Main Report 1992

THE NORWEGIAN DAM SAFETY PROJECT

Sponsored by:

NVE – Norwegian Water Resources and Energy Administration
Safety and Emergency Planning Department
VR – Water System Management Association

Cover photo: Dam Vinkelfallet, Midt-Gudbrandsdal Energiverk as, under flood May 23th 1992.

Main Report 1992

THE NORWEGIAN DAM SAFETY PROJECT

Sponsored by:

NVE – Norwegian Water Resources and Energy Administration
Safety and Emergency Planning Department

VR – Water System Management Association

FOREWORD

In recent years there has been a considerable reduction in the constructioı of new dams for hydro-electric power and water supply in Norway. A pos sible result of this is that professional expertise on dams and dam buildin; will disappear, and this in turn will have serious consequences for dam safet) Continous vigilance and awareness is needed to combat this problem.

Those who possess the ultimate responsibility for the operation of th dam installations in the future, do not always have a background in technica construction. Nor will they have experience from the period of constructioı of the dams. There is a danger that their attention will be directed, only to : very limited extent, to safety considerations related to the dam structure an operation of the dams.

Dam safety is the result of technical and ethical standards interactin; with financial considerations.

There is a danger that, in a future world where financial consideration are attributed greater emphasis, ethical and safety factors will be relegated t the backstage. The precedent from the shipping industry is an alarming one.

In many cases a dam can have a lifetime of several hundred years, bu this does not mean to say that it will function for the whole of that perio without problems. In the real world faults do arise, or to put it bluntl) anything can go wrong.

There is only one way to avoid mishaps. Systems for analysis, control an safety are needed to ensure that faults and weaknesses are discovered in time They should also ensure that the problems which do arise are solved befor they can develop into more serious accidents.

With oil production activities in the North Sea and increasing attentioı being paid to environmental disasters and other hazards arising fron industrial production, awareness of such issues is greater than it ever has beeı in the past. The oil industry has already adopted other analytical tools an safety procedures on which one can draw. This is the reason the Dam Safet Project was initiated in 1988.

The Project has examined the situation as it is to-day, looked at what caı be done to improve safety and put forward ideal requirements. The Projec has not considered itself bound by to-day's rules and regulations.

The report emphasises the duty of the dam owner himself to assum responsibility for the inspection of his own installations. The attitude tha " as long as we do not hear from the authorities then safety must be in order must be combatted.

Sound safety procedures require that each individual dam owner either on hi own or in cooperation with others, retains, develops and builds up the require professional expertise, and that systems are established which record how th dams were originally constructed, and how safety measures and maintenanc work have been and are being undertaken.

The report is divided into 3 main chapters and 6 short appendices:

Chapter 1 gives a summary of the contents of the report. Furthermore it looks at the question of responsibilities and describes how dams might be classified in groups on the basis of the consequences of failure.

Chapter 2 deals with the major risk factors and sets out a series of proposals for safety measures and procedures in connection with the operation of the dams.

Chapter 3 examines the most important technical aspects of dam safety.

The Appendices contain amongst other things proposals for changes in the existing Norwegian Dam Regulations.

Our purpose is first and foremost to set in train a process whereby dam safety work is directed to a greater extent towards problems in existing installations.

We hope that this report will initiate a very necessary debate within the professional milieu, and that many reactions and comments will be received. This will hopefully ensure that the work on dam safety issues will be brought up on to a plane where both those responsible for dam safety and society as a whole can cooperate.

Oslo
December 1992

The Steering Committee:
Bjarne Nicolaisen   Jan Daleng   Thorleif Hoff   Dagfinn Lysne

Project Manager:
Svein Larsen

TABLE OF CONTENTS

1 DAM SAFETY – RESPONSIBILITY AND IMPACTS

1.1 Dams and Accidents

Modern Norwegian dam building started around the turn of the century when we began to exploit our hydropower resources. In the beginning masonry and concrete dams predominated, but later on, especially after 1950, large embankment dams began to dominate the scene. Throughout this period Norwegian dam technology has maintained a high professional standard, and the dams compare favorably internationally in terms of quality and safety.

A failure can have catastrophic consequences

A water reservoir behind a dam represents an enormous energy potential which might cause catastrophic damage in case of dam failure.

It is felt by everyone involved in the establishment and operation of a dam that the structural safety of the dam must be such that failure is unthinkable.

We do know however that dam failure catastrophes have occurred, and they occur now, even in countries which are technologically advanced. In Norway we have not experienced large dam catastrophes. We have however had a number of failures of smaller dams below 15m height.

A dam cannot be regarded as an absolutely safe structure. It is through recognition of the presence of the risk factors that one can work to reduce and remove these factors so that the end result is acceptable.

Allowance must be made for abnormal operating situations

In the intense construction period we have experienced in Norway in recent decades, the concept of dam safety has been closely associated with planning and construction, and methods of calculation, loads, material properties and construction have been central concepts. But dam safety is also to a large extent dependent on how we supervise, operate and look after the dams, how well we understand and are prepared for various occurrences and situations which may arise in the operating phase. This especially was what made NVE (The Norwegian Water Resources and Energy Administration) initiate a project of cooperation with VR (the Norwegian Association for Watercourse Management) and dam owners on dam safety in 1987. The preliminary project issued the report: "Risk analyses for dams" in 1987 and the project itself started by establishing a steering committee in the autumn of 1988.

The manager of the project started work in April 1989, and this is when the practical work started. The project was completed in 1992.

The project has been based on the present situation and has made proposals as to how to maintain dam safety during the operating phase. Several questions relating to this problem, such as ageing, flood diversion, overtopping, leakages, operating safety of flood gates and contingency planning have been examined. In addition such issues as the bringing together of practical experience, dam failure statistics and risk evaluations are also dealt with.

Some subjects are dealt with in separate subsidiary reports. This main report contains material both on the subjects dealt with in the subsidiary reports and on other subjects discussed in the dam safety project.

1.2 Target Groups

- All categories of dam owners represented by the individuals who are responsible for planning, building, operation, inspection and maintenance of dams.
- Advisors giving assistance to dam owners.
- Public authorities with administrative responsibility for the safety of dams.
- Public authorities with responsibility for rescue operations in case of catastrophes.

1.3 Summary

1.3.1 Division of responsibility

Both the dam owner and NVE-T (the Norwegian Water Resources and Energy Administration – Safety and Emergency Planning Department) are responsible for dam safety and it is important that the roles, division of work and types of responsibility are known and reciprocally acknowledged by the two parties.

In many cases actual roles may differ from the formal ones. This may lead to uncertainty and a reduction in dam safety.

The dam owner carries main responsibility for dam safety

The dam owner carries main responsibility for maintaining dam safety at an acceptable level and he himself must initiate the necessary measures to achieve this.

NVE-T shall, on behalf of the public, ensure that the dam owner carries out the necessary measures and that the dams have an acceptable standard of safety. In introducing new concepts such as requirements to internal quality control, some uncertainty may arise in relation to roles and division of work.

1.3.2 Safety programme for existing dams

The dam owner must have a safety programme.

The responsibility for the safety of a dam lies with the dam owner. In order to fulfil this responsibility, he must carry out a number of activities which should be set out in a safety programme. In Chapter 2 we propose contents for a safety programme for existing dams.

In comparison with present practice it contains some new elements:

- Contingency planning for abnormal situations
- Safety revisions
- Load recording
- Damage and accident reporting
- Risk analyses
- Discussions on failure probability and studies on the impact of failure.

1.3.3 Safety revisions

A central element in any safety programme is to undertake safety revisions. This is more fully discussed in Section 2.7.

Safety revisions must be carried out when safety norms are altered

It is especially important that safety revisions are carried out when for instance safety norms are altered.

Safety revisions are carried out with respect to actual physical dangers.

In the project we have dealt with the following in particular:

- Safety against failures due to floods
  - Flood loads (Q_{1000} and PMF)
  - Blockage of spillways
  - Functional failures in gated spillways
  - Capacity evaluations of shaft/tunnel spillway
  - Overtopping of embankment dams
- Leakages through embankment dams
- Slides into reservoirs
- Ageing of concrete dams.

1.3.4 Impact related safety

Major potentials for accident require major safety provisions

There is reason to believe that a failure in one of our large dams would be an accident of the worst possible dimension in Norway, while a failure in one of our smaller dams could pass without serious consequences.

We therefore propose that dams be classified according to their failure consequences and that appropriate safety standards are laid down in relation to the failure consequences.

The failure consequences will have a bearing on standards in relation to:

- Dam owner's safety programme
- Dam owner's organisation and professional competence
- Requirements associated with accidental loads
- The extent of NVE-T's inspection.

1.4 Responsibility and Division of Work

The division of responsibility and tasks between the dam owner and NVE must be clear

It is normal to divide dam safety work into two main parts. The first part concerns the work directly connected with individual dam installations. The second includes a general part which is of indirect use in the security work on an individual installation. There will be a natural interrelation between the two parts in that experience from individual dams will affect the general part and it will also affect Acts, regulations, guidelines, norms and experiences.

On the other hand, the content of the general part will form the basis for the safety work of individual dam installations.

■ **At present there are two main parties responsible for dam safety:**

- Dam owner
- NVE, Safety and Energy Planning Department (NVE-T).

It is important for dam safety that roles, division of work and type of responsibility are recognized and mutually accepted by the two parties. In such relationships actual roles often deviate from formal roles. If this deviation is too great it may lead to weakening of dam safety.

1.4.1 Safety work for the individual dam installation

The dam owner

The individual dam owner plays the principal role in this safety work because *the individual dam owner must make sure that dam safety is at an acceptable level for the dams that he owns.*

NVE

The role played by NVE-T is dictated by its main task: *NVE-T shall, on behalf of the public, control and approve the safety standards of the dam owner's dams.*

An important element in dam safety work is determining what is the acceptable safety level. Both parties are independently responsible for this.

The safety level and the dam owner's job are set out by the dam owner himself on the basis of:

1. Acts and regulations
2. Norsk Standard (Norwegian Standard)
3. General recommendations or guidelines worked out by NVE, dam owners' organisations etc
4. Internal company guidelines
5. Unwritten, general professional norms
6. Direct requirements or requests from NVE-T concerning the individual dam
7. Dam owner's evaluation and assessment regarding the individual dam.

1.4.2 General safety work

The general part of dam safety work consists of developing and maintaining:

General basis

- Acts and regulations
- The Norwegian Regulations for dams, part II, rules and recommendations
- Norwegian standards
- Guidelines, norms and experience.

NVE is responsible

NVE-T bears principal responsibility for Acts, regulations and the Norwegian regulations for dams, part II. Development and maintenance of these should however take place in close cooperation with dam owners' organisations, dam owners and other bodies in the field (consulting engineers, research institutes suppliers and construction companies).

Cooperation

All parties participate in developing and maintaining informal guidelines, norms and experience, but it seems natural that the principal responsibility for this should lie with the dam owners' organisations and NVE-T.

1.4.3 War and sabotage loads

A practice has been established that the safety level associated with these types of loads is stipulated by the authorities. This task originally fell to KSFN (The Electricity Supply Civil Defence Board), but is now the responsibility of NVE-T.

Traditionally, the safety level for the individual dam was defined through detailed instructions relating to design and construction.

1.4.4 Acts and regulations

Two Acts have a central place as regards dam safety.

- Watercourse Regulation Act (Act of 14 December 1917 No 17 on water course regulations) with revisions.
- Watercourses Act (Act of 15 March 1940 No 3 on watercourses) with revisions. The Acts stipulate main principles, but give no indication of what is acceptable safety.

The Watercourses Act forms the basis for two regulations:

- "The Norwegian regulations for planning, construction and operation of dams" (the dam regulations) which came into force on 1 Jan. 1981.

This is principally a technical regulation for planning and construction of dams and it contains detailed safety requirements. Chapter 5 of the regulations contains requirements in relation to the operating phase. These are more generally formulated than the requirements relating to planning and construction and Chapter 5 does not contain any detailed recommendations in the dam regulations part II.

New installations
Technical regulations

"The Norwegian regulations for planning, construction and operation of dams" apply formally to dams built after 1981, and the regulations contain no specific provisions for dams built prior to this. The regulations will apply to alteration of old dams. For dams constructed prior to 1981 the provisions of the regulations will serve as a professional norm.

- "Regulations for inspection of installations in watercourses" came into force on 4 Feb. 1992. The regulations principally set out provisions for the official inspection of dams carried out by NVE-T.

Older installations

For owners of older dams (built before 1981) the regulations imply that operation and maintenance shall be carried out in a warrantable manner, and in accordance with orders from NVE-T. What constitutes "warrantable manner" is not specified, but a plan of operation corresponding to the requirements in the dam regulations subsection 5.3 "Plan of operation" would constitute a norm.

For dams not subject to official inspection in accordance with watercourse licenses granted for development or permissions complying with the Watercourses Act, the dam owner must submit plans, information and programmes relating to construction, operation and maintenance to NVE-T for assessment and approval.

It would be an advantage if the regulations contained a definite order for all dam owners to submit such necessary information to NVE had this not been submitted previously.

1.5 Internal Quality Control

"Regulations for inspection of installations in watercourses" were revised by Royal Decree 10 Jan. 1992, and the revision came into force 4 Feb. 1992.

Section 4 of the regulations states:

"The installation owner can be ordered to carry out internal quality control and provide systems for internal quality control to ensure that requirements laid down in these regulations are complied with".

Since the introduction of the regulations there has been some uncertainty and divergent views within the profession as to the implications of this section.

The reasons for this are as follows:

General internal quality control

The concepts "internal quality control" and "systems for internal quality control" derive from "Regulations for internal quality control" which were introduced 1 Jan. 1992. They apply to all enterprises and official activities.

The intention of the Regulations for internal monitoring is that the companies themselves shall arrange for and carry out a systematic control that current requirements pertaining to health, the working environment and safety, as set out in the Regulations are complied with. The different inspection authorities will coordinate their work and will to a large extent abandon detailed quality control.

The Regulations for internal quality control apply to a number of Acts (with Regulations) and the relevant inspection authorities. Acts (Regulations) which regulate dam safety and NVE-T's inspection activity in this field are not covered by the internal quality control regulation.

The rules on internal monitoring are determined on the basis of comprehensive Norwegian research work (NOV 1987: 10 and 32, O.t. prp. No 48 (1989-1990), recommendation No. 43 (1989-1990)).

The introduction of "internal quality control" in "Regulations for inspection

Internal quality control in the hydropower profession

of installations in watercourses" has taken place without any special thought as to what the implications would be for the individual dam owner, NVE-T and dam safety.

The Ministry has made comments linking this to the general use of internal quality control.

The hydropower profession and NVE have cooperated in initiating "project internal quality control" in order to establish guidelines for what an internal monitoring system should include and how it should function. The guidelines will be available in the middle of 1993.

In the field of dam safety we presently have a comprehensive system of regulations which imposes requirements on the dam owner in planning and construction of a dam. Internal monitoring systems which encourage adherence to these requirements are important in dam safety work. To define the dam-owner's and NVE-T's tasks and roles in this monitoring work should be a natural part of this "internal quality control project".

Operating rules

With regard to requirements to be imposed upon the dam owner during the operating phase, present regulations are inadequate. The dam owner is responsible for dam safety during the operating phase, but this is not reflected in the Regulations. In order to give the internal monitoring system any value, it is a prerequisite that more detailed requirements are set out in operating regulations for dams. This should be done through the ordinary system of regulations and not through "internal monitoring rules". "Internal monitoring" does not mean to set out the requirements to be complied with, but to formulate a plan of action which will ensure that the requirements are complied with.

"Internal monitoring" in its proper definition also means that the inspection authority (NVE) should aim at shifting its activity from monitoring the dams themselves to monitoring the dam owner's internal monitoring systems.

NVE's inspection arrangement

An evaluation of the consequences for dam safety involved resulting in such a change of strategy should be closely examined before deciding on this as the official policy of inspection. Our largest dams represent such a potential for damage that it is a sensible arrangement that NVE itself inspects the safety of such dams at regular intervals.

1.6 Methods for Risk Analyses

1.6.1 General comments

Calculated risk implies a combination of the probability for unwanted occurrences (dam failures) and the extent of the consequences connected with these occurrences (damage resulting from the failure). The risk can be indicated in numerical values if the consequences and probability can be expressed in figures or by describing a set of occurrences and associated consequences.

In dam safety work the use of risk analysis methods can give a better basis for clarifying risks associated with dams than traditional ways of indicating safety.

1.6.2 Impact analysis for dam failure

An impact analysis of a dam failure will consist of three parts.

Hydraulic evaluation of the condition of the dam

1. Outlet discharge from the reservoir

This waterflow/time curve will form the basis for the assessment of damage downstream. The picture will often depend entirely on which assumptions are made concerning the outlet waterflow.

The decisive factors are:

- Maximum extent of the failure and the development of the failure
- Reservoir water level
- Size of inflow flood

The calculations should be based on an actual failure situation and should select assumptions which are unfavorable but within realistic limits.

2. *Dam breach and calculation/evaluation of the failure wave*
The most important parameters are:
- Maximum flow downstream with associated water levels
- Time from failure to wave front and maximum flood level occurring
- Characteristics of the wave front.

There will always be great uncertainty attached such calculations. The need for accuracy depends on the intended application of the calculation/evaluation. In many cases a single evaluation will be sufficient. This will especially be the case for small dams in unpopulated areas, and where distance is short to downstream reservoir. In some cases it may be necessary to employ sophisticated calculation methods in order to estimate the extent of the failure wave downstream in the watercourse. In any case an advanced knowledge of hydraulics is necessary to carry out such calculations.

In an evaluation it must be made clear whether dam failure is expected in a flood situation.

3. *Damage impact assessment*
On the basis of the failure wave evaluation a damage impact assessment must be carried out. This is discussed in more detail in Section 1.8.

Impact analyses may have the following objectives:

Objective

- *Combine with a probability analysis to give a quantitative assessment of the risk at individual dams or groups of dams.*

  Risk in terms of:
  - Loss of life
  - Financial loss.

