse-plug) in the USA (left side somewhat lower to facilitate initiation).

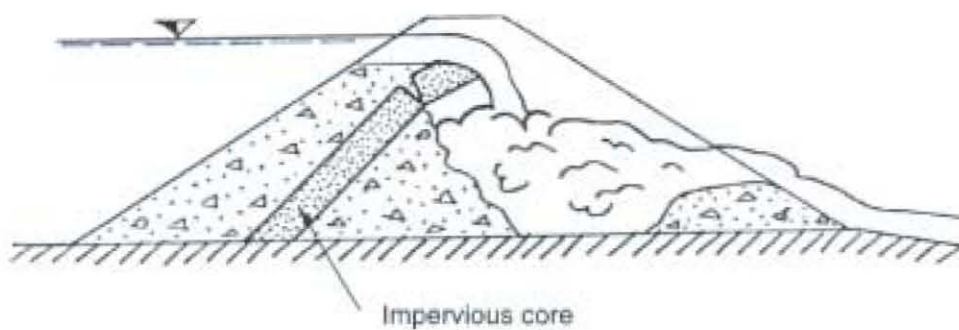


Figure 6.11. Erosion mechanism in an erodible section.

that have been less studied and which are specific for Swedish conditions, e.g. freezing of the material, as well as new problems appearing when a fuse-plug is introduced at an existing dam are also mentioned.

Some of the recommendations and conclusions of the report are as follows:

As a result of the ongoing river dimensioning review based on the new Swedish guidelines regarding design flood, some of the dams may be used for flood mitigation and others may need to be provided with an increased discharge capacity.

In cases where the discharge capacity has to be increased, the choice of a fuse-plug as an auxiliary spillway may be advantageous if the floods passing over it have a return period of more than 100 years. The advantages are a generally lower cost as well as the fact that the fuse-plug activation system is independent of the main spillway activation system and usually automatic (self-acting).

The required discharge capacity during design flood has to be unconditionally available at all times. To guarantee this, redundant systems may be used for activating the opening systems for gates. An alternative solution could be to build an emergency spillway, for instance a fuse-plug with an automatic activation system, independent of the activation system of the main spillway.

Many parameters and circumstances determine the choice of solution, especially when building auxiliary spillways at existing dams, and therefore each case has to be studied individually. Besides the technical and economical aspects there are also legal problems that have to be clarified as well as psychological effects on the population living in the vicinity of the dams. The fact that the experience of building and exploiting fuse-plugs is limited makes the analysis of this solution more difficult compared to others.

When adapting existing Swedish dams to the Committee's guidelines, increased spillway capacity or emergency spillways may be required at some dams. In these cases, a fuse-plug, for example an erodible section of the dam, may be an alternative. The report analyses the preconditions for this solution as well as its advantages and disadvantages. Various types of problems and solutions that are covered in the investigation in connection with fuse-plugs (e.g. downstream erosion protection) may also be of interest for other types of spillway or in order to study flows through dams. Studies of the function of an erodible section of dam may also be of value for dam safety analyses in general.

When choosing solutions, it is important also to deal with problems that occur in connection with unintentional activation and, as far as emergency spillways are concerned, the case in which not only the normal spillway but also the auxiliary spillway opens by mistake. A risk study of the alternatives is recommended.

6.5. Discharge through the turbines

During the course of the Committee's work, it was discussed how to view the question of water release through the turbines, and the Committee decided, with the justification that it would be reduced owing to a high tailwater level, that it should not be counted in the discharge capacity (during the calculation work it is (according to the guidelines) assumed that the turbine drive flow will stop from and including the ninth day of the flood sequence, when the extreme rain occurs). Another reason for not counting turbine drive flow is the risk

of a station being shut down (tripped), the probability of which is greater during a high flood situation than under normal conditions. There may be stations, however, where the tailwater level has little or no effect, and at which it is thus possible to use discharge through the turbines as an alternative to building a new spillway. For this reason, a case study has been made concerning the possibilities of using the turbine waterways.

In order to gain an overview of the potential and problems involved, data from a real hydro power station with Kaplan-type turbines has been used and alternative ways, in a high flood situation, of discharging through the turbines without connection to the grid have been studied, i.e. without the braking effect of the generators. A shutdown of power plants following a loss of the grid must be assumed to be likely during a high flood situation.

The main alternatives identified are:

- the runner blades on the unit are removed
- the unit is locked to prevent rotation
- the unit is allowed to race at high speed without being braked

(There may also be alternatives incorporating house turbine operation and wrongly combined (over-opened) turbines which, however, have not been studied in any greater detail).

As a basic focus for the study, a discharge (min 220 m³/s) of the same size as the turbine drive water flow was selected. At a flow that is so high for a measure of this type to be necessary, large head losses occur downstream in the case studied (a tailwater level 2-m higher than normal). The upstream level is judged in this case to depend also on the fact that this increase is needed in order (together with discharge through the turbine) to obtain a sufficiently high discharge capacity at the spillways.

If the **runner blades are removed**, the flow through the turbines will only be controlled by the guide vane openings. It has not been possible to find any model tests that show the flow as a function of the guide vane openings, but it is judged purely theoretically to be possible to discharge 250 m³/s at the heads in question. In this case too, there will probably be vibrations and a risk of damage to bearings, runner chamber, tailrace tunnel, etc. Whichever method is used to remove the runner blades depends on how much time is available, but the fastest and at the same time most drastic way would be to cut away the blades by carbon arc cutting. The method may be judged as being feasible and realistic, but owing to the cost of replacing the runner blades and the risks involved in the dismantling operation, which is expected to take place under water, the remainder of the study was focused on the other alternatives.

In the alternative involving **a permanently braked unit** and runner blades opened to the maximum extent (and locked), the flow is estimated to be approximately 130 m³/s according to model tests. Before adopting this method, further studies are required, for example concerning locking methods for the shaft, load cases, etc.

In the alternative involving **racing without braking**, two cases can be identified:

- racing with combined turbine
- uncombined racing

Following contacts with the manufacturer, it is deemed that long-term racing in excess of twice the synchronous speed should not be allowed, which in the case studied means a restriction to 150 rpm. A reservation is, however, made regarding the possible harmful vibrations and that the bearing temperature does not become too high.

In the case of **racing with uncombined turbine**, the study showed that in the most unfavourable case the maximum speed would be reached at a head of somewhat below 5 m and the discharge would be approx. 240 m³/s. At a head of 7 m, the speed would be 190 rpm and the flow approx. 290 m³/s. The runner blades and guide vanes are assumed to be locked. The assessment made was that even if the desired flow could be achieved in this case, harmful vibrations would be likely to occur, which could shake the bearings, runner chamber, tailrace, etc. apart. A limitation of the speed could be achieved by throttling the flow with, for example, a tailrace gate.

In the case of **racing with a combined turbine**, it is deemed theoretically possible to achieve a flow of 250 m³/s, and up to a net head of 7 m a speed of 150 rpm should not be exceeded. In order to determine the flow (i.e. how large a guide vane opening can be permitted), which can be released through the unit without serious problems occurring, a plant test was deemed to be the most suitable solution. The continued work on the unit studied is being focused on this.

During contacts with turbine manufacturers, it has been discovered that model tests were carried out for several French power stations during the 60s with regard to the possibility of allowing the unit to race for a longer period and determining the flow that could then be acceptable. Several tests were also carried out on installations. The results of the tests indicated that cavitation problems and instability in connection with uncombined units are the limiting factors and that large runner angles are favourable in order to allow through large flows. A certain number of trials were carried out in combination with a throttling tailrace gate, which gave very good results (quiet and smooth operation even when racing). Flows up to maximum operating flow were tested in this way.

The possibilities of using turbine waterways in combination with high flows appear to exist and can, at stations with favourable conditions, have a value both as part of the future solution for how to discharge the design flood and to provide the chance to improve the possibilities for coping with a very high flood that occurs before the facilities have been reconstructed, in which the discharge capacity shall be increased. Furthermore, the method could in certain cases provide standby capacity if one of the ordinary spillways is not working. In order to avoid blocking of intakes, ongoing efforts will probably be needed to clean them throughout the period in question.

If it becomes necessary to avert a dam failure with serious consequences, exceptional damage to turbines and generators can of course be accepted. A precondition for being able to use this option is that a comprehensive review and documentation be made of how it can be effected at the station in question and that the authority exists for making a rapid decision on action to be taken.

According to the assignment, an analysis of the discharge possibilities through the turbine has been conducted in the form of a short feasibility study and is not reported in any way other than that outlined above. The work has been carried out by Vattenfall Vattenkraft in co-operation with Vattenfall Utveckling AB and Vattenfall Hydropower AB.

It should be emphasised that the inclusion of discharge through the turbine waterways in the dimensioning work involves a departure from the Committee's guidelines and should therefore be approved by the VASO Dam Committee.

7. INVESTIGATIONS CONCERNING MONITORING AND EXAMINATION OF EMBANKMENT DAMS

7.1. General

During adaptation to the Committee's guidelines, the solutions in certain cases are judged to involve mitigation by temporary flood surcharge of certain dams. In order to be able to use this possibility, a determination must be made of what technically the dam can actually withstand – on the one hand more theoretically with respect to the structure of the dam, etc., as well as on the basis of what condition the dam is in. Furthermore, it is important to be able to assess the real cross-sections of the dam, in particular the levels of the impermeable core and the overlying filter as well as any low points for these along the dam.