This application of rigorous impact analyses is considered relevant for only a few of our largest dams.
- *To account for the dam's position in an impact grading system.*

The idea is that the impact grading will affect the demands made on the individual dam. In the first place these are the demands in connection with PMF (Probable Maximum Flood) and other accident loads as well as demands concerning inspection/contingency arrangements. Reference is made to Section 1.8.

The damage impact classification may also feature in a dam failure insurance arrangement where the insurance premium is made subject to the impact classification.
- *Combine as part of a contingency arrangement in connection with abnormal situations.*

Having a survey of likely consequences of a dam failure must be considered very important in order to reduce the extent of damage in critical situations. Reference is made to Section 2.4.

■ Division of work between NVE-T and the dam owners

Division of work between the dam owners and NVE concerning impact assessment must be clarified

Calculations of dam failure waves and dam failure consequences were traditionally carried out by the former KFSN which now constitutes the contingency section of NVE-T.

We consider that the dam owners themselves should be responsible for carrying out such evaluations. It is however not expected that such work will be taken up by the dam owners without further clarification of this question from NVE-T.

We propose the following steps:
- The dam owners prepare a simple dam failure impact analysis for their dams (maximum three pages).
- On the basis of this NVE-T determines the dam's failure impact

classification and whether further analyses are necessary
- Previous analyses are made available to the dam owner.

Alternatively the impact analyses could be carried out in a special project or a work group.

1.6.3. Probability analyses for dam failure

■ Analyses based on dam failure statistics

International experience

International statistics give valuable information concerning dam failure frequency with respect to:
- Dam type
- Age of dam
- Year of dam construction
- Cause of failure
- Geographic location.

Analyses based on general experience help to estimate the probability level for failure in a group of dams. There is little point in carrying out analyses for individual dams based only on such general figures. It may however be relevant to employ such figures for certain causes of failure in combination with other methods.

Appendix 6 contains data on probability levels for dam failure based on international experience.

■ Analyses based on assessed design failure loads, and an assessment of the probability of these occurring

The analysis principle may be used for causes of failures such as:
- High water level
- Wave impact
- Leakages.

Such analyses are very well suited to bring out differences in safety levels for embankment dams with different design, different reservoir operation and different types of spillways. The analysis may be supplemented with experience of other failure factors.

■ High water level

How high must the water level be for the dam to fail?

The dam's failure limit for water level load is determined. This is the highest water level the dam can tolerate without failing. Reference is made to Section 3.8 and subsidiary report no 5.

The probability for the occurrence of failure water levels is determined. This is arrived at by considering the following conditions:
- Probability for natural inflow flood
- Probable transfers
- Anticipated probability for reservoir level equivalent to NWL (Normal Water Level)
- The discharge capacity of the spillways at different water levels
- Uncertainty in determining flood frequencies, discharge capacities and failure water levels.

■ Wave impacts

How the water level comes about and what is the probability of it occurring?

Failure wave capacity is determined for the dam. The failure impact is indicated by a combination of significant wave height (H_S) and duration and should be based on the following conditions:
- The dam's ability to resist damage at upstream slope depending on:
  - Rock size
  - Number of layers
  - Degree of interlocking.
- The dam's ability to resist complete washout above NWL should damage

occur in upstream slope. This depends on:
 - Freeboard from top of dam to NWL
 - Rock size in crest protection
 - Width of dam crest.

How big must the waves be for the dam to fail?

- The dam's ability to resist wave runover over the crest:
  - Freeboard from top of dam to NWL
  - Rock size in crest protection and upper part of downstream slope
  - Rock size in dam toe.

Probability

The probability of failure wave impact occurring is determined with respect to the following conditions:
- Probability for wind velocity/duration in unfavorable direction (100^g sector)
- Relation between wind velocities over water and land
- The effective fetch of the reservoir

Damage to slope protection has often occurred in Norway and several cases of repair work are recorded. A more detailed theoretical analysis of the probability of dam failure due to wave impact should therefore be given priority.

The relation between wind velocity/duration and probability must be indicated by the Meteorological Institute for the different zones of the country and is possibly dependent on height above sea level.

■ **Leakages**

Failure as a result of leakages is not easily amenable to probability analysis for individual dams.

Drainage capacity, i.e. the amount of water the dam toe can drain from the dam without a failure occurring, may be determined specifically for each dam.

The probability of a leakage of a certain size occurring is more difficult to determine accurately for each dam.

How large leakages can the dam withstand?

It is however possible to indicate some standard probabilities which consider certain conditions at the dam.
- Maximum dam height
- Filter coarseness
- Any previous leakage irregularities
- Any design features like extremely steep valley sides
- Leakage surveillance
- Age of dam.

Reference is made to Section 3.7 and subsidiary report no. 3.

■ **Analyses based on the probability of failure of individual parts leading to dam failure**

Analyses of gate operation failure is such a form of analysis. The weakness of such an analysis is an inadequate basis for indicating probabilities. The figures for probabilities are therefore uncertain. Such analyses are nonetheless of value in order to clarify the following conditions:
- Which occurrences can lead to gate handling failures and which contingency system has been planned.
- How great is the probability for dam failure due to gate handling failure.

Reference is made to Section 3.5 and subsidiary report no. 6.

■ **Which types of analyses should be carried out**
- For existing and new dams with gates as flood diversion devices the dam owner should carry out a probability analysis for gate failure.
- For dams which can not discharge PMF, the dam owner should, with the help of an analysis clarify the probability level for dam failure as a

consequence of flood
- For dams with major failure impacts the dam owner should carry out probability analyses for failures as a result of overtopping/waves.

1.7 Resistance to Failure

Greater effort should be put into identifying possible failure consequences

Traditionally the safety of dams has been analysed and expressed in terms of design standards and loads. In analysing failure situations it is possible to obtain a more direct indication of security against certain occurrences as dams may have varying degrees of tolerance to impacts over and above the design standards.

■ **The following evaluations of failure resistance should be carried out**
- The dam's ability to resist high reservoir levels without failing
- The dam's ability to resist strong wind and waves without failing
- The dam's ability to resist large leakages without failing
- The dam's ability to resist large slides into the reservoir without failing.

It should become standard practice to carry out such failure resistance evaluations for all new installations.

Subject to failure consequences such evaluations should also be carried out for existing installations.

1.8 Impact Related Safety and Grading System for Dams

1.8.1 Background information

There are very large differences in failure consequences

We estimate that there are around 2 500 dams in Norway large enough to be subject to NVE-T's inspection.

The height of these dams vary from 2m to 140m. There is reason to believe that a failure in one of these dams with large damage potential could represent an accident of the worst dimension imaginable in Norway. A failure in one of our smaller dams could however occur without any serious damage. With this in mind it would seem obvious that the objectives to aim for in dam safety work should vary according to damage potential of a failure.

This thinking has been instrumental in influencing dam owners' and advisors' attitudes to dam safety, but it has not yet won through as a principle in the dam regulations.

The requirements for dams in relation to wars, the threat of sabotage etc. have however come about as the result of failure grading. This has included around 200 dams and there have been three different classes.

1.8.2 Objective

The objective of grading is to divide dams into groups where it is possible to set more or less similar requirements to dams within one group.

1.8.3 Criteria (Set of standards)

The damage potential of a failure will consist of several elements and an assessment of damage potential will also have to be based on a rather rough assessment based on dam failure wave evaluation.

The most important factors should be:

■ **Likely loss of life**

Extent of habitation

Critically affected area

This should be considered on the basis of the number of dwellings and to some extent the number of holiday homes in the affected area (10 holiday homes = 1 house). The critically affected area is the area downstream of the dam where a dam failure wave will arrive so suddenly that natural warning through rising water levels in the river will not take place.

Downstream of larger lakes the wave will subside sufficiently to give natural warning through rising water levels.

■ **Material damage**

There may be damage in connection with:

- Dwellings and holiday homes
- Farms and cultivated areas
- Industrial areas
- Roads
- Railways
- The dam installation with reservoir.

■ **Domino effect on downstream dams**

Account must always be taken of whether a small dam with an apparent limited failure damage potential could lead to failure of bigger installations downstream.

■ **Ground damage**

An extensive failure in an unhabited valley may lead to such large ground damage that the dam should be given high grading for this reason.

■ **Psychological impacts**

Confidence

Apart from physical consequences, a major dam failure in Norway would have psychological impacts. The public's feeling of security against dam failure is to a large extent a question of confidence in the profession, and this confidence would suffer a major setback following a failure, irrespective of consequences.

1.8.4 Grading system

A future grading system should be a joint system for war and natural loads and it should be based on the main divisions of NVE-TB's (Emergency Planning Section) present grading system (200 dams – 3 grades).

In the table below a system with 5 grades is outlined. The lowest grades consist of dams which are not included in NVE's inspection. Consideration should be given to establishing special grades for:

- River power plant dams in larger watercourses
- Temporary dams and coffer dams
- Special dams, such as tailings dams.

There is a natural and critical distinction between failures where human life is lost and where it is not.

Otherwise the boundaries between the grades will be quite arbitrary, and these should be adjusted during the classification work based on the desired number of dams in each grade.

Dam height

Physical damage potential

For the sake of simplicity the grading may be based on dam height. In addition, the number of dwellings in the critical area should be considered as a measure of how many lives are in danger. The other factors will be considered discretionary and may constitute a basis for the grading.

Classification Table

Grade	Dam Height	Total Dwellings in the Critical Area	Estimated No. of Dams
1	> 60 m	> 100	about 50
2	15 – 60 m	20 – 100	about 350
3	8 – 15 m	1 – 19	about 600
4	4 – 8 m	0	about 1500
5	< 4 m	0	

1.8.5 Requirements subject to impact grade

The majority of dam requirements are related to the service state, and these should be independent of impact grade. The type of requirements that may be reasonably differentiated are the following:

Exceptional loads

- Requirements as to whether the dam should resist exceptional loads, like PMF, congestion of spillways and slides into the reservoir

Quality control

- Frequency and quality of inspections and safety reassessments by the dam owner and NVE-T
- Requirements for operating reliability in extreme weather and flood conditions
- Requirements for the quality of all types of documentation on safety
- Requirements for the dam owner's organisation and professional qualifications
- Requirements for the warning and rescue services at a possible dam failure.

1.9 The Need for Revision of the Dam Regulations

1.9.1 General comments

The dam owner's procedure for ensuring the safety of a dam is laid down in general terms in **three** types of regulations:

- *Acts and regulations*

Included in these are the Dam Regulations part I. These are formally laid down by the Ministry of Industry and Energy.

- *Regulations for dams part II*

"Rules and recommendations". These are formally laid down by NVE-T.

- *Informal norms and practices*

These are laid down by the dam owner and his advisor in cooperation with NVE-T. This project: "Project dam safety" makes proposals which are included in this category.

Advantages and disadvantages of regulations

There will always be a question of balance to know how much "informal norms and practices" should be formalised in the Dam Regulations part I and II.

It is not the case that dam safety is improved by having more norms and regulations formally laid down in the Dam Regulations parts I and II. The transfer of norms and practices to provisions in regulations have negative aspects e.g.:

- The regulations may be practiced in a more inflexible way than norms and practices
- A provision set out in a regulation will carry more weight than norms and practices and this may lead to less vigilance on the part of the dam owner. The process of establishing regulations must be subject to strict quality control

- A regulation may be less flexible with respect to necessary future revisions.

The advantages of having provisions formalised in regulations is to indicate more clearly the level dam safety work should have for the dam owner and NVE-T.

Decisions as to such a level are laid down in two types of provisions:

- Provisions to the effect that the dam owner (or NVE-T) shall carry out certain types of tasks (such as safety evaluations, inspections, material examinations etc.).
- Provisions with respect to safety levels necessary for the dams (for example PMF, filter requirements, freeboard).

Existing installations

For existing dams the regulations requirements should principally be of the first type.

Through the work the project has had carried out within different fields the need for possible revision of the regulations has come to light. As a result of this "Proposals for revision of the dam regulations" is presented in the appendix. It must be pointed out that the project has not carried out a thoroughgoing examination of the dam regulations with the intention of revision.

NVE-T should initiate a complete discussion of the dam regulations and follow up with a revision of the regulations. The work should take place in cooperation with the profession and a central element in this work should be to formulate regulations and "rules and recommendations" (Dam Regulations part II) for the operating phase.

1.10 The Need for Rehabilitation and Strengthening

The following measures may be necessary to rehabilitate some of our dams in order to secure them:

Floods

- **Rebuilding/removal of bridges across fixed spillways**

This may be relevant where there is serious danger of blockage in high floods and where the consequences of blockage are unacceptable.

- **Stoping of tunnels and shafts in spillways**

This may be relevant where existing spillway capacities are too small in relation to probable maximum water level.

Waves

- **Heightening of embankment dams, alternatively constructing concrete parapet**

This may be relevant where the original freeboard is too small in relation to present requirements for freeboard and flood sizes.

Leakages

- **Placement of large rock dam toe at existing embankment dams**

This may be relevant where the dam's drainage capacity to handle potential leakage must be increased

- **Improve upstream slope protection of embankment dams**

The quality of former upstream slope protection has in practice often proved to be inadequate. It will probably be necessary to improve the quality of upstream slope protection on many dams where damage has not yet taken place.

- **Increase flood capacity in gated dams**

This may be relevant where there are flood gates and embankment dam sections, and where overtopping of the embankment dam sections is unacceptable. In dams where the flood diversion takes place with the help of gates, maximum capacity will often be lower than probable maximum flood.

Operating safety

- **The installation of different standby systems for operating floodgates**

This is most relevant for installations where there may be serious consequences if operating the gates as intended is difficult.

- **Reconstruction of old needle/beam dams**

Operating such dams during extremely large floods calls for an organisation and manning that is not available today, and a reconstruction (modernization) of such dams will often be necessary for safety reasons.

Ageing

- **Rehabilitation and strengthening of concrete dams**

Different ageing processes work on concrete. Various types of rehabilitation of our concrete dams may be relevant from a safety point of view in order to keep the ageing processes under control. In the most extreme cases, total reconstruction may be necessary.

- **Rehabilitation and strengthening of masonry dams**

Masonry dams require regular maintenance of joints to avoid leakages that threaten the safety of the dam. In some masonry dams the safety requirement for stability may be lower than is the requirement today, and the ability to withstand overtopping may largely depend on the quality of the stone at the crest.

An improvement of the safety will in many cases be achieved by reinforcing the dam at the water side and at the crest.

At spillway sections there may also be necessary to reinforce dams at downstream dam toe to prevent single blocks from falling out. Masonry dams are a type of dams in which a number of failures have been experienced.

- **Rehabilitation and strengthening of wood and steel frame dams**

This dam type is of a less durable quality and total rehabilitation must be considered.

2 DAM SAFETY DURING OPERATIONS

2.1 General Comments

- Measures to avoid failures
- Measures to reduce damage in case of failure.

The main part of the work will concentrate on measures to avoid failures and such measures should be divided into the two groups:
structural safety and operational safety.

2.1.1 Structural safety

The structural safety consists of basic safety level from the time of construction and modification of this over time.

Physical modifications

The modification of safety levels arise from:

- Deterioration of the structure over time as a consequence of different ageing processes.
- Changes in actual external loads.
- Changes in the design conditions for operation and loads.

Such changes entail an actual change in the safety levels, but there may also be a need to improve safety levels as a result of a changing notion of safety.

Changing interpretations of safety

Such changes may be:

- Changed norms for what are acceptable safety levels. (e.g. the Dam Regulation's provisions of floods and freeboard.)
- Improved methods of analysis.
- Improved basis for determining loads.

2.1.2 Operational safety

Operational safety means ensuring that the dam installation functions as intended in order to prevent the water level from rising too high. The operational safety is taken care of through several components in the dam owner's safety programme:

Operating rules

- Operating routines for normal conditions
- Operating routines for extraordinary conditions
- Regular operating maintenance
- Testing of equipment and operating exercises.

It is important, but difficult to ensure safe operation under extraordinary conditions.

This is discussed in more detail in Section 2.4. There have been occurrences where the dam did not operate satisfactorily during extraordinary conditions.

The operational function of the dam (reservoir) may pass through several development stages before a failure may occur.

Normally however, the various development stages will be covered by three sets of operating rules.

- Operating rules for normal conditions.
- Operating rules for flood conditions.
- Operating rules for critical conditions, (contingency plans for abnormal situations at dams.)

At what stage in the development one set of rules is abandoned to be replaced by another will vary.

A common operating situation will be as follows:

1. Normal operating situation
   This situation is covered by operating rules for normal conditions.
2. Floods and bad weather are forecast
3. The forecast floods and bad weather have started. Flood diversion and other operation function normally. Minor faults arise and are corrected.

Development stages 2 and 3 are covered by operating rules for flood conditions.

4a. Floods and bad weather develop towards a possible catastrophe and/or flood diversion and other operations do not function normally or
4b. serious, sudden structural damage occurs.
5. The situation is sufficiently serious to lead to failure
6. The situation is sufficiently serious to mobilise warning and evacuation of the population downstream
7. The situation is so serious that it will very likely lead to dam failure
8. Dam failure takes place.

Development stages 4 to 8 should be covered by the contingency plan.

2.1.3 Dam owner's safety programme for the operating phase

Dam safety during the operating phase should be based on the following principles:

Basic steps:

Dam safety

The dam owner is responsible for the safety of his dam.

Dam safety means ensuring that there are no uncontrolled, damaging water discharges (as a result of wrongful operation or dam failure) or that water levels higher than expected occur.

The responsibility of the dam owner entails actions in various detailed steps below.

Detailed step 1:

Safety programme

To fulfil his responsibility the dam owner shall prepare, carry out and control programmes for the activities he considers necessary for safety in the operating phase. The extent and the content of the plans shall be adapted to type of dam, level of safety and dam failure consequences.

Organisation

Professional expertise

The dam owner shall be backed by an organisation with relevant professional competence and finances that enable him to carry out the above tasks. Some skills may be provided by the organisation while others may be hired. The dam owner's programme for maintaining safety must also be adapted to his organisation structure, size and degree of competence. The need for outside skills must be made clear in an overall picture.

Reporting to NVE

The dam owner's plans must also be arranged in such a way as to be accessible to NVE-T's inspection.