Status inspection is also important in the future in order to be able to detect and, where necessary, repair changes that may affect the function of the dam both generally and specifically in conjunction with a temporary flood surcharge. Dams are also affected by changes due to ageing, which means that the development of methods for monitoring and examination that can at an early stage detect small changes is also of interest from the point of view of general dam safety. The inspection of dams is carried out in different ways and with somewhat different aims throughout the lifetime of the dam.

During the construction stage, **construction inspection** is carried out and, in connection with the first impoundment, functional inspection that then continues for several years after commissioning.

Following this, dams are monitored during the operational stage in various ways as part of the work on dam safety by means of operational inspections that are carried out at various intervals. If damage is discovered, it is subjected to special examination. Similarly, a special investigation may be necessary if a study needs to be made of the capacity of the dam to withstand some form of new load, for example a flood surcharge. **Monitoring** aims, at an early stage, at detecting damage so that repairs or some other suitable action can be carried out at the right time. Monitoring also includes, for example, observing seepage through the dam and discovering settlements or abnormal movements. Monitoring can with certain methods take place continuously in terms of both time and along the entire length of the dam by instrumentation of the dam for e.g. leakage measurement, whereby the water that seeps through the dam is collected at a number of measuring points. With other methods, the monitoring is carried out at certain intervals in time or at certain selected points along the dam.

If damage is discovered, there will normally be an **examination** to determine the reason, extent and suitable measures in which context both well-tried, traditional as well as new investigation methods can be used. Once the damage has been repaired, a new examination can be made of the area in question to check that the results intended have been achieved.

Certain methods can be used for both monitoring and examination. When selecting methods, one important factor is whether the investigation can be carried out continuously along the entire length of the dam, for a plane through the dam, along a line or only give a local random sample or a mean value for, for example, a certain part of the dam. Another factor is what the method primarily investigates and what connection it has with the

condition of the dam. The more indirect factors are studied, the greater the risk can be of other factors, irrelevant to the safety of the dam, having an influence on the results and giving wrong indications or diffuse results that are difficult to interpret. In the same way, it is, of course, desirable that natural variations in the dam, for example regarding the level of compaction or water content, can be separated from faults and changes in the dam. During repair work, it may also be of interest to be able to follow how, for example, grout is dispersed and the effects of the repairs on, for example, seepage. It is also of interest in certain cases to know how long it takes to obtain the results.

Of particular interest are certain methods that make it possible, after damage has been discovered, to compare a measurement over the area damaged with an earlier measurement (fingerprint) and preferably, by for example computer tomography, obtaining a picture of the change. It is important in this context for the measurements to be corrected for different water levels in the dam on the measurement occasions.

Costs and time expenditure are other important factors in connection with choice of method and are strongly influenced by what measures need to be taken in the dam in order to carry out measurements. It is of course preferable that little or no measures need to be taken, for example ground-penetrating radar measurement from the top surface of the dam or that already installed equipment can be used, e.g. water level tubes. Methods that require measures such as sampling by drilling or the installation of new tubes for measurement always involve undesirable encroachment on the dam structure and often high costs, which may limit their use to limited areas where damage is indicated in other ways.

During more recent years, the power industry in co-operation with the Swedish Council for Building Research and the Royal Institute of Technology have carried out a number of projects in connection with the status inspection of embankment dams, including ground-penetrating radar measurements for checking the crest level of the impervious core and the impervious core from both the dam crest and between boreholes, which has made it possible to carry out tomographic analysis of the measurement area. Furthermore, automatic systems for seepage measurement by the collection of leachate have been further developed and methods for seepage measurement by the analysis of temperature variations in the dam have been developed.

Within the framework of the present report series connected with the Committee's guidelines, a study and compilation have been made of traditional methods for checking the status of embankment dams and several studies concerning more recent methods.

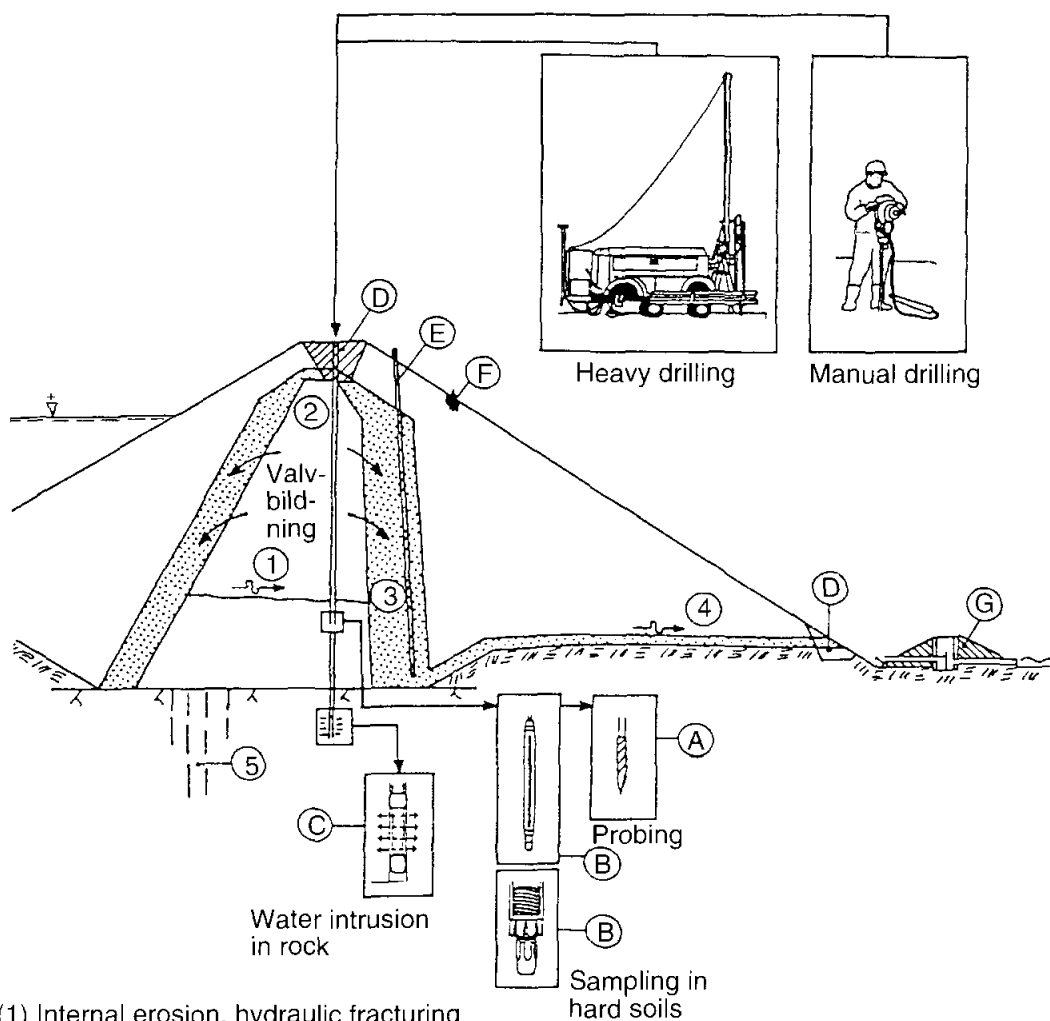
International experience and the fact that the installations are growing older have shown that there may also be a need for a more detailed evaluation of the safety of the facilities. Vattenfall has started a successive safety review of its most important facilities. The evaluations comprise for example a review of design data and comparisons with current guidelines for construction and operational safety, but also an evaluation of information gained in connection with status inspection. The studies carried out in connection with status inspection may also be of value in this context.

The investigations are presented below:

7.2. Established methods for monitoring and examination of embankment dams

The aim of this study is to describe established methods and it is presented in report 20, "Established methods for monitoring and examination of embankment dams":

The practice has been to design dams in order to provide a certain degree of safety when the water level lies at the retention level of the dam and floods occur which have



- (1) Internal erosion, hydraulic fracturing
- (2) Erosion, frost heave in upper surface of impervious core
- (3) Filter, blocked or separated
- (4) Leakage with a risk of erosion at toe of dam
- (5) Grout curtain seal impaired

Example of methods available for monitoring and investigation:

- (A) Probing
- (B) Sampling
- (C) Drilling, infiltration tests in soil and water intrusion tests in rock
- (D) Test pit excavation
- (E) Water level pipes
- (F) Measuring studs for deformation measurement
- (G) Seepage/leakage measurement

Figure 7.1. Examples of damage and methods for monitoring and investigation.

a return time of approximately 100 years. According to new guidelines for design flood determination, dams should be able to cope with design flows with a much lower level of probability than the level traditionally applied without suffering serious damage, which could jeopardise the retention of the reservoir. This means that we must determine the ability of dams to withstand loads, e.g. levels higher than the normal retention level, which it was previously assumed they would never be exposed to. Consequently, it is of interest to investigate how high the reservoir can rise above the normal retention level during flood events, without the dam collapsing. The aim of this study is to describe the methods available for investigation and surveillance of earth and rock-fill dams. The development of “new” methods is discussed in a parallel project in this series of reports.