Detailed step 2:
A programme should include the following components to ensure operational and structural safety:

■ **Programme components to ensure operational safety**
- Documentation of conditions for operation
- Plans for spillway operation
  - Normal conditions
  - Flood
  - Extraordinary flood conditions and operating accidents (part of "Contingency Plan")
- Maintenance programme for flood control devices
- Technical tests and exercises
- Reporting and assessment of extraordinary flood conditions experienced and operating accidents
- Supervision of dam safety related operations
- Reassessment of operational safety.

■ **Programme components to ensure structural safety**
- Documentation of the construction
- Inspection programmes
  - Routine inspection by dam personnel
  - Annual inspection
  - Main inspection
  - Special inspection during and after extreme load conditions
  - Underwater inspection
  - Material inspections
- Instrumentation and monitoring programmes
- Load registrations
- Reassessment of structural safety
- Reconstruction and repair works
- Damage reporting
- Preparedness in case of accidents.

■ **Joint elements**
- Main reporting (every 3–5 years)
- Main safety assessment (every 15–20 years)
- Reassessment of operational and structural safety programme
- Risk analyses
- Dam failure preparedness
  - Warning
  - Impact assessment
- Reporting to NVE-T

The programmes should be put together from the separate elements into practical programmes. In many cases several elements will be combined in one programme. For example a dam warden will execute several tasks concurrently during a flood. These may be:
- Controlling gates
- Supervise flood diversion
- Inspect the dam for any damage during extreme loads.
- Take instrument readings
- Observe and photograph wave loads.

Internal checking and control

The programmes must be built up so as to contain an element of automatic checking throughout the system. As an example a main inspection should include, in addition to the physical inspection, a review of the annual inspection reports to check that:

- The inspections have been carried out
- That the inspections are at an acceptable professional level.

In the reporting it must be stated that this has been checked, and any deviation from the accepted standard must be reported. The programmes must be formulated in such a way that any reports on deviation are made throughout the system up to main reporting.

2.1.4 NVE-T's supervision

NVE-T is responsible for ensuring that the dam owner fulfils his responsibility of ensuring dam safety.

NVE-T's supervision of dam safety should be based on a well thought out strategic plan which gives priority to different types of activities.
In the first instance distinction should be made between:

- Activities aimed at the safety of individual dams
- Activities aimed at dam safety in general.

■ The safety of individual dams

Different degrees of supervision by NVE

In its supervision NVE-T may organize different degrees of supervision. NVE-T should grade its supervision according to dam failure consequences. Dams with major dam failure consequences should receive a more comprehensive supervision than dams with small failure consequences.

NVE-T should also organize more comprehensive supervision for dams where weaknesses have arisen and where dam owners have not carried out their safety work to an acceptable standard.

NVE-T should also set its level of supervision according to the dam owner's organisation, professional level and financial position. The dam owner's lack of resources may lead to reduced internal dam safety work and a need to increase NVE-T's supervision.

NVE-T should set its level of supervision according to the dam's safety level. Today there are several dams in operation of varying degrees of safety. Dams that are planned and constructed in accordance with the Dam Regulations are of a high safety standard. Dams constructed earlier may have a lower safety level because of lower requirements for loads, materials and designs or because of weaker control and documentation.

NVE-T should grade its supervision according to dam type. Certain dam types such as trellis dams are more liable to safety reduction over time than structures of more substantial character.

2.2 Planning and Construction Documentation

2.2.1 The planning and construction phase

There must be documentation from the planning and construction phase which accounts for all relevant aspects of the dam and which must include the following points:

- General information on the installation
- Flood diversion and loads
- Site conditions and dam construction
- Supervision and safety measures
- Additional information

Repairs

It is important that the documentation also includes the alterations which have taken place during the construction of the dam. Such alterations may give rise to damage or even failure.

The documentation should take the following form:

Complete documents
- A complete documentation
- A list of the complete documentation

An overview
- Key facts which show the important data needed for an inspection and any emergency situation

An executive summary
- A summary of the documentation relating to the safety of the dam.

For the following circumstances the documentation is important, but often lacking:

The geometry of the flood diversion system and its capacity.

The geometry and material properties at the top of embankment dams.

Flood magnitudes. The Dam Regulations stipulate extensive requirements for methods of calculation and documentation, but in the past calculations of flood magnitudes are often poorly documented.

Preconditions for operations. In some cases a certain operations philosophy may have been established during the planning phase. Assumptions which have a bearing on the safety of the dam should be summed up in a separate document. Today there may be personnel in the operations organisations who know the assumptions as they participated in the planning and construction of the dam.

It is especially important to document assumptions for operations which concern abnormal situations, as these are not normally handed down from person to person in the daily operations.

2.2.2 Operations phase

The tasks of the dam owner during operations will be as follows:

Checking and supplementing the documents

- Examine and check that the documentation from the planning and construction stage is adequate and that it is accessible in practical form
- Inform NVE-T. These are tasks that should be carried out at the following points:
  - When the dam's status changes from a construction division to an operations division
  - Regularly at about 15 years' intervals
  - At major changes in the regulations or norms concerning safety and requirements to documentation. (for example the Dam Regulations of 1981).
- Supplement documentation if it is incomplete. The practical steps in this should be:
  - The dam owner makes a survey of the documentation available and the shortcomings in this documentation
  - The dam owner considers the possibility and usefulness of procuring the missing documentation and proposes a strategy for obtaining it
  - The dam owner informs NVE-T on the dam's documentation and any plans on supplements

– The dam owner supplies documentation which is sent NVE-T.
For dams constructed before the advent of the Dam Regulations the documentation will in some cases be very inadequate. The Regulations' requirements for documentation do not formally apply to such dams, but the Dam Regulations will provide standards for these too.

The extent to which the documentation should be supplemented will depend on the possibility and the usefulness of procuring such documentation. For older dams with small failure impacts the documentation supplement should be kept at a minimum.

Incomplete documentation

Incomplete documentation may arise from:
- The documentation is missing
- The extent, form and quality of the documentation are not sufficient for present-day standards
- The documentation is based on outdated safety standards

• The dam owner must supplement documentation when all types of maintenance, repairs or reconstruction work are undertaken. The dam owner must ensure safekeeping of the documentation which ensures:

Storing documents

- The practical application
- Security against damage
- Security against sabotage.

2.2.3 NVE-T's task

NVE-T's task will be as follows:
- Ensure that necessary documentation is supplied for dams which are constructed according to the Dam Regulations
- For dams constructed before the introduction of the Dam Regulations, the dam owners must supply necessary documentation where they have not already done so.

This can be done either on application to the individual dam owner or in general in that NVE-T asserts, either via a circular or a change in the Dam Regulations, that the dam owner is obliged to provide such documentation for existing dams.

2.2.4 Documentary evidence of public safety requirements

What requirements have been set by NVE and have these been met?

The safety of the dam is based partly on actual, detailed safety requirements, partly on the dam owner's notion of adequate safety. The dam owner must make sure that there is separate documentary evidence that all, relevant public safety requirements are satisfied.

This may be arranged as follows:
1. A list of Acts and Regulations which apply to the dam concerned and which are relevant to the safety of the dam
2. A list of actual, detailed safety requirements as set out in the Acts and Regulations under 1
3. A list of the safety instructions given by the authorities for the individual dam
4. A list of the dam owner's documentation of the requirements mentioned under 2. and 3
5. A list of the approvals by the authorities of the dam owner's documents mentioned under 4
6. Correspondence in respect of requirements/orders, documentation and approvals should be labelled and kept in a separate file
7. The dam owner's documents.

Like the dam owner, NVE-T should also establish such an internal system in order to maintain a picture of orders given and documentation received from the dam owner.

2.3 Operating Procedures

For a dam owner the purpose of the day–to–day operations is to produce power or supply water and there are many routines for these functions. In this report however, reference to operating procedures only refers to the operational safety of the dam.

This applies mainly to operating procedures concerning water level registrations and flood diversion.

Operating procedures for flood diversion

Sound operating procedures constitute part of the safety system at an installation and a programme for this should be worked out.

The following operating procedures should be included in the programme:

- Overall operating rules in connection with flood diversion. At most installations a flood situation will require attention to various tasks, such as:
  - Reducing flood damage in downstream reservoirs
  - Avoiding damage alongside the reservoir
  - Ensuring that flood diversion systems function without fail
  - Avoiding dam failure.

The overall requirements may to some extent be contradictory. The overall rules of operation should define certain main alternatives available to those faced with an actual flood diversion situation.

The programme should be realistic and well thought out. There will always be a number of details which will not be included in overall operating rules.

One should be aware that contradictory requirements in a flood situation can be one of the reasons why the operating rules have not been cleared up, as such a clarification would reveal that some of the requirements are contradictory.

- Operating procedures for handling all flood devices and diversion works
- Operating procedures for water level registration (especially between highest regulated water level and probable maximum water level)
- Special operating procedures for bad weather and flood situations
- Procedures with respect to training of new employees, reorganisation etc.

Procedures and arrangements for critical situations are also to some extent related to operating procedures, but such conditions are described in Section 2.4 "Contingency work".

2.4 Contingency Work

2.4.1 Background information

The concept of contingency is a general one and is used in many connections. For power companies the concept has traditionally been associated with the work of the former Kraftforsyningens Sivilforsvarsnemnd (KSFN, Committee of the Electric Power Civil Defence Organization) which today is carried on by the Emergency Planning Section of NVE (NVE-TB). The purpose of this contingency work was primarily to secure electricity supplies in a war situation and in a contingency situation (the period prior to war).

Securing power supplies

Securing dam safety

In the new Energy Act this field is extended to include contingency against sabotage etc. in peace time.

NVE has suggested that contingency to secure energy supplies in natural crisis situations, such as major storms should be included in this contingency work.

War and sabotage

The field of the Emergency Planning Section of NVE has also included dam safety contingency in connection with war, sabotage etc.

Storms and inclement weather

For a power company the principal aim in a storm situation will often be to safeguard the functioning of the power supply. The power company may also be responsible for dams with an extremely large damage potential in case of failure, and the safety of these dams will be put to the test in such situations.

It is important to distinguish between:
- Contingency work for dam safety
- Contingency work for energy supply (or water supply).

It is further important to distinguish between:
- Contingency for man-made situations (war, sabotage etc.)
- Contingency for natural situations (storms, technical failures).

On the project only contingency work for dam safety arising from naturally occurring events is dealt with. It is important that all associated contingency work is coordinated. Contingency work in dam safety means to:
- Prevent an abnormal situation from developing into an undesirable occurrence
- Reduce the extent of the damage if the undesirable occurrence takes place.

The relevant undesirable occurrences in dam safety are:
- Dam failure
- Unintentional opening of gate
- Dangerously high water levels.

2.4.2 How to improve dam safety through contingency work

In carrying out contingency work the dam owner will improve safety in the following ways:
- By participating in the planning work and having an operational contingency plan the dam owner's staff, leadership and organisation will better be able to handle critical situations without dam failure or other undesirable events taking place.
- Through the planning work weak points may be uncovered and righted before potentially critical situations occur. Such weak points may have different characteristics as follows:
  - Technical design of the installation
  - Parts of operational contingency plan
  - Resources to be used in critical situations.
- Through the contingency work planning the dam owner's contingency measures are documented for NVE-T. This allows NVE-T to consider this in an overall consideration of the dam's safety and to address possible weak points in the safety levels.

2.4.3 Contingency work components

The contingency work may be divided into the following main parts:
- Situation analysis
- Operational contingency plan
- Plan for testing of equipment and training
- Carrying out and reporting on training of personnel and testing of equipment
- Reporting on and assessment of the handling of critical situations and near-critical situations.

■ Situation analysis

The situation analysis should result in measures in the form of:
- Operational contingency plan
- Plan for training and testing
- Technical improvements of the installation
- Plan for reserve equipment.

Situations of risk

The analysis may be divided into the following parts:
- Clarification and analysis of situations which may constitute a failure risk. These may be:
  - Large flood events
  - Operational errors in adjacent installations
  - Faults in spillway functioning
  - Obstruction of spillways
  - Sudden leakages
  - Slides
  - Failure in an upstream reservoir
  - Sudden serious damage to the dam.

  The most common events that call for attention are floods and bad weather with the risk of obstruction and faults in the operation of the spillways.

  Analyses of functional safety of spillways are an important part of contingency analysis. This is discussed in more detail in Section 3.5. Such analyses answer most of the following questions:
  - How does functional failure occur at the flood control devices
  - What measures can be taken to avert functional failure.
- Description of the dam owner's organisation, technical installations, communication and resources
- Description of the resources in the local community
- Impact assessments and ultimate limit assessments.

The consequences of various undesirable occurrences should be scrutinised in a contingency analysis. Such occurrences may be:
- Abnormally high water levels in the reservoir (in possible combination with high waves)
- Will handling of gates or needles be hindered?
- At what water level will dam failure start?
- Leakages
- At what leakage levels could dam failure start?
- Dam failure
- What are the consequences of a failure?
- What inhabited areas and means of communication will be affected?
- What available time is there for warning and evacuation?

■ Operational contingency plan

The operational contingency plan should be put into action when an abnormal situation arises. The plan must clarify:
- The dam owner's own organisation of the work during the contingency situation
- Warning procedures
- Performance plans which describe possible measures for different events
- Resources
- Internal and external information flows
- The dam owner's responsibility and authority during the contingency situation vis-a-vis other organisation's responsibility and authority (the police, NVE-T).

2.5 Inspection Procedures

The dam owner's inspections constitute an important part of the safety work for structural safety and it has always been normal procedure to carry out inspections, but after the introduction of the Dam Regulations in 1981 the work has been carried out more systematically.

Inspections alone are not enough

Inspections on their own are not sufficient to maintain structural safety and other elements which are discussed in chapter 2 must be included in a comprehensive programme.

It is possible that the emphasis on the need for inspections has detracted somewhat from other necessary elements of safety work.

Normal practice today on inspections is by and large satisfactory, and the project has therefore not devoted much attention to this subject.

It should be pointed out, however, that in addition to visual inspections, submarine and material inspections should also be carried out.

The elements of an inspection programme should be as follows:

- Visual inspections
  - Regular inspections carried out by operating personnel
  - Annual inspection
  - Main inspection
  - Special inspections under and after extreme load situations
- Submarine inspections
- Material inspections.

Alarm systems must be inspected frequently

The need for inspections varies greatly with dam type and the general condition and safety level of the dam. this should be reflected in the inspection programme.

As mentioned above it is important that other components apart from inspection are included in a comprehensive programme. This may be organised in various ways, but it will often be natural to carry out some of the tasks in connection with the main inspection.

Such tasks may be:

- To assess the dam owner's additional inspection activity.
- To summarize and assess the results of field monitoring
- To summarize load registrations
- To assess the need for altering the dam owner's safety programme
- To assess the need for more detailed safety considerations
- To assess the need for improvement work
- Provisions to the effect that the dam owner (or NVE-T) shall carry out certain types of duties (for example safety considerations, inspections, material examinations etc.)
- Provisions on the required safety levels of the dams (for example PMF, filter requirements, freeboard).

Through the project work, the need for revision of the present regulation has come to light. As a result of this, "Proposals for Revision of the Dam Regulations" is presented in Appendix 1. It should be emphasised that the project has not carried out a complete examination of the Dam Regulations with a view to revisions.

NVE-T should initiate such an examination of the Regulations, and then undertake a revision of the Regulations. The work should take place in cooperation with the profession, and in this work a central element should be to formulate "regulations and recommendations" (the Dam Regulations part II) for the operating phase.

2.6 Field Instrumentation and Monitoring

Programme of field measurements

Instrumentation of dams for measuring deformations, pore water pressures, stresses, seepage, temperature and other physical entities will be part of the dam owner's safety supervision.

The dam owner must have a programme for his measurements and monitoring during construction and operation. The programme must be adjusted

Professional assessment

to dam type, age and condition. The programme must be based on a clear philosophy and purpose of the measurements. The measurements must be supervised by professional assessment of competent personnel. The extent of the monitoring should be reassessed at intervals of approximately 10 years. The extent of monitoring may decline after the first 10 years of the dam's lifetime.

New measurements

The need for new measurements must also be considered in connection with damage or abnormal situations at the dams. Special monitoring needs may arise at very old dams, and the technological development also entails new technical possibilities for measuring.

The object of dam instrumentation and monitoring is mainly to register the condition of the dam and constitutes part of the arrangement to secure its structural safety.

Instrumentation is also part of the programme for operational safety. The object of field instrumentation is to register reservoir level, gate positions and other technical aspects relating to gate control.

A programme for dam instrumentation and monitoring should consist of the following:

- The principles and purpose of measurement
- Report on frequency of individual measurements and specifications of the persons responsible for carrying out the measuring
- Rules on recording, analysing and interpreting the measurements.

The results may not have to be interpreted as frequently as the measurements are undertaken. Assessment of the measurements during construction, initial impounding and first 10 years after construction should be carried out by a competent person. This should also be the case if subsequent measurements deviate from the norm.

Are measurements adequately considered?

- Extract of theoretical calculations with which the measuring results may be compared
- Rules on the reinterpretation of the measuring programme
- Rules on internal reporting and reporting to NVE-T.

The most important form of measurements are the following:

- **Leakage measurements for embankment dams.**

Such measurements are important throughout the operating life of the dam. More details on this are given in Section 3.7.

- **Surface deformations of embankment dams.**

Most deformations of embankment dams occur during the first ten years after construction. Long term deformations after this time may be followed up by measurements at longer intervals if the deformation pattern is normal, and total settlements is far from exceeding the camber of the dam.

The objective of measuring long term deformations is to ascertain whether the top of the sealing element and dam crest remain at adequate levels. This is done by levelling of bolts on dam crest and seal.

For larger dams our understanding of the movement patterns will increase by measuring the horizontal long term deformations and by carrying out the measurements some way down the slope.

Are older dams measured unnecessarily often?

Are older dams measured unnecessarily often?

During construction, initial impounding and the early years of the dam's operating time, it may be useful to measure frequently and to employ measuring points throughout the dam body. Such an extensive measuring programme is unnecessary when the dam is older and behaves normally.