Dam owners have established routines for the surveillance of dam plants. Scheduled checks comprise regular inspections by the operators (weekly as well as a yearly reported inspection), and an engineering examination once every four years. International experiences, and the fact that the dams are ageing, have also shown that a more extensive evaluation of the safety of the plants is required. Vattenfall has initiated such a successive safety evaluation of its most important plants. This evaluation includes, for example, a review of the design data and comparisons with current guidelines for construction and operational safety.

Instrumentation in the form of devices for measuring seepage, surface deformation and pore pressure is, where practically possible, to be regarded as “basic instrumentation” for all important earth and rock-fill dams. Reductions in the amount of personnel at the plants, in combination with the rapid technical development of signal transmission and computer monitoring, have resulted in the fact that dam instrumentation has become increasingly automated.

When selecting an examination method for detecting and recording the extent of an area in the impermeable core of a dam where internal erosion damage is suspected, knowledge of normal variations in the parameters to be examined is required, as well as the accuracy of the examination method.

Construction specifications, for example, permit maximum variations in the porosity of the moraine of approximately 8%. The examination of one dam has revealed that the moraine, which is very loose in some areas and has internal erosion damage, has an approximately 4% higher porosity than permitted in connection with construction.

The report describes the most common geotechnical methods, i.e. test excavation, sounding and drilling. The Swedish weight sounding method, static cone penetration testing and ram penetration testing are those sounding methods described. Field investigations that can be carried out in boreholes and examples of laboratory tests that can be performed on extracted soil samples are also mentioned.

An indication of the resolution of the Swedish weight sounding method can be obtained from the example mentioned above, where sounding in combination with sampling provided a clear picture of the damaged section. The example shows that this method was able to register differences in porosity of $\pm 4\%$.

Field investigation methods necessary to investigate how high a reservoir may rise above the normal retention level during a flood surcharge may comprise a test excavation in the crest of the dam in order to determine levels of different materials

used. Knowledge of the particle size distribution of the downstream support fill, and of the position of conceivable discharge points, is also required in order to assess stability and susceptibility to erosion.

7.3. More recent methods for monitoring and examination of embankment dams

In this study, an inventory has been made of various methods with the aim of finding "new" measurement methods that could be suitable for different types of measurement in connection with embankment dams either today or in the future. The investigation is presented in report 21, "More recent methods for the status inspection of embankment dams":

Measurements in embankment dams are made for continuous monitoring of important parameters and also for the special examination of additional parameters to ensure that the information is comprehensive, which may be essential when estimating the status of the dam. In this study, new methods (i.e. methods with either no or limited experience from embankment dam examinations) have been investigated to find methods both for continuous monitoring and single more detailed measurements.

The methods have been evaluated from a model, based on different categories of damage. Many types of damage, such as piping and arching, are related to internal erosion. Other damage categories, such as damage to the riprap, can often be observed by visual inspections.

Parameters influenced by internal erosion (expressed by increasing porosity) have been examined in order to identify those most appropriate for further observation. This has shown that parameters that are dependent on the changes of the flow, such



Figure 7.2. Radar measurement with five antennae for localising the crown of the impervious core.

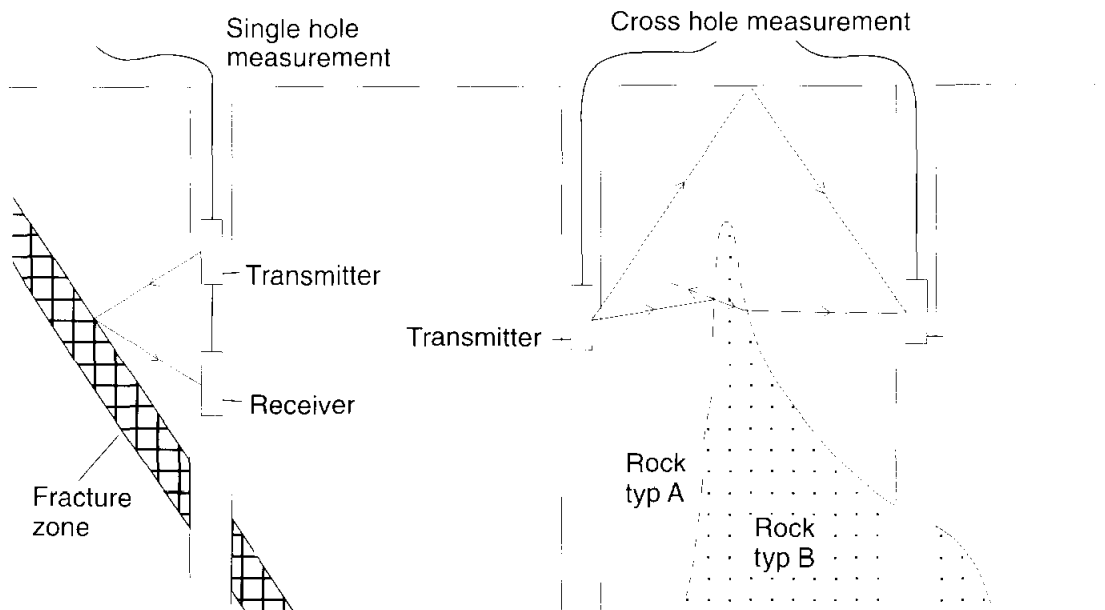


Figure 7.3. Singel hole and cross hole measurement by means of borehole radar according to Andersson et al (1992).

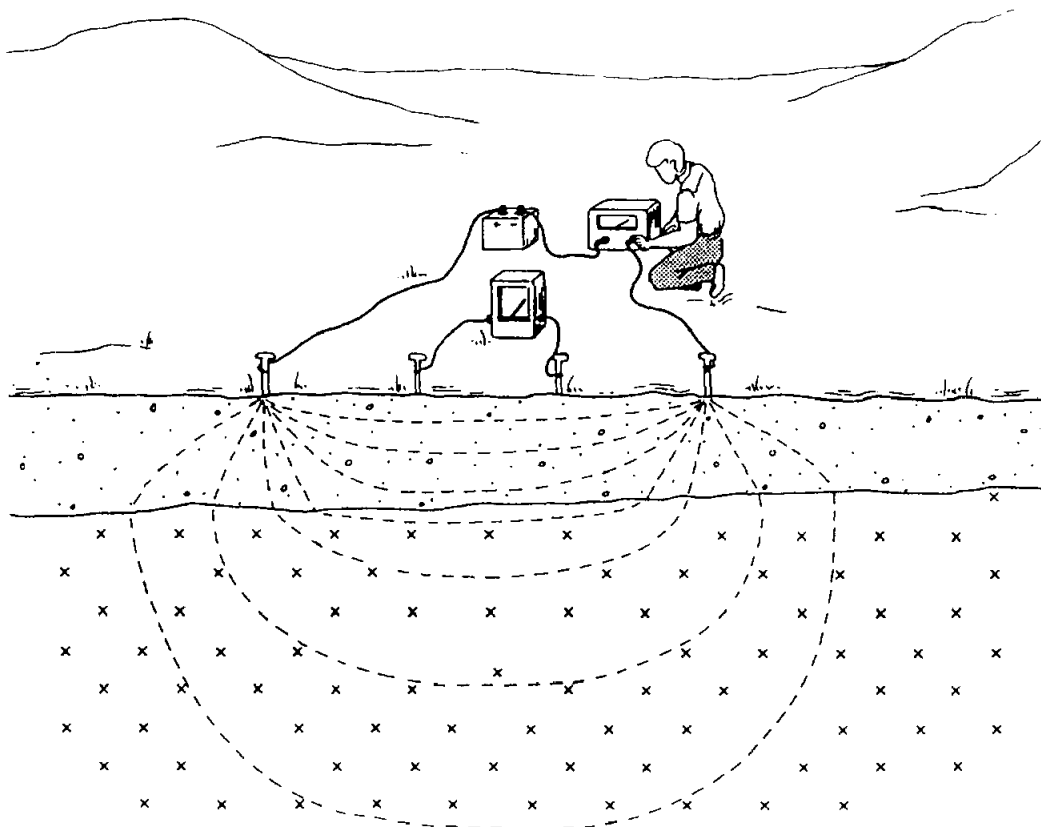


Figure 7.4. Principle for electrical resistivity measurement (modified from Robinson and Coruh, 1988).

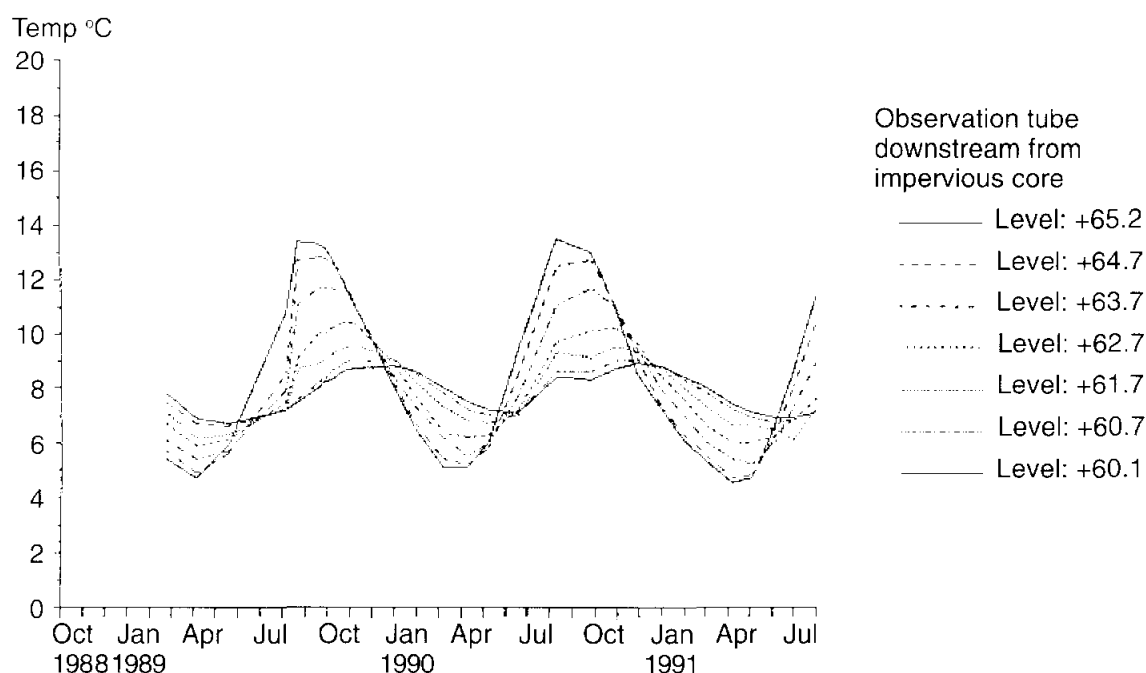


Figure 7.5. Temperature variations in a water level pipe at defined levels.

as hydraulic conductivity, are more sensitive than parameters dependent on changes of the soil matrix, for example density and resistivity. The evaluation model also includes an assessment of accuracy and resolution. The methods have been divided into Non-Destructive Testing methods, Borehole methods and Other methods. Major conclusions regarding the most appropriate methods are summarised below.

Non-Destructive Testing

Ground-penetrating radar measures differences in electric conductivity or in radio wave velocity in the soil. These parameters depend on grain size and porosity. The potential for the method is examination, if possible by repeated measurements.

The resistivity in embankment dams is mainly dependent on water content. At present resistivity measurements are quick but the accuracy is presently not so high. However, the method can be further developed.

Different rates of leakage water will cause anomalies in the self-potential along the dam. These variations can be used for leakage detection. Measurements of resistivity and self-potential are suitable both for regular monitoring and for more detailed examinations of dams.

Borehole methods

The basic principle for borehole radar and ground penetrating radar is the same. By using tomographic analyses on measurements between two boreholes, the accuracy can be increased. The method is appropriate for single examinations of dams.

The sonic cross-hole and the borehole radar methods use a similar technique, but instead of analysing electromagnetic waves the Sonic Cross-Hole method analyses sound waves. The methods are very much the same regarding accuracy and applications.

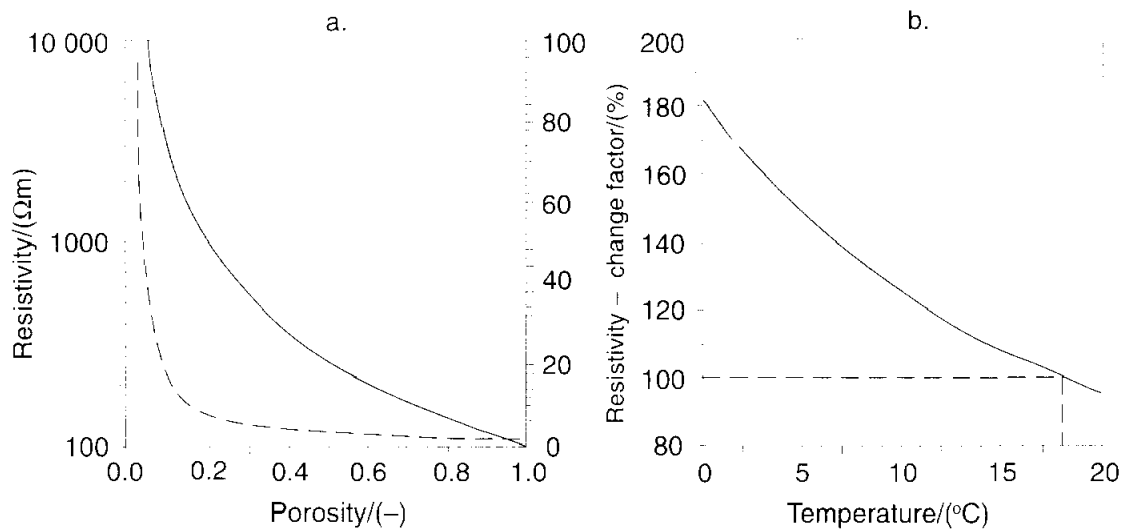


Figure 7.8. a. Dependence of resistivity on the porosity in clay-free material according to Archie's law.

($\rho_v = 100 \Omega m$, $a = 1.0$ $m = 1.4$).

b. Dependence of resistivity on the temperature (temperature coefficient $a = 0.025$).

TEMPERATURE acts as a tracer in the leakage flow and is therefore dependant on the flow. Measurements are easy to perform. The best result will be obtained with regular measurements for monitoring of dams.

Other methods

By continuous HYDRO-CHEMICAL analyses, variations in the quality of the leakage water can be detected and used as an indication of changes inside the dam. With increasing leakage, the TURBIDITY (ie. the content of particles in the water) can also indicate internal erosion. If the leakage or movements inside the dam cause noise, these can be detected by ACOUSTIC measurements.

Result

Today, there are some new methods available for regular monitoring and for single detailed examination in embankment dams. At the moment these new methods cannot replace conventional ones. Since the experiences from old measurements are also considered to be valuable, an interruption of existing measurements is not to recommend.

Monitoring of dams can be made by measuring SELF-POTENTIAL, RESISTIVITY and TEMPERATURE. The first two methods are Non-Destructive and can be installed for measurements covering the whole dam. Temperature measurements are made in boreholes or in some cases from the surface using infrared cameras. Hydro-chemical and turbidity measurements in the leakage water can also be used for monitoring. However, the accuracy of these methods is strongly affected by the way in which the leakage water is collected. If flow measurements are made for the entire dam, the local increased flow (due to internal erosion) must be relatively large before it becomes significant. All these methods can be installed permanently. They can also be controlled by a computer for storage and evaluation of data.

None of these new methods are generally recommended for examination of the capacity to allow water level above reservoir water level. However, georadar measurements can be useful to identify sections with low levels of the core crest.

The location of the leakage must be known before a detailed investigation. Thus, quick and non-destructive methods such as SELF-POTENTIAL, GEORADAR and RESISTIVITY measurements are recommended, despite little or no experience of the methods in Sweden. After localization of the leakage, more detailed measurements can be made using borehole methods, such as BOREHOLE RADAR and SONIC CROSS-HOLE measurements. In many cases TEMPERATURE measurements can be useful.

The investigation summarises and compares the suitability of more recent methods for different purposes in the present situation and for the types of damage that may occur in embankment dams, and also comments on the potential of the methods for development.

In connection with the above, pilot projects have been conducted for several different methods, namely one project that aims at determining where the seepage comes from by means of isotopic analysis of the water and two projects which aim at detecting deviations in the water flows in dams by means of electrical methods.

7.4. Isotopic analysis of seepage from dams

The project aims at testing a method in order to determine whether the water found downstream from a dam is seepage from the reservoir or local runoff from the downstream side of the dam. The investigation is presented in report 22, "Isotopic analysis of seepage from dams":

Analyses of the stable isotope oxygen-18 were used to determine if water, found downstream from a reservoir, was seepage or local runoff generated from an area downstream from the dam. The concentration of the stable isotope was analysed in samples from the reservoir, the groundwater and also the suspected seepage. The reservoir level, the seepage hydrograph and precipitation were also analysed to study their interaction. The method was applied to the Grundsjö dam in the River Ljusnan and the Flåsjö dam in the River Ljungan. It was shown that the water found downstream of the Flåsjö dam probably originates from the reservoir, while the suspected leakage at the Grundsjö dam is probably locally generated runoff downstream of the dam.

An assessment of the potential offered by the method, however, is that the results of the pilot tests were not entirely unanimous and that a certain amount of support must be accepted in order to verify the interpretation. Furthermore, the isotope analysis has to be carried out in the laboratory, which excludes methods in those cases where an automatic monitoring is required.

7.5. Monitoring of the impervious core by measuring the self-potential and resistivity

The project is presented in report 23, “Monitoring the function of the impervious core by measuring the self-potential and resistivity”:

Internal erosion in embankment dams is a common cause of dam failures. The use of geophysics in the mapping of electrical phenomena and also the monitoring of changes in parameters addressing geo-electrical methods is considered to be a technique with high potential for detecting inhomogeneities at the dam core which may later lead to fatal internal erosion.

A project was started in 1992 with the principal aim of developing a prototype for a dam monitoring system based on frequent measurements at many points of the apparent resistivity and self-potential of a dam.