- **Deformation measurements for arch dams.**

Such measurements reveal long term deformations in the concrete or abnormal deformations in the abutments and foundations.

- **Pore pressure measurements in the core of embankment dams and in dam foundations.**

2.7 Safety Considerations

2.7.1 General comments

Basic security

Total security against any hazard or a load consists in principle of a basic safety from the time of dam construction and alterations over time.

Alterations

The inspection arrangements and the instrumentation and monitoring arrangements define which alterations are occurring to the structure, but this in itself gives no picture of the overall safety pattern. In order to define this, the dam owners must carry out safety studies based on today's safety standards.

2.7.2 Schedule for safety considerations

Safety studies should be carried out at the following periods:
- During planning and construction
- During reconstruction and major repair work
- On the appearance of damage or abnormal occurrences on the dam (such as damage to rip-rap and abnormal leakages)
- On major alterations of safety standards (such as the introduction of Dam Regulations)
- If inspections, instrumentation results, load registrations or other circumstances should indicate the need for safety assessments
- If new methods of analysis offer a considerably improved basis on which to assess safety compared with former methods
- At regular intervals (around 20 years).

2.7.3. Various hazards and loads

- Floods
  - Flood sizes
  - Obstruction of spillways
  - Gated spillways
  - Shaft/tunnel – spillways.
- Overtopping of embankment dams
- Leakages in embankment dams
- Slide into reservoirs.

Other types of considerations which may be relevant are:
- Wave protection of embankment dams
- Stability of concrete dams
- Foundation stability of concrete dams
- Earthquake resistance.

Some overall considerations may also be relevant:
- Clarification of the consequences of a dam failure
- Clarification of overall probability of dam failure
- Risk analyses that contain elements of both above.

2.7.4 Recommendations

In today's situation we recommend that dam owners carry out the following:

The dam owner

- **Reassess the safety of their dams according to present norms.**

The dam owner should clarify and define what reassessments of safety are considered necessary to carry out, and then discuss this with NVE-T. In the assessment the dam owner should consider:
  - Dam failure consequences
  - Perceived hazards for the dam
  - Extent, quality and safety norms in previous safety studies.

The dam owner carries out the safety studies which are regarded necessary.

- **Incorporate rules on safety considerations in their operating programmes.**

In some cases dam owners may have difficulty in proposing what should be done. It may be difficult to decide what is necessary and what is unnecessary to carry out. In such a situation it will often be a case of doing what other dam owners are doing, and what is normal practice. It will therefore be difficult to bring about a change in practice.

Clarification of usefulness and need for safety assessment, and indicating the dam owner's responsibility in defining the necessity (or the lack of necessity) for such assessments will contribute to a change in practice.

NVE-T

NVE-T should themselves however assess the need for such reassessments of safety for some types of hazard (such as obstruction of spillways, or instability in arch dam foundations), and in a planned and coordinated way direct groups of dam owners to carry out such reassessments where it is considered necessary.

2.7.5 Revision of the Dam Regulations

A change in practice so that the dam owner himself carries out reassessment of safety may be achieved by including provisions about this in the Regulations.

Our present system is such that we, through the Dam Regulations have provisions on:

- What type of safety assessments that should be made
- Determination of what is satisfactory safety level.

These provisions pertain to planning and construction.

Older dams

Where the new provisions for dams include provisions which are either new or deviate considerably from former practice, provisions may be included making it necessary to supply safety documentation for previously constructed and approved dams.

2.8 Damage- and Accident Reporting

2.8.1 General comments

Reporting on damage and abnormal operating occurrences and follow-up of such cases is an important element in dam safety. Reporting has several objectives:

- It should ensure responsible treatment of the case within the organisation
- It should ensure NVE-T's participation in the case
- It should ensure flow of information to a central register of accidents and damage in relation to dam safety.

2.8.2 Reporting procedures

Reporting of damage/abnormal situations should take place through three separate procedures:

- Normal reporting concerning inspection, operation and maintenance
- Emergency damage/accident reporting
- Damage statistics reporting.

Reports from inspections

■ General reporting

Reporting on damage, completed repair work and on abnormal situations that have arisen should be included in the general inspection reporting.

Documentary evidence of repairwork

Documentation of the construction period must be supplemented with a protocol where all damage/abnormal situations that have arisen and repair work are registered. Documentation of maintenance and the repair work must be added to the documentation from the construction period so that a complete picture of the work carried out at the dam installation will aid subsequent assessments.

The documentation should be such as to give a retrospective picture of the situation before the repair work, the technical assessments made in relation to the damage and the repair work, and technical documentation of the repair work itself.

Through contact with dam owners during the project work the following impression concerning the present situation remains:

- A systematic survey of the maintenance/repair works carried out at an installation is often lacking
- Documentation of the individual maintenance work is often lacking
- Reporting on abnormal occurrences, summaries of studies that are being made, conclusions drawn and measures implemented are seldom present in regular reporting.

■ **Urgent damage/accident reporting**

This is notification to NVE-T about an urgent situation. The objective is to report on the situation and suggest proposals as to how it can be resolved.

■ **Damage statistics reporting**

A separate complete reporting of statistics and registering of damage and accidents to dams does not take place today in Norway. Such registering should be carried out by NVE-T, and by the dam owners' organisations.

The objective of such a reporting and registering system is to obtain a picture of the total amount of damage and accidents, and from this obtain an overall picture of the problems in order to counter them.

Damage/accident reporting should be standarised and include the following:

- Relating to the damage:
  - The gravity of the damage
  - The point in time when damage occurred
  - Type of damage.

Registering on the basis of the gravity of the damage, can be done on the following scale:

- Damage, accident that lead to failure
- Damage, accident which likely would have lead to failure unless measures in the form of repair work or lowering of the reservoir water table had been implemented immediately. (ICOLD-accidents type 1)
- Damage, accident of such a type that measures in the form of temporary repair work or lowering of the reservoir water table were immediately implemented. Dam failure might have occurred had the damage/accident been of a more serious degree/duration
- Damage/accident of a type that necessitates repair work within one year
- Damage/accident that necessitates repair work within five years
- Damage/accident where repair work may be postponed indefinitely.

Registering on the basis of when the damage occurred can be done on the following scale:

- Construction period
- Initial impounding
- Age of the dam 1–5 years
- Age of dam 5–100 years
- Age of dam more than 100 years.

- Concerning repair work
  - Year of repair work
  - Type of repair work
  - Cost of repair work

- Concerning the dam
  - Type of dam
  - Height of dam
  - Year of construction of the dam
  - The function of the dam.

- Identification
  - The name of the dam
  - The owner of the dam
  - Number and name of the watercourse
  - Reference to reports concerning the damage and repair of the damage.

2.8.3 International dam failure statistics

Dam failure statistics are collected through work that is carried out by the International Commission on Large Dams (ICOLD) and the separate national committees.

In the dam safety project we have examined international dam failure statistics in order to see what they can teach us about risk level at Norwegian dams. Appendix 6 "International dam failure statistics" refers to this.

2.8.4 Experience of damage and accidents

■ Water level registrations

Faults in water level registrations are experienced at most water works, either because measurements are not registered or because they exhibit values different from the real one.

One should ensure that water level registration procedures are controlled and repaired. Faults in water level registrations very rarely lead to defective handling of gates or similar failures.

Faults with the gates

■ Gate controls

Dam owners have experienced different types of failures and abnormal situations with regard to gate control. The cases are related to the following conditions:

- Faults in the electricity supply
- Faults in the control mechanism
- Frozen gates
- Vandalism
- Blockage from flotsam
- Damaged lifting mechanism
- Damaged gate.

Log-/needle courses

Some older type of log-/needle courses are constructed so that they have to be operated before the floods come. The system is in fact impossible to handle during a flood. In these older installations there may also be unclear procedures for handling in flood situations.

At some installations the time aspect is so critical that a back-up system automatically starts functioning if and when the main system fails. Faults in such automatic back-up systems have also been registered.

■ Damage to dams

The following types of damage have been reported from dam owners:

- Dam failure because of overtopping of older masonry dam
- Rip-rap damage to embankment dams
- Erosion at bedrock of steel frame dams
- Downstream erosion damage

- Erosion damage to crest because of wave runup
- Damage to concrete because of alkaline reactions
- Overtopping of secondary embankment dams during floods
- Joint damage in flat slab deck dam
- Large leakages and erosions in dry stone dams
- Large deformations in dry stone dams.

Major repair works have mostly been related to the following points:
- Reconstruction of spillways from needle/gated spillways to modern gates
- Repair of rip-rap in embankment dams
- Raising embankment dams/increasing capacity of spillways.

■ Critical situations

Only in exceptional cases do dam owners describe situations or occurrences as critical.

Problems in opening gates or other gated spillways are the type of critical situations dam owners have experienced most often.

The most serious situations arise in those cases where the reservoir level rises very fast because of failure of diversion capacity.

Transfer of experience

It is typical that experience from abnormal situations is individual and only recorded in writing to a very limited extent. It was also the exception rather than the rule that NVE-T was made aware of this type of problem (contrary to the usual cases of damage observed on a site inspection).

2.9 Recording External Loads

How great are the true loads?

The main loads on a dam will be:
- Floods
- Waves
- Temperature.

These loads are arrived at on the basis of theoretical calculations. The basis for calculations and theoretical models may contain major inaccuracies. Recording actual loads on a dam structure would be an important step in discovering erroneous calculations in establishing these loads.

■ Floods

The largest annual autumn and spring floods (inflow floods) should be determined. This can be done with the help of:
- Water level recording in the reservoir
- Operating information concerning net supplied water through transfers and power stations.

How large inflow floods have really occurred after the dam was built?

Recording floods should take place at the biggest and most important of our dam installations. Reporting should take place in connection with the main inspection reporting (3–5 yrs) or in connection with a major reassessment of safety at the installation (15–20 yrs). The dam owner should consider whether his installation is of such a type as to make it desirable to have such flood recording, and if so include it in his procedures. NVE-T should be informed.

Palagnedra dam in Switzerland

The following case history from Switzerland demonstrates the importance of recording major floods. After around 20 years of operation the dam was exposed to a big flood. The dam was overtopped and suffered partial failure. The size of the flood was estimated at 3 x design flood level. On closer examination of data it turned out that design flood had been superseded altogether 6 times in the course of the dam's 20 years operating time.

After the accident the dam was rebuilt and given a bigger flood diversion capacity.

Recording wind and waves

■ **Waves**

Exceptional wave loads may be recorded by:

- Instrumentation in buoys
- Manual recording and photographing during bad weather conditions.

Wave loads may also be recorded indirectly through wind measuring. Wind measuring should include wind intensity and wind direction.

Recording of wind and waves should be initiated at a number of selected dams so that the different areas are covered. NVE-T should coordinate this and direct a selection of dam owners to carry this out.

2.10 Maintenance, Repair and Reconstruction Work

What is maintenance and what is reconstruction?

In reconstruction and major improvements the requirements for documentation and safety levels of the dam regulations must be complied with. In some cases there may be doubts as to whether the work is sufficiently extensive as to come in under this provision. In such cases one should always inform NVE-T in advance about the work one intends to carry out on the dam.

In his programme for ensuring safety in the operating phase the dam owner should include provisions on administrative procedures for all types of improvement works. It is especially important that the works are well documented for future reference.

Such documentation should include:

- Drawings and descriptions of finished work
- Calculations and safety considerations
- Description of the basis for the repair work.

3 TECHNICAL ISSUES

3.1 Protection Against Floods

Floods represent the most important security threat to dams

Security against floods means security measures to prevent dam failure due to flood conditions. Such failures generally develop as a result of overtopping. This has happened in the case of many dam failures, and overtopping arising from floods is one of the most common reasons for dam failure. Failures can also arise due to erosion in the spillway itself.

Reasons for overtopping

From a technical point of view overtopping can occur for the following reasons:

- Floods which occur are more extensive than originally anticipated (greater volumes of water, more flotsam, a more complicated overall situation)
- The dam does not withstand as high water levels as originally anticipated
- Spillways do not possess the capacity originally anticipated.

Floods are not volume of water alone

Where the capacity of the spillways is less than originally anticipated, the reasons can be as follows:

- The spillways' actual capacity on the ground is less than the theoretical calculations indicated
- There is(are) an obstruction(s) in the spillway
- Gates and/or sluices have not been opened as they should have been.

The analysis of dams' security against failure should encompass all of the above points. Unfortunately it has been the custom to limit flood calculations and capacity estimates to assessments of the water volumes alone in open waterways. An extreme flood constitutes a catastrophic situation which must be properly analysed.

Within the Norwegian Dam Regulations, the specifications applying to flood situations are those which probably vary most from previous practice. However the Dam Regulations are also stricter than previous practice in their treatment of wave situations and the requirements for freeboard. These must be viewed together in context.

A complete analysis of dam safety against failure due to floods will comprehend the following main elements:

- Flood analysis (see Section 3.2)
- Spillway analysis (see Section 3.3)
- Analysis of overtopping (an analysis of the dam structures ability to withstand high reservoir water levels) – see Section 3.4
- Wave analysis
- Conclusions.

A reassessment of a dam's security against floods should contain a compilation of assumptions and results, and a well-founded conclusion as to why measures are necessary.
Three types of conclusion can be distinguished. These are:
- that they meet the requirements of the Norwegian Dam Regulations
- that they do not meet the requirements of the Norwegian Dam Regulations, but are regarded as unnecessary
- that they do not meet the requirements of the Norwegian Dam Regulations, and the measures are necessary.

If measures prove to be necessary, then this must be followed up by proposals for reconstruction.

3.1.2 Reassessments of safety

Obstruction and functional failures

It is recommended that the dam owners undertake complete analyses of security against failure due to flood for all new and existing installations. The extent of the analyses should be in accordance with the consequences of dam failure. In particular this refers to the analyses of obstructions and of functional failures in manoeuvrable flood devices. In the reassessment of existing installations an assessment of previous calculations and modelling work should be undertaken in addition to any new evaluation work. This should include assumptions and results as regards:
- Flood size
- Diversion capacity
- Floodwater levels
- Wave heights and wave breaking
- Freeboard.

Tunnels/Shafts Spillways

It is particularly important that reassessments are carried out for installations which are vulnerable to increased flood loads. In the first instance these will be:
- Installations with tunnels/shafts in the spillway
- Installations with gates on the spillway.

3.2 Flood Analysis

Flood analyses can be divided into the following parts:
- Incoming floods (Q-1000 and PMF)
  - incoming floods from the local basin
  - incoming floods from a higher reservoir area
  - transfers from other basins
  - emergency draining from a higher reservoir area
- Discharge floods (Q-1000 and PMF)
- Reservoir water levels at Q-1000 and PMF

The Norwegian Dam Regulations provisions and subsequent practice concerning flood analyses are generally sound, but some points should be raised concerning certain individual elements within the analyses.

3.2.1 The Probable Maximum Flood (PMF)

Strict PMF requirements

Section 6.8 of the Norwegian Dam Regulations states that exceptional loads shall be equivalent to the Probable Maximum Flood (PMF). This provision applies to all dams governed by the Regulations i.e. dams over 4 m in height and constructed after 1981. For dams built before 1981, the Regulations can be used as an informal standard, together with any other requirements set out by the authorities. In general, a general requirement that all dams shall withstand the PMF appears too rigid. In the case of new installations and the rebuilding of smaller dams and for simple run-of-the-river electricity dams, the PMF standard should be modified.

In assessing existing installations built or planned before 1981, a certain degree of flexibility is required. The need for measures for such dams will have to be viewed in light of the following factors:

- The installation's flood diversion capacity in relation to the Probable Maximum Flood (PMF)
- The consequences of dam failure
- The practical possibilities/costs of meeting the PMF standard
- The probability of failure due to floods.

Consideration should be given to the possibility of leaving out a PMF calculation where it can be shown that the dam in question can withstand water levels well above expected maximum water levels.

3.2.2 Uncertainty in the analysis process

The bases for the analysis can be of highly variable quality. It appears that existing practice does not take account of this fact. Although the basis for an analysis is usually to be found in the written paperwork, there must be some correspondence between quality and the uncertainty within the analysis itself. In cases where the basis for the analysis is particularly poor, this must be reflected in the conclusions of the analysis.

3.2.3 Transfers from other basins

In certain installations, transfers from other basins make up a large proportion of the incoming floods. In these cases calculation of the maximum transfer capacity should be undertaken with particular care.

Capacity calculations in the planning of an installation have normally been subject to economic analysis and therefore reflect an average expected capacity. In a flood analysis a capacity should be employed which has been established on the basis of a high Manning's value (37). If the cross-sections have not been measured, and only the theoretical cross-section is known, then the analysis should be based on an assumed average cross-section where allowance is made for a high percentage of surplus material.

3.2.4 An area reduction factor for precipitation

In the calculation of flood amounts based on estimates of precipitation, the basis for the calculation will be the precipitation at a specific point. Average precipitation within an area will be estimated using an Area Reduction Factor. The value of this factor should be reassessed. Using the existing rules, the size of floods in small basins (under 10 km^2) seems too small in relation to a normal basin (100 km^2), whilst the size of floods in large basins (over 2000 km^2) seems too large.

The table below shows the relative Area Reduction Factors for precipitation which ought to be used in Norway and Sweden (24 hours).

Basin Area km^2	Relative Area Reduction Factor	
	NORWAY	SWEDEN
1	1.05	
10	1.03	1.22
100	1	1
1000	0.95	0.80
10000	0.89	0.59

3.3 Spillway Analysis

A spillway analysis should contain the following elements:
- Capacity assessment
- Erosion assessment
- Obstruction assessment
- Assessment of operational safety in the manoeuvrable flood devices.

3.3.1 Assessment of capacity in open spillways

This is the normal type of assessment for a system of spillways and gates anc has standards similar to those set out in the Norwegian Dam Regulations There is therefore no particular need to reassess procedures in this case However it will be necessary to undertake a qualitative assessment of previou: calculations. It will be necessary to ensure that the actual spillway which wa: constructed and its performance is in conformity with the calculation assumptions and designs made for it. An assessment should also be made oı the co-efficients employed, and one should consider whether particulaı skewed flows exist which must be taken account of.