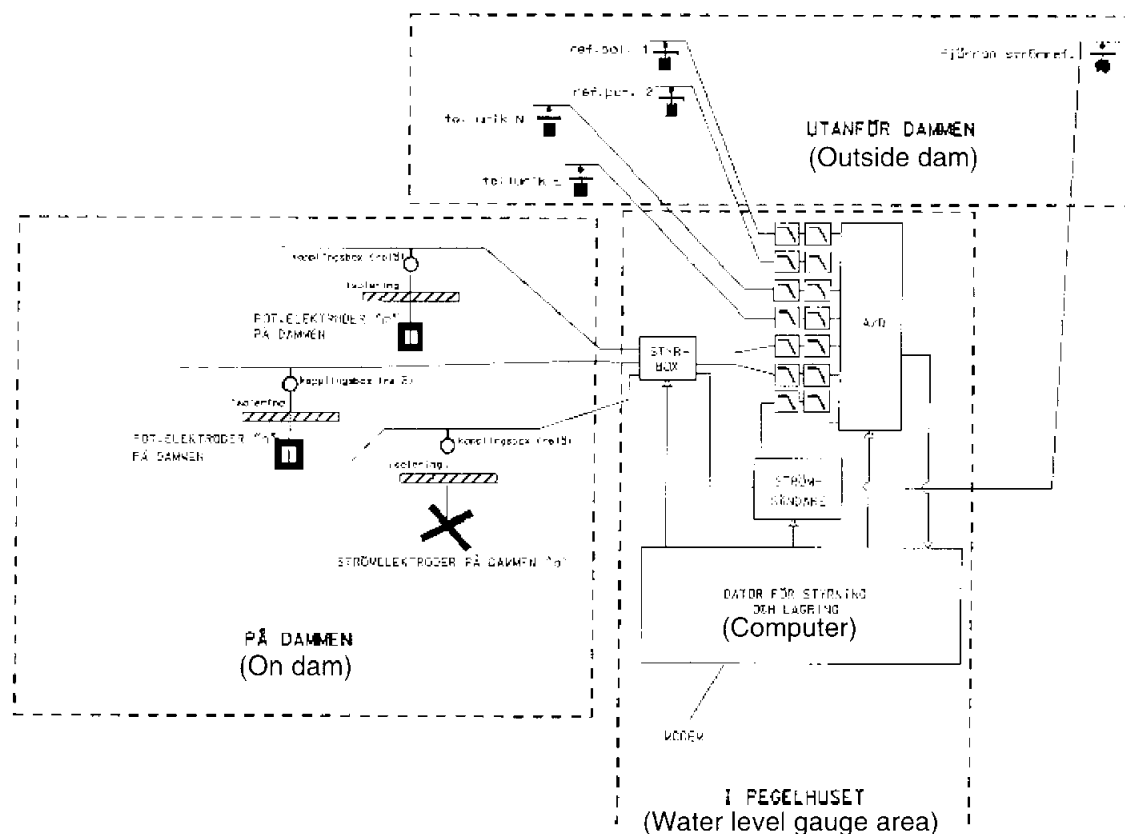


Figure 7.6. Basic diagram of measurement system.

The system was developed and installed in the Suorva dam in 1993, where measurements have been carried out since August 1993.

The system performs these measurements automatically. Communication with the system is maintained via modem. For example this allows the remote setting of parameters for data acquisition as well as remote error diagnosis.

In general, the data quality has been satisfactory. During the period with unfrozen ground (May-October) the data quality has been very good. However, frozen ground during the winter has prevented the injection of a current strong enough to maintain good signal to noise ratios, hampering effective resistivity surveys.

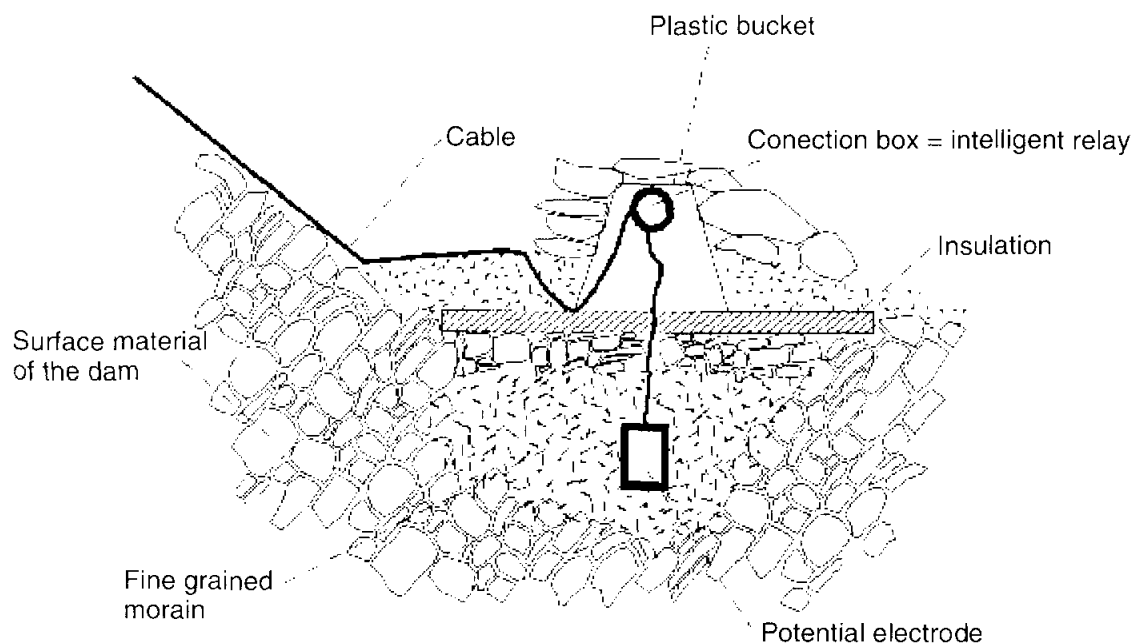


Figure 7.7. Basic model of electrode installation.

Self-potential measurements show that a streaming potential is developed within the dam, thus enabling studies of the homogeneity in seepage and changes in zeta-potential with time.

The results indicate four (possibly five) sections in the dam where anomalous behaviour in the self-potential is recognised and interpreted as inhomogeneous seepage.

The resistivity data from this dam are difficult to interpret as several different sources for resistivity variations probably interact. The problems are emphasised due to lack of resistivity monitoring of a closed cycle in water levels where there is a hiatus of 10 m.

The results of the self-potential measurements appear to be particularly promising. In the following related project, a study has been made which includes, among other things, the effect of temperature on resistivity reaction.

7.6. Monitoring of the impervious core by analysing variations in resistivity

The project is presented in report 24, "Monitoring of the function of the impervious core by analysing variations in resistivity":

International experience has shown that there is a need of developing methods and methodology for seepage monitoring in embankment dams, which is the background and motive for this project. Of particular interest are methods able to register small seepage changes in the dam, i.e. in an early stage before internal erosion starts to affect the security of the dam.

Since temperature affects the resistivity, the basic hypothesis of this project is that the seasonal resistivity variation, as well as the temperature variation, can be used for detecting increased seepage. The aim is also to attempt to quantify the water flow by studying the resistivity variation and further develop the interpretation methodology developed for temperature measurements.

The data acquisition system used is computer controlled and includes a resistivity meter, a switch box and multi-core cables. In this application measurements are carried out by using permanently installed electrodes, which each time are connected to the multi-core cables. The electrodes consist of stainless steel plates buried in shallow pits which were back-filled with fine-grained material. Only a cable end is visible at each electrode after the back-fill.

Resistivity measurements were carried out in the embankment dams at Lövön and Moforsen with approximately two months interval. In total, eight measurements were carried out at Lövön and six at Moforsen. Wenner configuration was used both at Lövön and Moforsen. In addition, pole-pole configuration was used at Moforsen to increase the depth penetration on the relatively short dam.

Qualitative interpretation of resistivity data was made by plotting data in pseudo-sections. Quantitative interpretation was carried out by using two-dimensional numerical inversion, where the software automatically adjusts the interpreted model resistivities to fit the field data.

The quantitative interpretation of water flow through the dam is based on the fact that a variation in resistivity in the reservoir water will propagate into the dam with the seepage water. The variation due to variations in ion content will travel with pore velocity, whereas the variation due to temperature will move with the thermal velocity. The time variation in the resistivity in the dam can be monitored by means of repeated resistivity measurements.

The simplest way of evaluating consists of comparing extreme values for the absolute resistivity in the reservoir and the interpreted resistivity in the embankment dam. The diagrams are used to calculate phase shifts for the highest and lowest values.

Evaluation of the amplitude can be made on the assumption that observed resistivity variations in the embankment dam emanates from the temperature variation in the reservoir. The attenuation thus arising can be attributed primarily to heat conduction perpendicular to the flow direction. An independent evaluation can thus be made with the two methods, which allows some control of the result.

The measurements from Lövön show a significant variation along the profile. The Wenner measurements gave very stable results. Comparisons with temperature measurements were made in one section in a standpipe located in the filter downstream. Evaluation of the resistivity data according to the amplitude method gave approximately the same result as the phase shift method. However, the temperature measurements gave a higher flow concentrated to a smaller zone, whereas the results correlate better at depth. The differences are reasonable considering the higher vertical resolution of the temperature data compared to the resistivity data.

The resistivity measurements at Moforsen were carried out along three lines: along the dam crest and the two terraces. The variation in measured data is smaller than for Lövön, but the interpretation resulted in significant variations with time. The pole-pole configuration gives a larger depth penetration than Wenner, but poorer vertical resolution. In addition, pole-pole data is more susceptible to noise, due to the long reference cables.

At Moforsen temperature measurements were carried out in three standpipes, where the result can be used for comparison between the methods. Evaluation of the resistivity measurements gave results in rather good accordance with the temperature measurements.

SP-measurements at Lövön gave stable results, with a small variation. However, at Moforsen the SP-result is considered unreliable.

In conclusion, the water seepage can be detected and to some extent quantified by the interpretation of resistivity data. The method can be further improved in all parts of the system, as in installations, resistivity interpretation, seepage evaluation and presentation of results. By using new numerical models, the influence of 3D-effects and other various sources of disturbance can also be assessed.

At present the method is most suitable for longer dams. Both measurement and interpretation are more complicated for short and high dams, and a different methodology needs to be used. Thus there is a need for further development for such dams. The potentially low detection levels mean a possibility of detecting internal erosion at an early stage. Since the method is non-destructive the development in time can also be monitored.

The method appears to be promising for the monitoring of dams, particularly in combination with temperature measurements.

8. INVESTIGATIONS CONCERNING THE STATUS INSPECTION OF CONCRETE DAMS

8.1. General

When adapting to the Committee's guidelines, the solution is deemed in certain cases to involve mitigation by the temporary flood surcharge of certain dams. In order to be able to utilise the possibilities for surcharge, checks must be made to ascertain what the dam in question can actually technically withstand, on the one hand more theoretically with respect to the dam structure and on the other on the current status of the dam. This applies, of course, not only to earth-fill dams but to a large extent also to concrete dams. Consequently, an investigation has been made on these questions together with a compilation and evaluation of methods for status inspection in connection with concrete dams. Traditional methods and possible non-destructive testing methods are described. The emphasis has been placed on more recent methods.

International experience and the fact that the installations are increasing in age have shown that there may also be a need for a more detailed evaluation of the safety of the facilities. Vattenfall has started a successive safety review of its most important facilities, in terms of both embankment and concrete dams. The evaluation comprises, for example, not only a review of the design data and comparisons with present guidelines for construction and operational safety, but also an evaluation of the information gathered in connection with status inspection. The studies carried out in connection with status inspection may also be of value in this context.

8.2. Status inspection of concrete in hydro power installations

The study is presented in report 25, "Status inspection of concrete in hydro power installations":

A condition assessment of concrete structures in hydro power stations is described in the report. The traditional methods and the possibilities of using non-destructive methods for the testing of concrete are reviewed.

Various forms and signs of ageing processes in concrete are described. The description includes both outer signs of damage, which can be viewed on the surface of the structure and the actual damage to the concrete on the surface or in the interior of the structure. The state of damage in concrete structures in hydro power stations is described, and it can be concluded that anything from material degradation to large defects can be found. The damage can be discovered in structural parts of various sizes and shapes. However, in many cases the damage does not affect the load-bearing capacity and is relevant only when it comes to durability.

The current procedures for surveying concrete structures are described. A review of traditional methods and procedures when inspecting concrete shows that a good knowledge about the material degradation is received from destructive methods. A satisfactory estimation of the physical condition of the structure can be achieved with traditional methods. However, a need for supplementary information is identified



Figure 8.1. Layers of lime on wall.



Figure 8.2. Porous concrete on the surface of a canal wall at a fracture.



Figure 8.3. Flaking of material on the surface of a spillway column.

concerning the relative quality and degradation judgements within a structure as well as for the detection of internal defects. The possibilities of covering this need for control with NDT methods is considered to be an interesting subject worth investigating.

The investigation provides an overview of the methods for condition assessment that are applicable to concrete testing. The state of the art for NDT techniques based primarily on stress wave propagation, propagation of electromagnetic waves, and dynamic response is presented. Moreover, methods based on X-rays, thermography and electrochemical measurements are presented. The description is focused on information about the method, the measurement technique and the evaluation method, and it describes some of the recent developments as well as activities going on in Sweden. The potential of each technique for checking concrete in structures is reviewed and it is concluded that most techniques have at least some potential. Some of the methods, such as ultrasonics and X-rays, are considered to be applicable mainly when testing structures of limited size, but on the other hand they can be used to characterise deterioration. When testing large structures in order to detect larger

defects, methods based on electromagnetic waves and low frequency stress waves can be used.

The procedures based on NDT, which can be used for evaluating the general state of a structure, are discussed. Such an assessment of the general state can be made on the basis of local detection of defects using for example stress wave echoes or radar echoes. Another possibility is to use an automated testing procedure such as scanning.



Figure 8.4. Sampling with a core drill gives an idea of the concrete in the structure.

The evaluation will benefit from this since measured data represent a certain location on the structures by its relation to other measured values. Overall structural integrity can also be evaluated using the dynamic response as in experimental modal analysis.

It is apparent that only a limited number of methods are immediately available for concrete inspection, and that their capacities for defect detection in structures are not fully evaluated. There are also many interesting possibilities for further development and testing.

The report describes both traditional methods as well as non-destructive testing methods for inspecting concrete. The development of new methods is in progress within both the power industry and in other areas, e.g. for the status inspection of bridges. As the installations become older, the importance of effective methods of monitoring and status inspection increases. Consequently, this type of development work is important.



Figure 8.5. Typical damage in concrete with alkali-reactive aggregates.

9. INVESTIGATIONS CONCERNING RISK ANALYSIS

9.1. General

It was the task of the Committee to submit proposals for design floods, and the process of adaptation to these floods is under way. The hydrological safety can thus be regarded as satisfactory. Dam safety in general, however, depends also on a number of other factors and it is, of course, important to have a well-adapted safety level in connection with these factors, and in those cases where some form of reconstruction or modification is to take place it is perhaps advisable to review the whole situation in order to avoid further changes perhaps having to be made a few years later which, for practical and financial reasons, should have been co-ordinated with the first change.

One step in this direction is the introduction of a programme for systematic dam safety evaluations of existing dams.

In order to deal with the risks in a systematic way, use is made of risk analyses, for example within the aircraft and power industries. A similar approach would also be suitable for use, as an aid in work on dam safety and a number of studies have been carried out.

In 1990, Vattenfall conducted a risk study in connection with the discharge capacity at Stadsforsen [8], which indicated potential risks attached to the simultaneous automatic opening of all gates in the power station located immediately upstream and at the same time shed light on the importance of redundancy for the discharge system power supply during maintenance work on the DC system and that functional inspection of the KAS system involves the entire chain of functions.

As part of the project on the functional safety of gates, a fault tree analysis and an operational safety assessment of spillway gates were carried out by Sydkraft Konsult AB, which are briefly described in report 7, "The functional safety of spillway gates".

At the Hydraulic Engineering Department of the Royal Institute of Technology, two licentiate theses have been performed with the support of the power industry, which were published in 1995. The reports describe the systems and certain conclusions that were drawn, among others the importance of the filter function and the risk of the spillways becoming clogged with floating debris.

Within the framework of the present report series, a study has been made of risk analysis issues within the field of dam safety, which is largely based on the documents produced in connection with the two Institute of Technology theses mentioned above.

9.2. Risk analysis in work on dam safety

The study concerning risk analysis is presented in report 26, "Risk analysis in work on dam safety":

The objective of this report is to spread knowledge about how risk analysis could be applied on assessment and management of dam safety in Sweden. It is based on

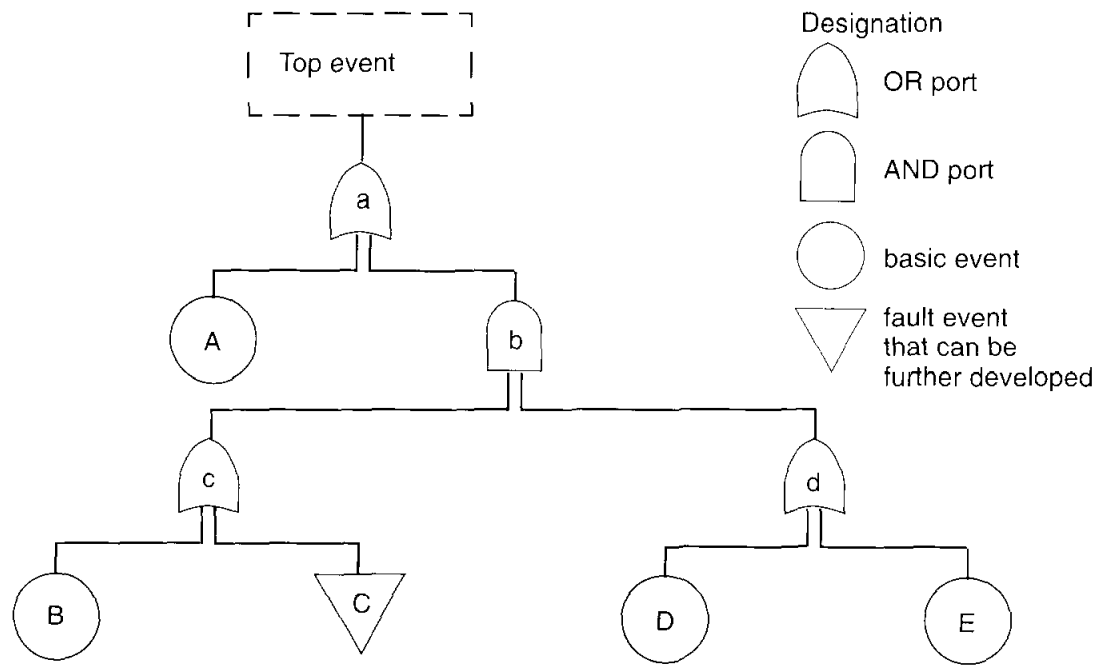


Figure 9.1. Basic example of a fault tree.