3.3.2 Tunnel/shaft spillways

Special care is needed in establishing capacity

An installation in which the spillway consists of a tunnel/shaft system belov a fixed spillway or gate has fewer safety margins than is normal. Certain safet) standards should be established for such installations so that they are more rigorous than when the facility was first planned. A reassessment of the capacit) of such spillways must therefore be undertaken in connection with a flooc safety analysis. Reference is made to Section 3.6 and Annex 4.

3.3.3 Assessment of obstruction

Previously assessments of spillway capacity did not include assessments o obstructions. Such assessments should now be undertaken for new and olc installations. More details are to be found in Section 3.4 and Annex 2.

3.3.4 Assessment of operational safety of spillway gates

Previously assessments of spillway capacity did not include these assessments These should now be carried out for new and old installations. More detail: are to be found in Section 3.5.

3.4 Obstruction of Spillways

Obstruction of spillways by floating material (flotsam) is not an uncommor occurrence during floods. In particular in areas where landslides occur ir loose deposits on steep slopes, large amounts of trees with roots and branche: can end up on the watercourse as happened at Palagnedra Dam ir Switzerland. Stories from "Storofsen" in Norway in 1789 tell of valley side: with houses, and forests sliding down into the Lågen River. There are example: from Norway of avalanches and landslides blocking spillways. Obstruction o the spillway is one of the most important risks associated with flooding, anc can cause spillways to have less capacity than anticipated thereby contributin; to dam failure.

Assessment of obstruction should be carried out

An assessment of obstructions should be part of an assessment of exceptiona loads and the first step ought to be an assessment of the consequences of ઃ complete blockage of the spillway. The main elements of such an assessmen will be the following:
- **Avalanche/landslide assessment:** Assessment of the possibilities of a slid(giving rise to flotsam upstream of the dam.

- **Possibilities for obstruction:** The spillways' ability to divert flotsam should be assessed.
- **State of preparedness:** The dam owner's potential for discovering and stopping flotsam should be assessed.
- **Consequences/Impacts:** The consequences of obstruction have to be assessed.

3.4.1 The assessment of consequences

In concrete dams secured against overtopping, obstruction is acceptable

The following possibilities exist:
- The dam will not fail
- The dam will fail. The failure will only have minor and acceptable consequences
- The dam will fail. The failure will have major and unacceptable consequences.

Only in the last case will it be necessary to require security against obstruction as an exceptional load. However all dams should be able to withstand some flotsam (1 to 5 trees) without failure taking place in combination with a normal (50 year) flood.

3.4.2 The assessment of the avalanches/landslides situation

The assessments should contain a brief description of the extent and nature of potential landslides areas upstream of the dam, and of previous experience from landslides and from flotsam in the river course.

The avalanches/landslides which can cause large amounts of flotsam to enter the river course or the spillways will normally be of the following type:
- Normal landslide or debris flow
- Quickclay slide.

All areas upstream of the dam which are drained by a river or stream are potential hazard zones. The triggering of such slides has a close physical relationship with large precipitation and flooding.

The assessment should conclude with a ranking of the following factors:
- The probability for avalanching/landsliding
- The extent of avalanching/landsliding
- Specification of the maximum tree height within potential avalanching/landsliding areas.

3.4.3 The assessment of obstruction

Obstruction can arise in several ways e.g.:
- Flotsam can block whole or part of the spillway
- Flotsam can hinder the effective operation of spillway gates
- Sudden falls of snow, stone or other detritus can cause direct blockages of the spillway
- Snowdrifts and ice can impede or block the flow of water at the crest of the spillway
- Ice formation in the tunnel/shaft can reduce capacity
- Ice formation can reduce capacity of the spillway
- The spillway can be reduced by gradual collapse or blockage by vegetation.

An assessment of all these possible obstructions should be carried out.

The most important forms of obstruction are the first two, and it is these two which will be examined principally in this report. The other forms are only dealt with briefly. An assessment of the spillway's capacity to divert flotsam should provide conclusions on the probable extent of obstruction under exceptional load conditions.

On an ungated spillway with no bridge, obstruction does not occur

■ Ungated spillways

The possibilities for obstruction with an ungated spillway have been investigated in model tests. Reference is made to subsidiary report no.4

Bridges constitute a major obstruction hazard

"Obstruction of Spillways" (in Norwegian).

A fixed channel spillway with no bridge is regarded as a type of construction safe from obstruction/blockage. Blockage by trees will be of a temporary nature in channels with low clearance

Where there is a bridge crossing the channel, obstruction by trees represents a considerable security risk. The distance between columns will often be such that blockage will occur if enough trees are to go past the dam.

■ **Gate openings**

The current at the gate opening will be such that floating trees will be able to align themselves with the direction of the current, and therefore avoid obstructing the channel. However trees can get stuck between the base of the gate and the column and hinder any manoeuvring of the gate itself.

■ **Shaft/tunnel spillway**

Blockage of the shaft/tunnel will occur if the size of floating material (trees) is large as compared to the cross-section of the shaft/tunnel. The critical points will be the entrance to the shaft and the junction of the shaft and the tunnel.

Account must be taken in the assessment of the fact that a temporary blockage can first occur at the crest of the spillway, and that a number of trees may then come together in a wave at the mouth of the shaft.

■ **A sudden slide blocking the flow of water in the spillway**

Consideration must be given to whether the topography around the spillway can give rise to possible slides.

Where conditions appear uncertain, consideration should be given to improving matters by some form of physical intervention e.g.

Physical intervention

- construction to prevent slides
- fixing slopes subject to sliding
- moving the spillway channel.

Ways of reducing the risk of such slides are to carry out inspections during floods or to place an automatic water meter in the reservoir to warn of abnormally high water level or TV monitoring of the spillway.

Monitoring

In Norway we have witnessed rockslides filling part of the water channel of the spillway. However the slide was discovered and the rock was removed before causing further damage.

■ **Snow and ice on the crest of the spillway**

By means of inspection the dam owner should form an impression of whether snow drifts and ice are forming in the spillway. In many cases such drifts will be formed. However by the time the spring floods are due, the drifts will have melted.

Register conditions

Dam-owners experiencing such conditions should note when the drifts are formed and what time of the year they disappear. If the filling of the reservoir one year is abnormally early then the spillway should be inspected and appropriate measures implemented before the reservoir reaches NWL.

If the spillway is completely covered over it is recommended that some of the drift is removed so that the water can run freely across the spillway. This is particularly relevant for spillways with shaft/tunnel. In special cases it may be necessary to roof over the spillway. How long it will take for water to cut its way naturally through a snowdrift is very uncertain, and this procedure is not to be recommended unless the situation is under full control and the snow or ice can be removed as and when necessary.

Measures

■ **Ice formation in the shaft/tunnel**

By means of inspection, the dam owner should form an impression of how ice

Keeping the air out

is formed and how it melts. Ice formation can reduce the capacity of the shaft/tunnel at an early stage of the flood. In assessing the acceptability of this it is essential that the flood does not develop quickly. The formation of ice can be reduced by preventing air from flowing through the mouth of the tunnel.

Running water gets rid of ice over time, and this can be dangerous if a solid plug of ice is formed in the shaft or tunnel.

■ **Surface ice**

Where an overflow can occur in winter with ice in the reservoir, one should assume reduced spillway capacity corresponding to the effect of the ice.

■ **Gradual collapse or blockage by vegetation in the spillway**

Where the spillway arrangement does not consist of a fixed and defined threshold, but of an excavated or naturally occurring channel, the capacity can be gradually reduced over the years by collapse or blockage by vegetation. In such spillways it will be necessary through inspections and surveys to find out whether the cross-section is as planned, and if necessary to carry out cleaning operations. Reduction of the cross-section can also create problems in areas in front of and behind a fixed threshold.

3.4.4. Arrangements for dealing with obstructions

The overall assessment of obstruction/blockage in a dam installation will also be included in the assessment of a dam-owner's arrangements for dealing with obstructions. Such an assessment should consist of the following:

- arrangements to discover flotsam
- arrangements to stop flotsam before it reaches the spillway
- arrangements to discover and remove obstructions in time.

3.5 Operational Safety in Manoeuvrable Spillways

3.5.1 General

Spillway capacity can be less than planned because of failures in the handling / manoeuvring system

There will always be a possibility that spillway capacity in a flood situation will be less than originally assumed because of failures in the handling system. A complete analysis of the capacity of manoeuvrable spillways will therefore have to contain assessments connected with failures in the manoeuvring system. The Project has carried out examples of these analyses and these are presented in subsidiary report no.6, parts I and II.

Manoeuvrable spillways in practice mean gated spillways or emergency gates.

3.5.2 The purpose of the analysis

A functional/security analysis of a manoeuvrable spillway can be useful in several instances as follows:

- Contingency plan

The analysis will make up part of the analysis section of a Contingency Plan and form the basis for an action plan in case of major functional failure.

- Back-up potentials

The analysis can throw light on how to improve the back-up systems within the facility.

- Technical design and organisation

The analysis can form the basis for decision-making on whether to change technical design or organisation of the work in conditions of flood.

- Safety assessment

The analysis can present a better picture of the overall security against overtopping. The overall probability for overtopping consists of two parts:

– probability for overtopping with all spillways open

– probability for overtopping with different types of functional failures.

The analysis can indicate the decisive types of functional failure and the levels of probability for these.

- Operational security for power production

The project's starting point for proposing analyses of functional safety is based on dam safety. Such analyses can also assist in reducing financial operating losses.

3.5.3 Prescription for the analysis

Local knowledge

Need for a fresh perspective

An analysis should be undertaken in the form of cooperation between operating staff who are familiar with the installation and a professional expert (external or internal) who can view problems from a fresh perspective. Some help from staff with expertise in analytical methods may be desirable in bigger analyses.

Contents of the analysis

The analysis should consist of the following elements:

■ **Description of the flood discharge system**

The analysis should be based on a description of the existing technical system and relevant organisation for operating the various flood control devices technical data on gates and lifting devices

- Technical data on gates and lifting devices
- Technical data on water level metering, signal transmission systems and control systems
- Organisation and staffing
- Regulations and practice in operating flood control devices
- Back-up and spare parts systems.

■ **Effects of high reservoir levels**

When does the water hinder further operations?

The analysis should contain a systematic analysis of the various possibilities for blockage occuring at different water levels, in relation to manoeuvring devices. Examples are:

- Cranking by hand is impossible at NWL + 1.0 m
- Normal opening of gates impossible at NWL + 1.5 m
- Automatic water level metering does not work over NWL + 2.0 m
- Embankment dam section fails at NWL + 4.0 m.

■ **Related installations**

Abnormal water flows from installations above

Naturally occurring floods will always constitute one of the loading phenomena which will need to be analysed. However operational failures in a related facility which in turn affects water levels in the installation under study, will also constitute a critical loading factor. Study of such situations must also be included in the analysis. The ability to control such loading situations can be more difficult in winter, and it may become necessary to identify "winter conditions" as a special loading situation.

Typical examples of loading factors from related facilities are:

- Sudden halt in operations in a power station because of inflows into the reservoir
- Sudden and unexpected opening of floodgates at the closest facility lying above the installation in question.

■ **Impact assessment of dam failure**

The significance of having high functional security in flood diversion works and the level of security measures against overtopping should be related to the

Impact dependent analysis

potential impacts of dam failure. Where impacts are small the standards can be set at a lower level, and the extent of the functional security analysis can be reduced. A compilation of the impact assessments of dam failure should be included in the analysis.

■ **Technical data on flood capacities, extent of floods and reservoir area**

These are the basic data needed for the analysis. The combined spillway capacity should be worked out under different assumptions for manoeuvring failures. An estimate of the reservoir area at the actual elevation of the dam crest will be needed in order to gain an impression of how quickly a critical situation can develop.

The extent of floods, maximum value and the series of events should be given for floods with a reoccurrence interval of 10 to 1 million years. In addition to estimating maximum values, it is important to estimate how quickly the flood is likely to increase. The estimates are usually made on the basis of calculations of flood values described in the Norwegian Dam Regulations (Q-1000 and PMF).

Flood risk is affected by the disposition of the reservoir

In some cases the use of these calculations can establish probabilities for flood, greater than they are in reality. This is because the design flood is calculated on condition of a full reservoir and theoretically unfavourable conditions relating to transfer of water to the reservoir. Probability analysis can estimate the probabilities associated with these assumptions. The effect of a reservoir which is not full can be twofold. In the first place, incoming flows can be absorbed in a reservoir above the installation in question, and in the second place incoming flows can be absorbed in the installation's reservoir itself.

■ **The development of water levels in different loading conditions**

How quickly will water rise if the power station is put out of operation and no gates are opened?

It is a straightforward hydraulic calculation exercise to estimate which loading conditions will result in undesirable water levels i.e. dam failure levels, and at what speed the water level development will take place. It is very important to gain an impression of how quickly a difficult situation can develop, in order to be able to assess the effect of corrective measures. Such an exercise should be undertaken at all installations with manoeuvrable flood control devices, whether or not a more comprehensive Problem Tree Analysis is being undertaken. A particularly important loading condition arises at an electric power station with only gates as a flood control device, when the power station is out of operation and no gates are opened.

The main questions for which answers are needed are as follows:

- How much time is available before the gates are blocked
- How much time is available before the water level reaches dam failure levels?
- What diversion capacity is there with closed gates?

■ **Functional security analysis (reliability analysis)**

What problems/failures can arise?

Causes and effects

The purpose of this analysis is as follows:

- To identify which faults can arise
- To identify the causes of these faults
- To identify how the effects of these faults can be avoided by providing spare parts or repairing parts.

An extension of the functional security analysis will be to systematise the measures taken to avoid faults as follows:

- Maintenance and testing to ensure that faults do not arise
- Distinct routines for repair.

Faults, causes of faults and effects of faults are all relative concepts as faults can arise at different levels. A fault at one level can become a cause of faults at the next level.

In the analysis of functional security for flood gates, the highest fault level (level 1) should be of two types as follows:
1. The water level in the reservoir is higher than a given undesirable water level (e.g. dam failure water level)
2. Sudden, unplanned water flow, in excess of the given water flow

Causes of faults can be divided into three types in level 2 as follows:
- 1.1 All gates operate in combination with a flood greater than Q_1
- 1.2 One gate does not operate in combination with a flood greater than Q_2
- 1.3 Several gates do not operate in combination with a flood greater than Q_3

The contents of level 3 should be adapted to type of construction, but for fault 1.2 (above) can be as follows:
- 1.2.1 Defective power cable to a gate
- 1.2.2 Defective motor
- 1.2.3 Defective lifting mechanism.
- 1.2.4 Jammed gate
- 1.2.5 Defective signal for opening the gate

Further division of causes of faults into levels has to be adapted to type of construction and the extent of the analysis. It may be natural to split individual faults up into more levels than others. The purpose of all further sub-division should be to bring out different requirements for repair and spare parts for different types of fault.

Failure 1.2.3 "Defective lifting mechanism" for example can be sub-divided into the following sub-groups:
- 1.2.3.1 Defective winch
- 1.2.3.2 Defective lifting mechanism lever
- 1.2.3.3 Defective lifting mechanism clamp

Further sub-division is unnecessary as the repair and spare part needs of all three faults are quite similar.

3.5.4 Analytical methods

The analytical model which is constructed will be a simplification of the real system. It is necessary to select a degree of detail which is "necessary and adequate" for the model to be sufficiently realistic for the purpose of the analysis. It is important to be aware of which factors require a high degree of detailing. Several different methods are available for undertaking reliability analyses. These are:
- Modes of failure and Fault Effect Analysis (FMEA)
- Graphic Fault Development Analysis (GFDA)
- Fault Tree Analysis (FTA).

FMEA is a method for predicting the effect of faults in components and in sub-systems of the overall system. An FMEA form is used to describe the individual component, the fault and the effect of the fault.

Fault Tree Analysis

FTA is a formal method which permits a systematic analysis of the possibility of a certain undesirable state coming about. The method starts with the undesirable state and works "backwards" through the system and examines each level in order to register individual events which can bring about the undesirable state. By using a Fault Tree Analysis it is possible to identify the ways in which an undesirable state can come about, and to create a probability model for calculating the probability for failure, when data on individual events within the Tree are known.

Logical block diagram

In some cases it can be more useful to employ a Logical Block Diagram (a Reliability Network) instead of a Fault Tree. The block diagram represents a functional model of the system. The system function is maintained as long as it is possible to come from the entry point to the diagram to the exit point by way of blocks which represent functioning components. Each block can be regarded as a valve which is either open or shut. If it is open, then the component which the block represents is functioning. The system as a whole can function as long as a fluid can flow through the entire system. If two blocks are in parallel to each other then both blocks must be shut off (that is a fault occurs) for the entire system to fail. If two blocks are in series then it is necessary for only one block to fail for the whole system to fail. Use of the Fault Tree and the Logical Block Diagram (reliability network) is demonstrated with examples in subsidiary report no.6. It is found that the use of the Logical Block Diagram is particularly suited to analyses of failures in gates. The GFDA is a more comprehensive method in which the Fault Tree Analysis is part of the method. The cause of the functional fault and its effects are presented in the GFDA diagram. The model is particularly well suited to the analysis of systems and situations where the sequence of events plays an essential role.

3.5.5 Quantification of failure probability

Poor basis for quantification

The statistical basis for establishing the failure probability for gate handling is very poor. Such an analysis has to be based on previous experience. It is important to examine the probability of failure in the light of the situation at the installation when the failure occurs. It is natural to exclude the following circumstances:

- Extreme flood conditions
- Winter conditions.

The probability of failure for some components will naturally be greater under such conditions than under normal conditions. In many cases a gradation of the probabilities for failure into broad categories will prove useful. In many cases the probability of failure can best be judged by estimating the probability of failure for an event at a relatively high level. An example of this is the probability that a gate will not open in a given period of time under flood conditions. Thereafter a division of probability according to the cause of the failure will be undertaken. In establishing the probabilities for failure it is important to take account of the time element. There is clearly greater probability of succeeding in an operation if three days are available rather than one hour.

Generally speaking analyses can be carried out without any quantification of the probability of failure, or a very rough form of quantification. They can still be of great value in identifying possibilities for failure and spare part possibilities. It is thus important that scepticism as to the quantitative part of the analysis is not extended to the analysis as a whole.

3.5.6 Conclusion

Action plan

The analytical work must be concluded by an assessment of the level of security within the flood discharge system, and what changes can be made to improve it. The dam-owner should work out a plan of action with the changes to be undertaken and indicate the time limits for these. In the examples given in subsidiary report no.6 discussion of different measures is set out in a specia chapter, but an example of a dam-owner's conclusions is not included. Annex 3 gives an example of how such a conclusion can be constructed.

3.5.7 Flashboards/stop-logs

Procedures

Uncertainty regarding the operation of flashboards/stop-logs is considerable Faults in operation can arise with obstructions and if enough flashboards stop-logs are not removed.

Flashboards/stop-logs have usually been employed on older dam installations and there is some uncertainty on the need to open these gates in flood situations.

Gate operation ahead of a flood

The operation of gates must often take place ahead of a flood, as this car be difficult when water levels are high. In the analysis of flashboards/stop-logs the following factors should be taken into account:

- What kind of operations the design flood assumes
- How the flood development is recorded and the need for operation
- The availability of personnel with experience in operating flashboards/stoplogs
- Who is responsible for establishing the extent of gate operations and what guidelines are available

Experience

- Mobilisation and transport of staff
- Possibilities for communication between the staff and the Operation Centre
- Access to necessary equipment during gate operation
- Any conflicts of interest in operating the gates and how to behave towards different interest groups

Equipment

- Summing up practical experience gained from the last large floods
- Need for training and further education
- Possibilities for using special equipment during gate operation
- Practical difficulties encountered in operating the gates with high water levels.

3.5.8 Gates

Functional failure can arise in many ways depending on the technical systen and the organisation of the flood discharge.

Technical failure

Any analysis must take account of technical, organizational and humar failures. Each individual phase of the flood development should also be studied.

Organizational failure
Human failure

Correction of faults should take place after a systematic inspection of al parts of the gate operation system.

This could include the following items:

- Water level recording: the recording system
  - Water Gauge
  - Float
  - Underwater Weights
  - Pressure gauge.
- Water level recording: the reading system
  - Manual reading and reporting
  - Manual reading, telephone reporting, mobile telephone or radio
  - Automatic reading through the telephone system, radiolink or the high tension network .
- Water level registration: the recording frequency
  - Less frequent than every 10 days
  - Once every 2 to 10 days
  - Once a day
  - Several times a day
  - Continuous 1 shift
  - Continuous on a 24 hour basis.

- Normal staffing at other operating units within the organisation.
- Responsible for defining the need for, taking decisions on, executing and controlling gate operations
  - On site dam guards
  - Foreman at the operations centre
  - Operator at the operations centre
  - Engineer on duty at the operations centre
  - Supervising engineer at the head office
- Operating rules for the flood control devices
- Practical procedures for gate operations
- Phases in flood development
  - Normal operational phase without flood
  - Preparatory phase prior to flood
  - Normal flood phase
  - Catastrophic phase.

■ Different types of faults

Faults can always arise

Faults can always arise under various circumstances. For overall security it is extremely important that the systems are designed so that there is a possibility of discovering and rectifying faults in time. Analysis of faults should therefore contain assessments concerning this as follows:

The system should be such that faults are discovered and rectified before the consequences become too great

- Technical fault sources
- Mechanical conditions
  - fault in the water level meters
  - fault in the gate lifting devices
  - jamming/wedging of the gate
  - cable or panel fault
  - motor fault
  - fault in the control unit
- Infrastructure
  - fault in road access
  - electrical fault
  - telephone failure
  - availability of diesel/petrol
  - signal transmission
- Organisational conditions
  - mobilisation of personnel under extreme conditions
  - unclear command/responsibility structure
  - difficulty of access to equipment (reserve generator, motors, pumps, tools, fuel, vehicles, cranes etc)
  - lack of organisation, chaos, panic
- Human failures
  - fault assessment where the system leads to a human assessment
  - human error and faulty actions
  - forgetfulness
  - communication between people
  - stress and breakdown.

3.6 Spillways with Shaft/Tunnels: Design Rating and Capacity Calculations

3.6.1 Introduction

Uncertainty on capacity and the extent of floods

Flood and capacity calculations for spillways are normally undertaken by calculating probable values. For both types of calculations there are considerable uncertainties behind the estimates.

A spillway with a shaft/tunnel is less satisfactory than a regular ungated spillway

With a fixed spillway, the shape of the capacity curve is such that the uncertainties on the extent of the flood and capacity express themselves as only minor uncertainties in the actual water level. In a fixed spillway with a calculated water level equal to 2.5 m above the threshold for a specified water flow, an increase in the extent of the flood by 10% will only give a 0.16 m higher water level than the estimated 2.5 m. For a spillway with shaft/ tunnel below the fixed spillway, the shape of that part of the capacity curve which is determined by conditions downstream of the fixed spillway will be much less satisfactory. This is particularly true for that part of the capacity curve which is determined by the flow of water within the shaft/tunnel over a large head. The flow situation and the establishment of capacity is also more difficult to follow and less certain for a shaft/tunnel system than an open fixed spillway. The conditions referred to above require that for the rating and establishment of capacity in a shaft/tunnel system, one has to be particularly careful – as required by the Norwegian Dam Regulations

Special care in establishing capacity

Compared with the normal principles for calculation for fixed spillways, special care should be exercised for shaft/tunnel systems, by calculating capacities, using unfavourable assumptions and using appropriate reduction factors. In principle, but not in detail, the basis for establishing capacity should be in accordance with Part II, 8.2.4 of the Norwegian Dam Regulations. In addition some new criteria should be used for rating new installations. The project's proposals are set out in Annex 4 "Proposals for Rules for Rating Spillways with Shafts/Tunnels"

Unfortunate previous practice

A review of flood calculations and capacity estimates for existing installations with shafts/tunnels shows that previous procedures regarding the rating of these installations have been unfortunate. There is now a clear requirement to review these installations from a safety point of view. Reference is made to Annex 5.

■ The basis and quality

Site visits and surveys

One of the principal rules in calculating the capacity of a shaft/tunnel spillway should be that it is based on a site visit and measured lengths and cross-sections. Particular emphasis should be placed on carrying out as detailed a flood analysis as possible. Capacity calculations for spillways with shafts/tunnels must be undertaken by persons with expertise in such hydraulic calculations. The calculations should be checked at the point they are carried out and the Norwegian Water Resources and Energy Administration (NVE) should undertake a detailed check of the hydraulic calculations using qualified personnel. In special cases NVE should call in a special adviser to check. Results from model testing should always be supplemented by calculations.

■ Reassessments

Reassessments should be undertaken

Dam owners with an installation with shaft/tunnel spillways should carry out a reassessment of the installation in accordance with the requirements of the Norwegian Dam Regulations and other current recommendations and practice. Such reassessments should be undertaken even if previous assessments have been undertaken after 1981. NVE should now take an initiative to ensure that reassessments are undertaken by dam owners who have not yet taken such an initiative.

3.7 Leakages through Embankment Dams

3.7.1 General

International statistics on dam failures show that damage to embankment dams because of leakage actually constitutes an important proportion of all causes.

Rockfill dams

Abnormal cases of leakage have occurred in Norwegian dams., and the dam failure at Roppa in 1976 was the result of a leakage.

International statistics appear to indicate, however, that no large rockfill dams have failed even when large leakages have occurred. This has primarily been because the leakages which have occured have been limited and that the dam toe has been able to accommodate the leakage without instability occurring (i.e. adequate drainage capacity).

Earth dams

Where earth dams are concerned, international statistics shows that a number of failures have taken place where the cause is thought to be internal erosion. The failures have most commonly occurred at the first filling of the reservoir. However they have also occurred after many years of operation which clearly indicates that internal erosion can develop over long periods of time.

In Norway, apart from the rockfill dams there is also a large number of smaller earthfill dams. It is there in particular that the risk of failure due to leakage is important.

3.7.2 How to reduce the probability of failure due to leakage

The sequence of events in a dam failure due to excessive leakage can be divided into four stages as follows:

- a flow of water arises through cracks in the waterproofing or the foundation
- the filter and the waterproofing material are not self-healing
- the leakage increases to the point where the downstream toe cannot accommodate the volume of water
- the leakage is not discovered in time to be able to halt the sequence of events.

Measures to reduce the probability of a failure due to leakage can be introduced in all four stages, and the measures can be grouped as follows:

Measures for improved security

- Quality of construction
  - foundation
  - waterproofing/sealing
  - filter
  - dam toe
  - culvert structures
- Rate of embankment construction
- Rate of the first reservoir filling
- Monitoring of the first reservoir filling
- Permanent leakage monitoring.

Rockfill in the toe of the dam

For new structures information on all the above-mentioned factors is available. However in the case of older dams, it is the quality of the waterproofing, the toe of the dam and the leakage monitoring which are the factors which can be changed in practice.

3.7.3 A reassessment of safety

The dam's ability to withstand leakage

It is recommended that the dam owner undertakes assessments of embankment dams' safety against failure due to leakage. Such assessments should be part of the routine calculations in the construction of new dams. Assessments should also be carried out for existing dams. An assessment should consist of the following items:

- Assess the quality of the toe of the dam and calculate the dam's ability to accommodate leakage (drainage capacity given in m^3/sec)
- Reexamine the development of leakage throughout the history of the dam

- Assess the coarseness of the filter, given in terms of D_{15}
- Assess the quality and durability of any upstream waterproofing

Recording wind and waves

- Assess the leakage potential and protection against downstream erosion associated with through-going structures
- Clarify the relationship of any sink holes and subsidence with leakages
- Clarify the purpose and system for leakage monitoring
- Recommendations on measures regarding
  - waterproofing
  - the downstream toe of the dam
  - leakage monitoring
  - major reconstruction and repair.

The need to undertake such assessments is greatest for dams vulnerable to leakage, and dams where failure will have major consequences. A ranking of dams vulnerable to leakage can be based on the following criteria:

- Embankment dams in which the downstream toe of the dam consists of quarried rock, gravel or fine material

Dams vulnerable to leakage

- Embankment dams in which a major part consists of earth
- Dams which have previously experienced abnormal leakages
- Dams with through-going structures which can give rise to leakage
- Dams with coarse filters.

3.7.4 Systems for measuring leakage

The recording of leakage within a dam is important for registering abnormal conditions within the dam. Different measuring systems can be used, and the value of measurements varies greatly in accordance with the measurement procedures. It is important that the dam owner assesses the need for leakage measurements in the light of the dam's overall safety against failure due to leakage and the consequences of a failure.

Purpose

Leakage recording can have the following purposes:

- A check that the dam is operating as planned so that the true level of seepage is the same as originally planned for
- A check that the dam is not undergoing long-term changes which can give rise to an increase in the volume of leakage from year to year
- A check whether sudden changes in leakage occur
- To give immediate warning of sudden changes in leakage
- To be part of an internal programme for warnings of dam failure.

The systems can be divided into the following groups:

- Assessment on the spot with no special measuring arrangements. No quantified leakage volumes recorded
- Manual assessment on the spot with special measuring arrangements. Quantified leakage volumes recorded
- Manual assessment on the spot with special measuring arrangements. Quantified leakage volumes recorded. A signal is set off when the leakage volume exceeds a certain threshold value
- Automatic measurement on the spot during short intervals. Manual recording on the spot from automatic measurement equipment
- Automatic measurement during short intervals. Transmission of the results to manned control unit. Special signal transmitted automatically when leakage volume exceeds a certain threshold value.

Automatically transmitted measurements

The dam owner should develop a system of measurement which takes account of the purposes he views as necessary.

Embankment dams with major failure impacts should be equipped with automatically transmitted leakage measurements. Embankment dams which have experienced large sudden leakage volumes should also be equipped with automatic transmission systems.

The dam owner's procedures for leakage measurement should, besides the recording itself, also consist of assessment and reporting routines.

Random reporting

In many cases leakages will be discovered in a random manner outside the established routines for leakage recording. Such random reports must be subject to detailed investigation by the dam owner, and rules for handling such random reports must be included within the dam owner's established routines.

3.8 Overtopping of Embankment Dams

3.8.1 Introduction

The water level that the dam can withstand has to be specified

Failures resulting from overtopping of embankment dams are internationally among the most frequent type of dam failure in the world. This type of failure is such that the probability of failure is not reduced with the age of the dam.

An investigation of the safety of embankment dams must therefore include an analysis of such dam's ability to withstand failure due to overtopping. These analyses are relevant in a number of situations as follows:

- In a study of whether a dam can withstand exceptional accidental loads without being breached. For example an exceptional load can consist of a water level greater than the design flood level resulting from the probable maximum flood or a major blockage in the spillway
- In the course of emergency planning it will be necessary to establish at what water level the dam will fail
- In a risk analysis of dams it will also be necessary to establish the breaching limits of the dams.

By the term "overtopping" this report means the overtopping of the sealing element in the dam.

Overtopping analyses usually form part of a larger assessment of security against failure resulting from floods (Section 3.1). Subsidiary report no. 5 presents viewpoints, guidelines and advice connected to the carrying out of such analyses.

It is the opinion of the authors that overtopping analyses should be carried out for all embankment dams, and that these should establish what water levels the dam can withstand without failing.

3.8.2 Investigations of the dam crest

Any analysis will be based on a simplified picture of the real situation at the dam crest. The assumptions made at this point can often be of more significance than the accuracy of the analytical method used.

The following factors will have greatest influence on the results of the analysis:

Levels of the different zones within the dam

- Top level of the individual zones

Permeability

- Permeability in the individual zones.

In the first instance an investigation of the dam crest should concentrate on these two factors, but an assessment of the filtering action between zones should also be considered.

Where an assessment is to be made of the water level arising in several zones, it is the level in the uppermost zone which will be critical. If, for example, the water level is above the filter and the transition zone, then it will be essential to determine the top level of the transition zone. It will be less important to establish at what level the top of the moraine core is situated.

The same applies to the permeability coefficient. The greater part of the water will penetrate the uppermost zone where water flows through, and it is the permeability in that zone which it is essential to establish.

The assumptions on which the analysis are based should reflect the results and uncertainties from the investigations which have been undertaken. In an analysis of accidental loads (e.g. PMF) the assumptions should be selected so that there is some degree of certainty that the theoretical assumptions are no more favourable than conditions as they are in reality.

The need for field investigations should be decided by the nature of the problem. In an analysis based on a simple background, e.g. working drawings alone, the degree of uncertainty is great and assumptions should be chosen accordingly.

■ **Zone Levels**

There will be variations in the zone level along the length of the dam. The choice of assumptions in the analysis will have to reflect the variations found in the field investigations. Average levels should not be used.

Camber and settlement

If the basis for calculations are drawings or profiles prepared during construction, levels will have to be reduced for the settlements which have taken place between the time the dam was built and today. If measurements are available these should be used to determine the amount of settlement. In many cases measurements will not cover the entire period since the zones were constructed and correction will have to be made for this. Furthermore allowance has to be made for height reductions due to settlement for the next 50 years in accordance with what is known about the settlement characteristics of the dam. If no measurements of settlement have been made then the total combined settlement should be set at 1.5% of the dam at the relevant point.

If the basis is field investigations of today's conditions, then height reductions should be made only for future estimated settlements.

Investigation methods for the dam crest will, of course, be further developed and gradually it will be possible to obtain more experience from such investigations. Recommendations on the choice of different assumptions based on today's situation are set out below:

Different bases give different assumptions

- Working drawings

Zone-levels should be set at 0.5 m under the theoretical level if the work has been carried out without daily inspection during the time the dam crest was built. If there was such inspection then the zone-level should be set at 0.3 m below the theoretical level.

- Final cross section as constructed

The zone-levels should be set at 0.1 m below the profiled level.

- Test pit excavations

There should always be at least three shafts with no more than 200 m between each shaft. If there is a disparity in results then the number of shafts should be increased.

Where shafts are 200 m apart, the zone-level should be put at 0.2 m below what is found in the shaft. With distances of 100 m and 50 m between shafts this can be reduced to 0.15 m and 0.1 m respectively.

The level in the individual shaft can be established by average observations

- Drilling and sampling

The method of investigation corresponds largely with the sinking of shafts. However one obtains a less complete picture of conditions than one does with shafting and drilling and sampling should always be supplemented with the sinking of one shaft.

The choice of levels in relation to zone-levels should be similar for drilling and sampling and for sinking shafts.

- Georadar

Georadar (at its present level of development) gives a continuous picture of the moraine core top position. The position of the other zones is difficult to establish with georadar.

Neither does this method of investigation give a picture of permeability and the filter characteristics of the materials. Georadar should primarily be used as a supplement to shafting or drilling and not as a method of investigation in its own right.

■ Permeability

The permeability of the different zones is the other critical factor which has to be established in an assessment of resistance to overtopping.

Subsidiary report no.5 discusses methods for establishing permeability based on the zone's granular grading curve. This assumes that samples have been taken from shafting and drillings, or that granular grading curves are available from the building inspection records during construction.

The materials in the dam crest can be different from those described

Permeability can also be established by laboratory tests. However account must be taken of the possible differences between results from laboratory tests and actual permeability in the dam itself.

The materials used on the crest of the dam can be different from those used in the rest of the dam, even if the materials description is the same. It is therefore necessary to be careful in using material for analysis which does not come from the dam crest

A proportion of fine-grained material can be found in the stone material in the transitional zones and the fill support material, and in laboratory testing this can bring about low permeability. In the actual field conditions on the dam crest these fine-grained particles will be loose and will be washed away from the waterflow. Laboratory tests should therefore be undertaken where the smallest grain of stone material (the smallest 10%) is excluded from testing. Where variations in permeability occur in a zone, average observations can be employed.

■ Properties of the filter

If the materials possess poor mutual filtering properties, this can lead to particle transport out of a zone and into an underlying zone to such an extent that it has an effect upon the result of the analysis. However critically damaging particle transport will only occur where filter properties are particularly poor.