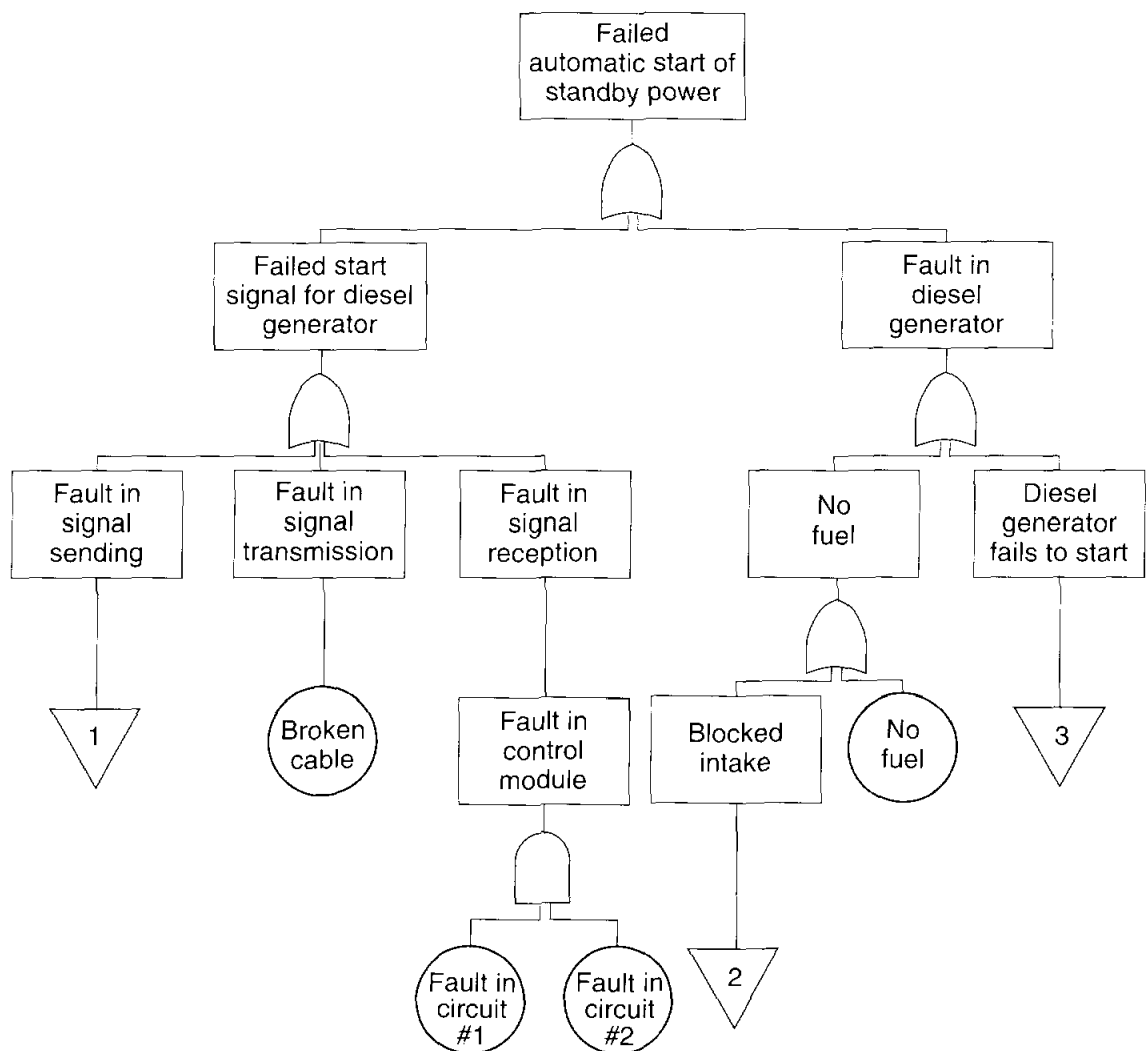


Figure 9.2. Basic example of a fault tree for faulty function of standby power.

international experience of risk analysis of dam installations, and describes the purpose, possibilities and principal steps of the methodology.

Of about 900 hydropower dams currently existing in Sweden, 143 are classified as high dams (i.e. dam height over 15 m). This dam population is ageing, placing more and more emphasis on the need for maintaining proper safety at these installations. Although dam failures are infrequent, the consequences of a single failure may be severe and should by all practical means be avoided. It is imperative that the risks placed on society by these structures are systematically evaluated and assessed in terms of improving overall safety and minimising the impacts of possible failure. In this, risk analysis can be an efficient tool.

The use of risk analysis is well established in performing safety assessment analyses of many different technical systems, but has only to a limited extent been used for the assessment of dam safety in Sweden. Since the 1970s researchers in several countries have tried to make risk analysis an effective means of dam safety evaluation. In recent years the work has been intensified, and today risk analysis is actively being used in this field.

Risk analysis is defined as any number of means or methods to identify and evaluate risks. Simply put, risk analysis for the assessment of dam safety involves identification of all series of events that may cause dam failure, estimation of the probability of these events, the consequences caused by them, and evaluation of the effect of remedial measures. The objective of a risk analysis safety assessment of a dam installation is to identify the major contributing risk factors of the system and evaluate how they may be minimised in an effective way. Ultimately, the aim is to reduce the residual risk to an acceptable level.

The purpose is not to determine an absolute measure of the safety of a dam installation. The real utility of the approach lies in assessing dam safety on a relative basis. That is, when one has determined the risk at a certain dam, one should evaluate the effects of alternative risk reducing measures.

A proper start-up of a risk analysis is a workshop where a project group, consisting of experts in all relevant areas, screens failure modes and derives failure probabilities. An appropriate application of risk analysis for Swedish conditions would best be accomplished by the use of both event trees and fault trees. Event trees can be used to analyse complete sequences of dam failure, whereas the analysis of sub-systems is better suited to fault tree analysis.

Today, the use of expert judgement for estimation of failure probabilities is essential. This is, among other things, due to the fact that the available documentation of dam installations and the database on historical incidents is commonly insufficient. The establishment of an adequate system for the reporting of incident data would be of considerable benefit for future risk analyses.

Risk analysis safety assessments are heavily dependent on the quality of the available data. Throughout the analysis all assumptions and reasoning, and the documentation they are based upon, should be carefully documented. This enables future up-dating

of the analysis, for example if further documentation and data becomes available or if the level of detail should be increased.

Risk analysis is deemed to be a valuable tool in connection with dam safety, primarily in order to give insight into where the weakest links are to be found and how resources for dam safety can best be apportioned. The method, which so far has only been tested to a limited extent in this country, is attracting considerable attention and can be expected to be used a lot more in the future. This is one of the areas being given priority by the power industry for continued development work. Work is in progress within the industry on introducing a common system for incident reporting, which is expected to give better input for future risk analyses.

9.3. Incident reporting

The feedback of experience from events and incidents that have taken place is an extremely valuable way of increasing safety. During the development of the power industry, the emphasis lay on transferring experience within the design and construction areas, and how systematic this process was varies from company to company and probably also in time.

During the operational stage there has also been a feedback of experience, which can be illustrated by several of the reports in the series. However, it has not been systematic in the operational stage, which means that a considerable amount of data on safety is missing.

Other areas have had effective systems of incident reporting for many years, particularly the nuclear power and aircraft industries, and experience from this has been extremely good.

As a step in the work on improving the safety, a system of incident reporting should therefore be introduced within the dam safety area, and in order to make it as effective as possible it should be adopted for common use throughout the hydropower sector. It is of course also important for the system to be used in order to reach conclusions and spread information on them. In report 7 "The functional safety of spillway gates", it was also proposed that the system for incident reporting should be improved by establishing routines for circulation within the power industry, which could lead to improved designs and safety procedures. The international exchange of experience within the field of dam safety is also of significant value in this context. A comparison can be made with co-operation within the nuclear power area between different owners concerning the registration and processing of component faults.

Work is at present in progress within the RIDAS project on developing a common incident reporting system for the hydropower area. During Spring 1997, work started on the testing of a proposal for a reporting system at a certain number of plants and the intention is, as soon as certain adjustments have been made, to apply the system within the entire hydro power sector.

10. RESEARCH AND DEVELOPMENT WITHIN THE FIELD OF DAM SAFETY

The power industry has in recent years conducted extremely active research and development work within the field of dam safety through the Association of Swedish Water Regulation Enterprises, VASO and the power industry's organisation for energy-related research, ELFORSK. The present series of reports is an example of this. The research within the area has also been supported by both project assignments and more general support to, above all, the Department of Hydraulic Engineering at the Royal Institute of Technology, Stockholm but also to the Institutes of Technology in Luleå (now Luleå University) and Lund.