It will be possible to gain an insight into this by undertaking test drilling or shafting. Theoretical assessments can give an impression of the possible extent of erosion which will occur if the filter standards are not met. In particularly poor materials an attempt can be made to estimate the eventual extent of erosion.

3.9 Ageing in Concrete Dams

3.9.1. General

The deterioration process

The concept of ageing of dams expresses the fact that dams undergo changes over the years.

The dam structure and its foundations are subject to forces of deterioration which can also lead to changed loading conditions. The process of deterioration can take place slowly or quickly, depending on the characteristics of the concrete and the foundations and the forces they have been exposed to.

Basic safety and the effect of deterioration

Ageing on its own gives no indication of a dam's condition or safety. This can only be established by clarifying the following:

- Condition of the dam and level of security when it came into operation
- Which processes of deterioration the dam has been subject to
- How quickly these processes are taking place and how far they have come
- What effect deterioration is having on the functioning and security of the dam.

3.9.2. Concrete dams

In subsidiary report no.1 "Ageing and Safety in Concrete Dams", the problem of ageing in concrete dams is examined. The most important mechanism in the deterioration of a dam is increasing cracking, often combined with leakages.

Cracking

To some degree it is possible to distinguish between dangerous and harmless cracks. Harmless cracks are those which do not develop further and in which water flow does not increase over the years.

Dangerous cracks are those filled with water subject to frost action. For such conditions cracking will continue to take place, often at an accelerating rate to constitute extensive damage to the concrete and the reinforcing. Even where there is no danger of frost action, cracks can offer a point of attack for corrosion of the reinforcing.

The extent of the ageing processes will very much depend on the design of the dam, the composition of materials and the quality of the work carried out.

Dams built before 1930

The general picture for concrete dams in Norway is as follows:

Many of our oldest dams built before 1930 were built using poor quality (porous) concrete and joints which were not watertight. Some dams were badly affected by frost, by weathering and cracking. Several of the dams were in such poor condition that, because of rapid deterioration, their security would be substantially reduced within a few decades. These dams have already been replaced by new dams or substantially improved by, for example, inserting upstream facing.

Dams built after 1930

A few dams built before 1930 and most dams built after 1930 are constructed from such good concrete that ageing through normal processes of deterioration takes place so slowly that there is unlikely to be any substantial reduction in security until the dams have reached an age of 200 years or more. A few dams (some old and some new) are in a sort of intermediate position whereby processes of deterioration can be expected to bring about a substantial reduction in safety after 100 years. This includes gravity dams of better quality than the poorest dams and possibly some flat slab deck dams with poor concrete in the buttressing.

Alkaline reactions

Dams exposed to alkaline reactions should be given special attention. It appears that alkaline reactions only show up after 20 to 30 years. Cracking as a result of the primary reaction has no special significance for the safety of the dam unless the content of active materials is so great that the reaction can take place over many decades. It remains to be seen if this is the case for

Alkaline reactions can also give rise to internal stresses and strains

Norwegian concrete dams. Probably the greatest threat will emerge through secondary cracks caused by frost action and corrosion in the reinforcing. However it will still take several decades for this secondary damage to lead to a substantial reduction in safety.

Dams which meet today's standards in terms of design and construction can suffer very extensive damage before the consequences for safety are such that there is a danger of dam failure. In accordance with normal procedures in Norway such damage will be repaired long before there is any danger of a dam failure. In the case of these dams ageing will therefore create no danger of dam failure in the course of the next 100 years or more.

■ Uncovering hazardous ageing processes

Visual inspections

It is essential in preparing measures against hazardous ageing processes that the dam owner discovers the hazardous development.

The dam owner should arrange a programme of inspection. In many cases this need only consist of visual inspections. Only when a visual inspection gives rise to the suspicion that hazardous processes of deterioration are underway will it be necessary to undertake more detailed investigations.

Systematic investigations

There is a need to introduce more systematic investigations of concrete dams. Nor should those parts of the structure which have been under water for many years be forgotten. Underwater inspections using divers or video should constitute part of an overall inspection programme.

Underwater investigations

More detailed investigations will consist of:

- Investigations of the solidity of concrete on the surface using an impact hammer. The results are however not completely reliable and only give an indication of the degree of solidity
- Core drilling to record possible cavities or differences in the quality of the concrete
- Drilling of concrete cores to check:
  - compressive strength
  - concrete composition
  - depth of carbonation
  - alkaline reactions
  - cracking processes
- Drilling of concrete cores with reinforcing to investigate corrosion in the reinforcing
- Investigation of the depth of carbonization by chiselling and the use of liquid indicators (Phenophtalein)
- Investigation of concrete covering using a "covermeter" or similar equipment
- Electrical voltage readings to investigate whether corrosion is taking place or not.

All concrete dams with particularly significant failure consequences should undergo these detailed investigations within an overall programme to ensure dam safety. The investigations must be systematic so that it is possible to obtain an overview of changes taking place over a long period of time. The time intervals between investigations can be long (20 years), with more frequent investigations of special matters e.g. alkaline reactions.

A continuous project of investigation

In order to obtain a more or less integrated picture of the development of Norwegian concrete dams, dam owners as a group e.g. the River Basin Association together with the Norwegian Water Resources and Energy Administration (NVE) should monitor the development of a selection of dams in a systematic and long-term programme of investigation.

Such a programme can be founded on previous projects e.g. "The Status of Norwegian Dams" so that it includes developments up to today's date.

The assessment of the safety of dams has to be based on a review of the structure's strength and stability compared to a review of overall condition. Representatives from the dam-owners, NVE-T and experts in concrete technology should participate in the project. The choice of dams should be made so that it represents the variety of concrete dams present in Norway.

■ An assessment of safety

As part of the dam-owners' overall safety programme during the operational phase, it is recommended that routine safety assessments be undertaken at certain time intervals and when major changes occur in relation to safety standards. This is discussed on Section 2.7 on Assessments of Safety.

The purpose of today's practice with frequent visual inspections supplemented by more detailed investigations of the status of the dams, is to reveal the overall condition and changes in this.

Classification by quality

However this procedure in itself is not sufficient to reveal those dams which, because of their construction and how it was implemented, do not meet today's standards.

To the extent that these matters are to be clarified, inspection and assessment of the dams' status will have to be followed by an assessment of construction and execution in relation to the requirements of the Norwegian Dam Regulations.

It is tempting to propose a system of classification based on the extent to which the dam meets the requirements of the Regulations and on the consequences of dam failure. Such a system of classification could provide the basis for a more practical system of inspection.

For dams which meet the requirements inspections every ten years or after any abnormal occurrence will be adequate. However dams which do not meet the requirements should undergo a more stringent system of inspection with frequent inspections until the requirements are met. In addition to these inspections it is assumed that the dam-owner will see to it that ordinary operating inspections are undertaken including the recording of any damage.

■ Ageing processes in different elements of the construction

In any dam structure, the ageing process can take place in different construction elements. The main type of ageing process is that which causes deterioration in the dam materials themselves (concrete and reinforcing). It is first and foremost this type of ageing process which subsidiary report no. 1 discusses.

However it is important to be aware that ageing processes can take place in other elements of the construction. In assessing these it is particularly important that professional personnel who know well the different construction elements and their importance for dam safety take part.

Elements of the construction in which the ageing process can occur are:

- the dam's anchoring to the foundation by normal rock bolts or mounting cables
- the dam's internal system of drainage
- the watertightness of the dam foundation (grout curtain) and drainage
- the shear strength properties of the cracks in the dam foundations
- erosion of rock and concrete in the dam toe and in the foundation downstream of the dam.

■ Other types of dams

Other dam types are also subject to ageing processes.

- Trellis Dams
  - The proportion of solid wood with full supporting capacity is reduced because of various processes attacking the wood

- Embankment Dams
  - the top of the waterproofing and the dam crest settle
  - deterioration of the rip-rap may take place
- waterproofing and drainage in the foundation changes
  - plant roots are established
  - wear and tear on the downstream slope caused by people, animals and water
- Masonry Dams
  - Watertightness of joints and drainage
  - Interlocking of iron clamps
  - Cracks and leaks can destroy the "fit" of block.

3.10 Landslides into the Reservoir

3.10.1 Background

Actual cases of landslides

Landslides into a reservoir area or downstream may affect dam safety. Waves generated by slides into the reservoir can destroy the dam or the spillway can be put out of action by slide material or flotsam which is introduced into the river basin by the landslide.

There have been examples of major waves generated by landslides at Loen and Tafjord in Norway. If these landslides had entered a dammed reservoir, they could have caused failure of the dam with subsequent loss of life and property.

The collapse of an entire hillside into the reservoir of the Vajont Dam in Italy is very well known. The dam withstood an 80 m high wave over the crest but nonetheless 2,600 people perished downstream.

Blockage of the spillway with flotsam is not unusual in flood conditions. Large numbers of trees, roots and branches can end up in the river especially where loose deposits slide down steep slopes. This type of problem is treated in Section 3.4, Appendix 2 and in subsidiary report no. 4.

3.10.2 Different types of landslide

Landslides which can cause waves within the reservoir are of the following types:

- earth slides
- collapse of a scree
- rockslide and rockfalls
- snow avalanches
- fall of ice from glaciers
- underwater slides.

It is the reservoir area itself which constitutes the potentially hazardous zone.

3.10.3 The Norwegian Dam Regulations provisions on landslides and avalanches

■ Documents and information on plans

Statements are required on the geotechnical conditions in and around the reservoir in the light of possible landslides or erosion, and on planned measures to hinder damage.

■ Accidental loads

During the planning process statements will be provided on which accidental loads can arise and typical values will be estimated from local conditions on the ground.

On the basis of this NVE-T shall establish the accidental loads which must be taken account of during the planning work

Amongst the possible accidental loads are:

- Rise in the water levels above the design water flood level brought about by blockage of the spillway
- Waves caused by landslides into the reservoir
- Landslides on to the dam itself.

Landslide danger has not been systematically assessed

3.10.4 Current practice relating to the assessment and documentation of landslides/avalanches in relation to dam safety

■ **Landslides causing waves**

In connection with the approval of licences to operate dams, it has been usual for some time to undertake studies of landslides/avalanches which create waves in reservoirs. However it has not been usual for these studies to be examined by the NVE from a dam safety point of view.

In some cases where there are clear dangers of landsliding and waves, conditions have been investigated in more detail by the NVE. However it does not appear that conditions are investigated on a regular basis.

3.10.5 Analysis of landslides/avalanches which create waves

■ **The main elements**

Assessments of landslides which create waves are associated with the assessments of accidental loads for a dam structure.

The main elements will be as follows:

- Landslide/avalanche assessments
  These should contain investigations of the following types
  - possibility/probability of a landslide which will generate a wave
  - type of landslide/avalanche
  - size and speed of the landslide/avalanche
  - the location of the landslide/avalanche.
- Wave assessments
  Any landslide/avalanche can create a wave whose characteristics will be determined by the size and nature of the slide. The development of the wave towards the dam will depend on the nature of the initial wave and topography around the reservoir.
- Dam assessments
  An assessment of what size of wave the dam can withstand without failing.

■ **Landslide/avalanche assessments**

Assessments on the possibilities for landslides/avalanches which can create waves can be sub-divided into several types as follows:

- Assessments based on topography alone
- Assessments carried out by experts based on geological, wind and snow conditions etc.

Assessments should be carried out for different types of landslides/avalanches. Areas which can create landslides which enter the dam area/spillway must be subject to special assessment.

■ **Rockslide and rockfalls**

From a topographical point of view rockfalls are possible in mountainous areas where slopes are steeper than 30 degrees. The steeper the slope the greater the probability for a fall. If there are special planes of weakness (joints), slides can occur on gentler slopes. For a rockslide to reach the reservoir, the line of sight from the edge of the water to the top of the slide should have an angle of more than 25 degrees.

■ Avalanches

Avalanches which create reservoir waves will normally occur on slopes with an angle of inclination between 30 degrees and 45 degrees, and with an area greater than 100,000 m^2 (1 hectare). In addition the line of sight from the edge of the water to the avalanche area's uppermost limit should have an angle exceeding 25 degrees.

■ Landslides in loose deposits

Slippage or sliding of different layers of earth (morainic materials) or screes can occur where the slope angle exceeds 30 degrees. Slippage or sliding will normally occur in connection with heavy precipitation.

Large quickclay slides can cause waves in lakes (e.g. the Rissa Landslide). The possibility of a quickclay slide occurring has to be assessed if it is likely that quickclay can occur along the reservoir edges.

■ Topographical assessment 1

The least favourable cross-section along the length of the reservoir should be drawn up on the basis of maps and the greatest slope angle (Ø1) and the greatest angle of line of sight (Ø2) should be calculated.

In a reservoir where Ø2 is greater than 25 degrees and Ø1 is greater than 30 degrees, rockslides can occur and further investigations are needed.

The potential for avalanching is examined by measuring the surface exposed to sliding.

■ Topographical assessment 2

The mountain areas where Ø2 is over 25 degrees and Ø1 is over 30 degrees should then be indicated on a map. Calculations of the volume of potential slide areas should then be calculated for each area and for the reservoir as a whole. The volume calculations should be undertaken for areas where Ø2 exceeds 25 degrees and Ø1 equals 30 degrees, 35 degrees, 40 degrees, 45 degrees etc.

■ Geologically based assessments

A geological assessment will be based on maps and aerial photographs. The purpose is to define fault patterns and potential slide areas in the valley slopes so as to delineate parts of the reservoir for more detailed investigation. A final geological analysis will be based on maps, aerial photographs and site investigations. The purpose is to determine the potential and probability for slides of different dimensions into the reservoir.

■ Conclusions

The dam-owner must set out his assessment of the danger for landslides and NVE-T (together with the dam-owner's experts) must decide whether it is a requirement that the dam must be able to withstand a landslide into the reservoir. A landslide into the reservoir must be treated as an accidental load, and in the first instance it ought to be dams where the consequences of a failure are great that should be able to withstand such loads.

■ Proposal for assessments of existing dams

- For all dams over 15 m in height NVE should require that the dam-owner produces a report on the possibility for landsliding into the reservoir. This should consist of Topography 1 assessment, and perhaps Topography 2 assessment together with a review of previous investigations of the potential for landslides into the reservoir.

- With this as basis, and together with an analysis of aerial photographs, a number (about 10) of reservoirs with potential landslide areas are selected. In addition a number (about 5) of dams where the consequences of failure are great will be selected. For about 5 of the 15 cases analyses should be carried out of wave heights and the ability of the dams to withstand these waves.

- NVE should now (1992) consider the way forward with a view to providing for all Norwegian dams adequate documentary investigations of the potentials of landslides/avalanches creating waves in the reservoirs.

APPENDIX 1 Proposals for Changes in the Norwegian Dam Regulations

1 Regular Reassessments of the Norwegian Dam Regulations

A systematic and regular reassessment of the Norwegian Dam Regulations should take place at intervals of 15 to 20 years. The initiative for this work should emanate from NVE-T. The work should be undertaken in co-operation with the dam owners and the sector as a whole. The work must be subject to strict quality control.

2 Rules on Existing Dams

Most Norwegian dams were built before the present Dam Regulations came into force, and formally, the Regulations apply only to new installations, reconstruction work or major improvement work. The Dam Regulations prescribes in regulatory form, required safety standards for new dams.

NVE-T prescribes the required safety standards for older dams by requiring on-going inspection of individual dams. The Norwegian Dam Regulations can also be applied in an indirect fashion in these cases where NVE-T chooses to require the safety standards for these dams to be up to the levels of those in the Dam Regulations.

By introducing provisions in the Norwegian Dam Regulations for these older dams or by introducing "rules and recommendations" it would be possible to give dam owners clearer formal responsibility for ensuring safety in existing dams.

Such provisions should be able to include rules for providing documentation and decisions on safety standards for individual dams in relation to the requirements of the Dam Regulations. Rules for decisions on safety standards for existing dams (safety assessments) are covered under Section 5.3 of the Norwegian Dam Regulations.

In the Finnish Regulations the authorities there have described which factors (including documentation) are also relevant for older dams and have specified within which time period the documentation has to be produced.

In Norway the regulatory requirements for older dams are dealt with in very little detail.

3 Assessment of the Impacts of Dam Failure

Paragraph 3.3.4.4 of the Norwegian Dam Regulations can be interpreted as a requirement to undertake impact analysis of dam failure.

However in practice to-day this is not undertaken by the dam owner. A clear requirement to carry out such analysis should be introduced and the provision should apply for any dam whenever it might have been built. The responsibilities of the dam owner and NVE-T must be clearly defined.

4 The First Filling of the Reservoir

From a purely technical point of view this is a critical phase for a dam's safety. The filling of a reservoir for the first time often takes place when responsibility is being passed from a building agency to an operating agency. Paragraph 5.1 of the Norwegian Dam Regulations require that the filling operation should be undertaken in accordance with an approved schedule. Consideration should be given to including supplementary provisions on what such a schedule should contain in the "rules and recommendations".

It is important that this is not simply a schedule which regulates the flow of water into the reservoir, but that it also treats the questions of the dam owner's inspections, monitoring and preparedness during this phase.

5 Provisions on the Programme for the Operating Phase

Consideration should be given to giving these provisions a more substantive form in the "rules and recommendations".

Alternatively thought should be given to removing the provisions for the operating phase from the present Norwegian Dam Regulations, and establishing a separate set of "operating regulations for dams". The provisions ought also to apply to existing dams.

Reference is made to Chapter 2 in this Report.

6 Provisions on Flood Calculations and the Design of Spillways (Norwegian Dam Regulations Chapters 7 and 8)

Provisions for these matters are of the greatest significance for dam safety and these two chapters in the Norwegian Dam Regulations must be looked at in this light.

The following problems are relevant to the discussion:

- **Does the PMF constitute a reasonable level of safety?**

Is it reasonable to set the PMF requirement in general for all dams whatever the consequences of dam failure? Current practice exhibits some reluctance in setting the PMF requirement for dams where the consequences of failure are small. If the requirement for PMF is ignored, other requirements (e.g. 1.5 x Q_{1000}) must be considered.The requirement for PMF should not apply to dams where the consequences of failure are small.