This has meant that the universities/institutes have in recent years been able to run doctorate and licentiate courses closely connected with dam safety issues, some of which have been completed.

Among the development projects carried out, mention can be made of methods for the status inspection of dams, in which the results of certain projects have been so good that the methods have been used for the investigation of sinkholes at the Bennett Dam in Canada, which is one of the largest embankment dams in the world.

In addition to recommendations and what is otherwise stated in reports included in this series, there is good reason to continue working on questions such as organisation, man-machine interfaces, preparedness and a continued investment in research and development efforts both nationally and internationally within both traditional dam safety issues and in connection with those mentioned above.

11. CONCLUSIONS AND RECOMMENDATIONS

The consequence classification and dimensioning guidelines proposed by the Committee for Design Flood Determination (the Committee) involves a significant tightening of the requirements for Consequence Class I dams with respect to design flood. A dam failure can have serious consequences, and the principal responsibility for the safety of a dam rests with the owners.

When they were issued in 1989, the Committee's guidelines were regarded by many as involving exceptionally high flows, but as calculations were successively completed for different rivers, and following the experience gained in connection with floods that occurred in Sweden in both 1993 and 1995 coupled with the heavy flooding that took place in Norway and Germany in 1995 and later, this view has changed and there has been a general acceptance of the level applied in the guidelines.

In addition to the recommendations and the other statements made in the reports included in this series, there is every reason to continue working on questions such as organisation, man-machine interfaces and preparedness, and to make further research and development efforts both nationally and internationally on traditional questions connected with dam safety as well as on those specified above. This work has already started.

It is important that the work which has already started on adaptation to the Committee's guidelines should be carried out in a responsible and competent way, and suitable that in this context an extensive overview should be made of the safety level so that the increase in the dam safety level aimed at in the Committee's work will really be achieved, even where factors other than high floods involve significant risk factors. This could, for example, concern the design of the dam or its current status. It is particularly important, of course, that consideration be given to other similar factors in time where rebuilding is to be carried out so that major resources are not wasted without achieving the required increase in safety level. Risk analysis is deemed to be a valuable tool in work connected with dam safety, including this particular aspect.

An incident reporting system is judged to give the preconditions necessary to continue working systematically on finding ways of improving dam safety. A system of this kind is at present being developed for the purpose of dam safety.

In certain cases, there may be uncertainty concerning the effects of certain factors. Should this be so, sensitivity analysis is recommended in order to shed further light on the matter. Consideration can be given to uncertainty regarding the real discharge capacity of a spillway, for example, by analysing which water levels in the reservoir will be the consequence of different assumptions. If there is considerable uncertainty, wherever possible testing should be carried out. A systematic way of analysing and evaluating the safety of existing dams is the so-called SEED analysis (Safety Evaluation of Existing Dams), which has been developed by the Bureau of Reclamation and is applied in the USA and various other parts of the world. Similar detailed evaluations of dam safety have been carried out for a number of dams in Sweden and are recommended in the power sector guidelines for dam safety, RIDAS.

During the adaptation or compliance process for existing dams, it is also important to

carefully review conceivable occurrences and thus learn the way the system functions while at the same time acquiring a mental preparedness for entirely unanticipated combinations of events in connection with high floods. For this reason, it is also important for personnel with positions of responsibility for the rivers to take part in or follow the work. It is also important to clarify instructions and areas of authority so that the measures assumed in connection with the dimensioning work are really adopted if the need arises. The same applies to agreements between different companies, which in a critical situation must co-operate in an effective way. It is also important for attention to be given to questions concerning dam safety, for example in connection with the increased use of contractors or where the manning situation changes, which may have an influence on call-out response times and thereby mean that the need for and demands on the reliability of systems for automatic monitoring and control increase in connection, for example, with spillway gates.

12. REFERENCES

12.1. Survey and Development Projects related to the new Swedish Guidelines for Design Flood Determination

1. Huvudrapport

Main report, see 2

Malte Cederström, Vattenfall AB

2. Main report (this report)

Malte Cederström, Vattenfall AB

3. Dimensionerande sektioner i vattendrag

Limiting sections in watercourses

Karl Rytters, VBB Anläggning AB, SWECO

4. Skred i nipor

Landslides in river bluffs

Rolf Christiansson, Vattenfall Hydropower AB

Erik Anér, Vattenfall Hydropower AB

5. Verklig avbördningskapacitet

Real spillway discharge capacity

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6. Drivgoods vid dammar

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7. Utskovsluckors funktionssäkerhet

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Michaela Dan, Royal Institute of Technology, Stockholm

9. Flödesdämpning vid svenska dammar

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Karl Rytters, VBB Anläggning AB, SWECO

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Klas Cederwall, Royal Institute of Technology, Stockholm

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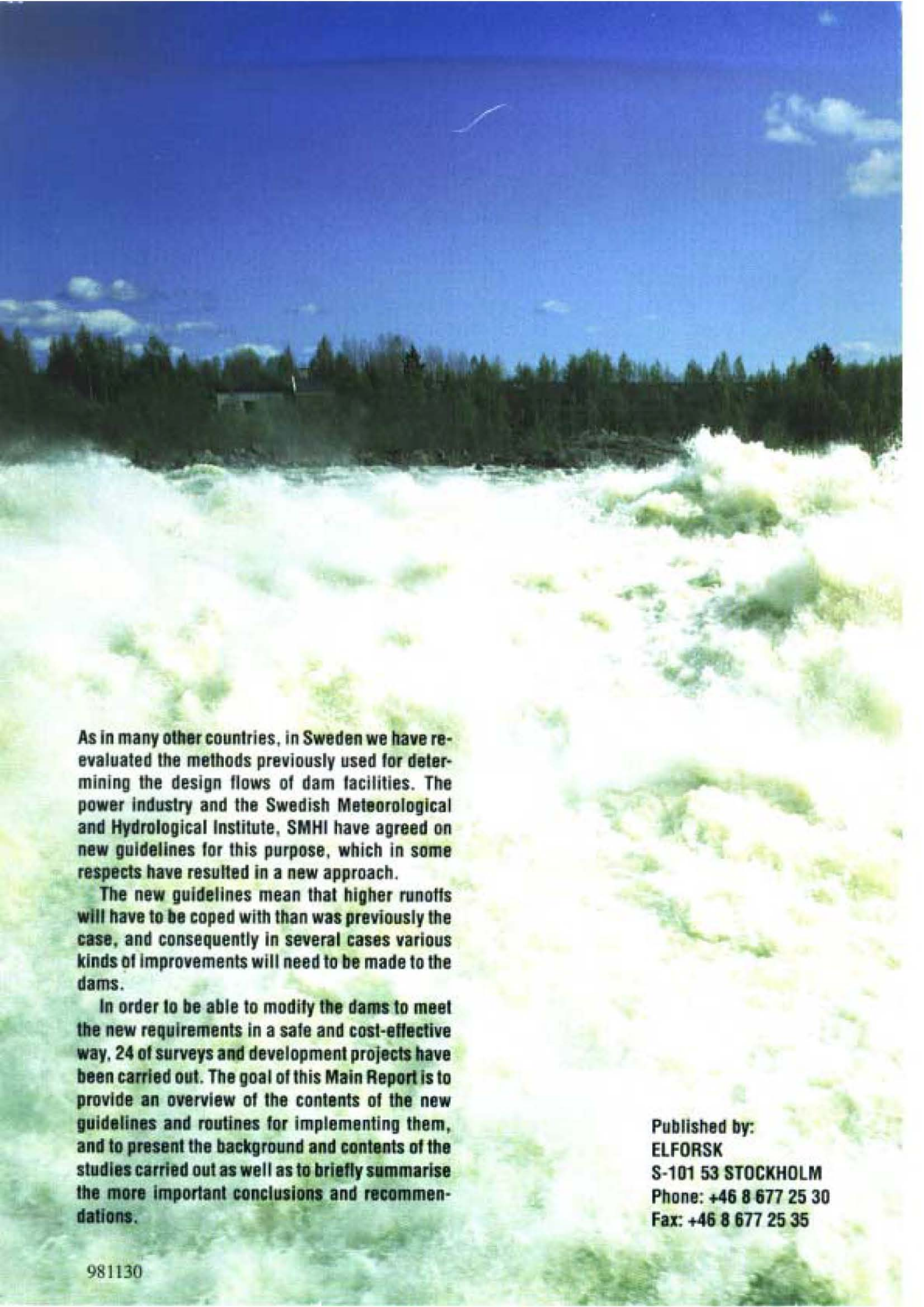
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26. **Risikanalys i dammsäkerhetsarbetet**
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As in many other countries, in Sweden we have re-evaluated the methods previously used for determining the design flows of dam facilities. The power industry and the Swedish Meteorological and Hydrological Institute, SMHI have agreed on new guidelines for this purpose, which in some respects have resulted in a new approach.

The new guidelines mean that higher runoffs will have to be coped with than was previously the case, and consequently in several cases various kinds of improvements will need to be made to the dams.

In order to be able to modify the dams to meet the new requirements in a safe and cost-effective way, 24 of surveys and development projects have been carried out. The goal of this Main Report is to provide an overview of the contents of the new guidelines and routines for implementing them, and to present the background and contents of the studies carried out as well as to briefly summarise the more important conclusions and recommendations.

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