- **PMF and run-of-the-river dams**

The PMF requirement should not apply to the typical Norwegian run-of-the-river dam. Normally the damage incurred in large floods will increase with dam failure. With run-of-the-river plants on the other hand, large floods can have a *favorable* impact. These assessments should be coordinated for certain stretches of the river course. A requirement should be made that studies should be made of what magnitude of flood would cause these dams to fail.

- **An assessment of dam failure can replace the PMF calculations**

The PMF calculations are undertaken in order to show that the dam can divert certain flood levels without failing. Experience shows that the PMF calculated on the basis of today's guidelines is approximately 2–3 Q_{1000}. PMF calculations can be extensive. A simplified method for the dam owner can be to show that the dam can withstand 3 x Q_{1000} without failing. This can constitute a simple form of documentation for many types of dams.

- **Spillway with shaft/tunnel discharge flow**

This type of spillway construction is to be found in a limited number of Norwegian dams (about 50), but the type of construction can represent a major risk factor in these dams. Capacity calculations for such installations should be undertaken so that it is made sure that these types of construction do not constitute any additional security risk in comparison with ordinary ungated spillways. The provisions in the "rules and recommendations" should be extended (see Section 3.6 and Appendices 4 and 5).

- **Obstruction of spillways**

A provision that assessments of obstruction in old and new installations should be undertaken, should be incorporated into the "rules and recommendations".

- **Gated spillways**

The principal existing provisions in the Norwegian Dam Regulations Part 1 (Section 8.2.3) should be extended by detailed regulations in the "rules and recommendations". These provisions should be more extensively used as a principle in new installations, and as a standard in the assessment of old installations. The use of gated spillways constitutes an additional risk in comparison with an ungated spillway. Gated spillways ought not to be used on dams where the consequences of failure are extensive.

On installations which are fitted with gated spillways a functional safety analysis should be undertaken. In the safety assessment of existing dams where the consequences of failure are extensive, it should be required that the PMF should be diverted without failure with the largest gate closed.

For characteristic run-of-the-river dams with gates used as flood control devices, there will be no requirement, in many cases, that the dam can withstand the PMF. In these cases consideration should be given to establishing alternative standards of the following type:

- diversion capacity with the design flood water level with one gate closed $k_1 . Q_{1000}$ (k_1 e.g. = 1)

- diversion capacity at the critical water level with one gate closed: $k_2 . Q_{1000}$ (k_2 e.g. = 1.3)

- diversion capacity at the critical water level with all gates open: $k_3 . Q_{1000}$ (k_3 e.g. = 1.5).

- **Recording actual inflow floods into the reservoir**

Provisions should be introduced for those dams where the consequences of failure are extensive, that the actual inflow floods into the reservoir be recorded, and the flood volumes should be reassessed at certain time intervals.

- **Climate change**

There is a possibility, in the course of the coming 50 years, that climate change will take place which will influence the magnitude of floods in Norway. For certain types of area there could be increases of up to 30%. There is considerable uncertainty today on the extent of climate change and its effect on flood magnitudes.

Where flood diversion capacity is being increased through reconstruction and where the reservoir has a catchment of the type in which climate change can bring about an increase in floods, extra provision should be made for climate change. Provisions on this issue should be incorporated into the regulations.

- **Combination of PMF and waves**

Today's rules contain provisions on the combination of the design inflow flood and the wave runup, but contain no provisions on the PMF in combination with wave runup. Such a provision should be introduced.

7 Introduction of the Principle of Relating the Consequences of Dam Failure to the Requirements

In principle, the requirements of the Norwegian Dam Regulations are independent of the consequences of failure for the individual dam. This appears illogical seen from the view point of risk assessment.

The introduction of requirements which are directly related to consequences of failure, seems most relevant for the PMF and other accidental loads. Similarly the requirements for the dam owner's organisation, professional expertise and operating provisions ought to be related to the consequences of failure.

Reference is made to Section 1.8.

8 Introduction of Requirements for Calculations of the Probability of Dam Failure

Risk analysis and analysis of the probability for dam failure are not discussed in the Norwegian Dam Regulations.

Consideration should be given to requiring such analyses for certain types of dam and certain types of failure:

- dams with consequences of failure which are extensive
- dams with an expected high probability of failure (cannot withstand the PMF)
- failure cause: overtopping, waves, leakages

Guidelines for such analyses should be worked out.

Reference is made to Section 1.6

9 Introduction of Requirements for the Quantification of the Dam Resistance to Failure

A requirement should be introduced, through regulations, that a dam's safety should be documented by assessments of the resistance to failure.

Reference is made to Section 1.7.

APPENDIX 2

Obstruction of Spillways

1 Establishing Typical Flotsam Characteristics

As a basis for making an assessment of obstruction in spillways, it is necessary to establish what the typical loading might be. A smaller load size should be set for normal design conditions and a larger load should be set for accidental load conditions.

Flotsam is normally derived from landslides after heavy precipitation with an extremely high water level in the catchment area. It will flow through the catchment area and into the reservoir.

Hazardous flotsam may consist of:

- individual trees or in clumps
- loose turf and grass
- houses, cabins, caravans and boat houses
- boats.

The load must be established on the basis of the following:

- forest conditions in landslide-prone areas within the catchment
- extent of landslide-prone areas
  - rock/loose deposits
  - steep slopes/flat terrain
  - size of the catchment and length of rivers
- previous experience of landslides in the catchment
- the consequences of failure of the dam.

■ **Typical load for the inflow of trees is described as follows:**

- Maximum tree length in the spillway. This can be specified as 0.8 times the typical maximum tree length in the area
- Number of trees

No landsliding danger:	**0 trees**
Limited landsliding:	**10 trees**
Medium chance of landsliding:	**100 trees**
High chance of landsliding:	**500 trees**

- Distribution of trees.

An even distribution of trees between the maximum tree length and 60% of the maximum tree length can be assumed.

2 The Spillway's Ability to Divert Flotsam

This assessment should arrive at a conclusion on the probable extent of obstruction under accidental loading.

Subsidiary report No. 4 on "Obstruction of the Spillway" can be of assistance in this assessment.

■ Ungated spillway without pillars

Temporary blockages can occur with low spillway clearance, but it can be assumed that the obstruction will dissipate and the flotsam will be transported over the crest of the spillway at a certain spillway clearance.

It can be taken as certain that obstructions will not dissipate with spillway clearances of less than:

0.1 times the maximum tree length in the surrounding area
equivalent to
0.7 times the diameter of the root

Obstructions will most probably dissipate with spillway clearance larger than

0.2 times the maximum tree length in the surrounding area
equivalent to
1.0 times the diameter of the root

■ Ungated spillway with pillars

The assessment of obstruction should be based on the fact that flotsam can come in at lower spillway clearances but get stuck across the spillway. With normal distances between pillars there will be few chances of this dissipating.

The decisive factor will be the distance between pillars. It can be taken as certain that the obstruction will not dissipate if the distance between columns is less than:

0.5 times the maximum tree length in the surrounding area
equivalent to
0.6 times the maximum tree length as flotsam

On the other hand it can be taken as certain that the obstruction will dissipate if the distance between pillars is greater than:

1.0 times the maximum tree length in the surrounding area
equivalent to
1.2 times the maximum tree length as flotsam

However there is considerable uncertainty attaching to this formula.

The other decisive parameter will be the free height between the crest of the spillway and the bridge. It can be taken as certain that an obstruction will not dissipate if the free height is less than:

0.1 times the maximum tree length in the surrounding area
equivalent to
0.7 times the maximum root diameter

It can be taken as certain that the obstruction will dissipate if the free height is greater than:

0.2 times the maximum tree length in the surrounding area
equivalent to
1.0 times the diameter of the root.

Even if the distance between columns and the free height are such that an obstruction can dissipate, this will only happen with a certain spillway clearance. It can be taken as certain that an obstruction will not dissipate where the overflow head is less than:

0.1 times the maximum tree length in the surrounding area
equivalent to
0.7 times the diameter of the root

It can be taken as certain that obstruction will dissipate where the spillway height is greater than:
0.2 times the maximum tree length in the surrounding area
equivalent to
1.0 maximum diameter of root

■ Establishing the degree of obstruction

The degree of obstruction (assuming conditions are present for obstruction) will depend on the volume of flotsam in relation to the overall overflow spillway crest length

Number of trees as flotsam:	**n**
Maximum tree length in surrounding areas:	**H**
Combined spillway length:	**L**
Degree of obstruction in %:	**T**

The following assumptions can be made in the assessment of the degree of obstruction:

$n \cdot H/L$	T_2
0.1	5 %
0.5	20 %
1	30 %
3	60 %
10	100 %

The overall degree of obstruction is established as follows:

$T = T_2 \times T_3$
$T_3 = 1$ **(in those cases where obstruction is certain to occur)**
$T_3 = 0$ **(in those cases where obstruction is not certain not to occur)**

Interpolation along a straight line should be made for intermediate values.

3 More Detailed Assessments and Model Tests

In more detailed assessments of obstruction differentiation must be made between different types of obstruction. Different types of obstruction will have different effects relating to:

- ability to stop new trees
- ability to hinder water overflow
- ability to dissipate by blows from new trees
- ability to dissipate with higher water levels

A distinction can be drawn between the following different types of obstruction related to which part of the construction the tree stops against:

1. Obstruction across the water flow
   1.1 Overflow crest
   1.2 Overflow crest/pillar
   1.3 Crest of the spillway/bridge
   1.4 Bridge/crest of the spillway/pillar
   1.5 Pillar/pillar

2. Obstruction in line with the water flow
- 2.1 Overflow crest
- 2.2 Overflow crest/downstream terrain
- 2.3 Overflow crest/bridge/downstream terrain
- 2.4 Overflow crest/bridge

Obstruction types 1.1, 1.2, 1.3, 2.1 and 2.2 will easily occur with small spillway clearances whatever the design of the spillway. However it can be expected that the obstruction will be dissipated relatively more often with a higher water level. The most serious form of obstruction is 1.5 where the trees in this obstruction form an effective blockage and there are few possibilities of dissipating it. Experiments carried out so far have relatively little to say on these conditions. However some conclusions can be drawn from the results:

- In experiments without bridges/pillars obstruction types 2.1 and 2.2 were clearly the most common. The trees got stuck easily and were often loosened by crashing together (not enumerated in the experiment). The experiments were carried out with a spillway height/tree length = Ho/Htree = 0.10-0.17. A lower spillway clearances obstruction type 1.1 could become more common.
- In experiments with bridges/pillar obstruction type 1.5 was especially in evidence. From the results it can be seen that the serious obstruction type 1.5 constituted only a small proportion.

It has to be accepted that obstruction type 1.5 is of such a type that it does not dissipate. The extent to which trees dissipate in other types of obstruction was not revealed in the experiments. The other types of obstruction are mainly 2.3 and 2.4.

APPENDIX 3

Functional Security Analysis of Gated Spillways

Examples of Conclusions for Two Case Studies

Installation A Braskereidfoss

1 Safety level

- The reservoir is small in relation to inflow floods. In case of flood, the diversion capacity must be increased in step with the inflow. In the event of a total breakdown in the operation of the gates, dam failure will take place after 16 hours of flood conditions.
- The consequences of dam failure will be moderate. There is no need for a requirement that the PMF shall be diverted without the dam failing.
- The diversion capacity with an open spillway will not be adequate to divert the PMF without the dam failing.

The PMF situation will be as follows:

Maximum inflow flood:	**13,200 m^3/sec**
Necessary diversion capacity:	**13,200 m^3/sec**
Existing diversion capacity:	**4,680 m^3/sec**
Existing diversion capacity flood gates:	**4,510 m^3/sec**

- Dam failure will occur under the following combination of flood volumes and gate operation:

Inflow flood Q > 4,680 m^3/sec	p_1 =	2.10 $^{-4}$	
All gates open	p_2 =	1	p = 2.10 $^{-4}$
Inflow flood Q > 3,670 m^3/sec	p_1 =	1.10 $^{-3}$	
1 radial gate fails	p_2 =	10 $^{-2}$	p = 10 $^{-5}$
Inflow flood Q > 910 m^3/sec	p_1 =	10	
No gates open	p_2 =	10 $^{-5}$	p=10 $^{-4}$

The specified probabilities for different gate management cases (p_2) re estimated and expressed for each case of flood. For the flood volumes average annual frequencies are given (p_1).

The overall probability of dam failure due to of flood is put at 3.10^{-4}. This failure probability is fairly high, but acceptable.

The most significant input to the dam failure probability derives from a situation where all gates are open.

2 Proposals for countermeasures

- Reconstruction

It is not considered necessary to reconstruct the dam on account of flood diversion safety.

- Functional security can be improved with the following measures:
  - Clamps to be fitted to the gates so that mobile cranes can be used
  - Mechanical fixture for holding the gate in the open position to be mounted
  - Socket outlet attachment for a mobile emergency electrical generator to be fitted
  - Reserve cable between the power station and the gates to be provided
  - Training exercises in the emergency lifting of the gates to be held
  - The functional security report to be reviewed in detail in order to consider other possible measures
  - Specific experiences within gate manoeuvring/operation to be included in the annual report.

- Other Measures

Further consideration is being given to whether it is possible to reduce the overall damage caused by dam failure, by opening the embankment dam section before failure occurs naturally. Consideration is also being given to whether it is desirable to raise the embankment dams in an emergency situation, and if so how this might be done.

Installation B

Olstappen

1 Safety level

- The reservoir is small in relation to inflow floods. Flood levels may rise rapidly and there will be little time available for gate manoeuvring/management.
- The consequences of dam failure may be extensive and provision should be made for a considerable degree of functional security for flood diversion. Provision should also be made for the maximum requirement for total flood diversion capacity (PMF).
- Diversion capacity with open spillways will not be sufficient to divert the PMF without dam failure taking place.

The PMF situation will be as follows:

Maximum incoming flood:	**1,388 m^3/sec**
Necessary diversion capacity:	**1,380 m^3/sec**
Existing diversion capacity:	**834 m^3/sec**

- Dam failure may occur with the following combinations of flood volumes and gate operation:

Inflow flood Q > 840 m^3/sec	$p_1 = 5.10^{-4}$	
All flood gates open	$p_2 = 1$	5.10^{-4}
Inflow flood Q > 550 m^3/sec	$p_1 = 10^{-2}$	
Radial gate closed	$p_2 = 10^{-2}$	10^{-4}
Inflow flood Q > 340 m^3/sec	$p_1 = 2.10^{-1}$	
All gates closed	$p_2 = 10^{-4}$	2.10^{-5}

The specified probabilities for different gate management cases (p_2) are estimated and expressed for each case of flood. For the flood volumes the average number of occurrences per year is given. The overall probability of dam failure is put at 6.10^{-4} per year. This probability of dam failure is regarded as unacceptably high. The greatest probability for dam failure is expected to be associated with the occurrence of floods which exceed the dam's diversion capacity with open flood control devices.

2 Proposals for countermeasures

- The dam should be reconstructed so that the total flood diversion capacity increases and the PMF can be diverted i.e. that the overall capacity is set at 1,400 m^3/sec. The increase in diversion capacity can be achieved by constructing an ungated spillway which is not capable of obstruction. In the calculating the overall capacity it is assumed that one gate is closed (radial gate).

Future diversion capacity will therefore be as follows:

Ungated spillway	**1,150 m^3/sec**	**1,400 m^3/sec**
Sector gate	**250 m^3/sec**	
Radial gate	**330 m^3/sec**	

The reconstruction of the dam will take place within 15 years.

- The functional security can be improved be the following measures:
  - The control room is moved to an area not subject to the PMF by 1995
  - The railings on the spillway footpath be removed from 1992
  - The functional security report is reviewed in detail with a view to implementing other measures. This should be done in the course of 1992.

- Other measures:
  - It must be recognized that remote control of the gates is not a form of operation which can substitute for staff and for the control of the gates from the dam itself under flood conditions
  - Consideration has to be given on how to use the reservoirs within a flood control strategy to reduce the probability of failure. This should be done in the course of 1993.

APPENDIX 4

Proposals for Design Standards for Spillways with Shafts/Tunnels

1 Design

Calculations and model tests must be based on the unfavorable hydraulic parameters described in more detail under point 4 below.

As a basis for design only drawings with theoretical dimensions will be available.

However designs can also be based on the assumed average cross-section of blasted out rock somewhat greater than the theoretical cross-section. In that case, evidence should be produced to show that such a cross-section can be anticipated with some degree of certainty, and this evidence should be produced using profiles of the actual cross-section blasted out afterwards. Should the cross-section prove to be less than anticipated in the design, then this cross-section must be enlarged.

- **Q-1000**

In new installations the design of the tunnel/shaft shall be such that the design outflow flood (Q-1000) has open channel flow through the system. This should also be aimed for in the extension of existing installations.

Open channel flow is defined as:

– the theoretically required cross-section of water shall occupy no more than of 80% of entire cross-section.

- **PMF**

The tunnel/shaft will be designed so that, under Probable Maximum Flood (PMF) conditions, the water level in the reservoir will be determined by the free overflow crest of the dam in front of the tunnel/shaft system. This can be achieved if the water level on the downstream side of the crest is no more than one third of the overflow head.

Under these flow conditions, the capacity of the system downstream of the crest of the dam must be at least 1.25 x PMF.

2 Calculation of the Reservoir Water Level

Calculation of the reservoir level consists of three distinct calculation operations for both Q-1000 and for the PMF as follows:

- The establishment of the inflow hydrogram
- The establishment of the capacity of the spillway as a function of the reservoir water level
- Calculation of flood attenuation in the reservoir.

The inflow hydrogram
The inflow hydrogram for flood loads Q-1000 and PMF are established in accordance with standard hydrological methods as for other types of spillway.

The capacity curve
The capacity curve for the spillway will be hydraulically determined by the crest of the dam for the lower part of the water level area This part of the capacity curve is determined in the same way as for a normal gated spillway (probable spillway capacity).

The upper part of the capacity curve will be determined hydraulically by conditions downstream of the crest. The determination of this part of the capacity curve will be made on the basis of assumed unfavorable hydraulic parameters described in more detail under point 4.

The capacity should be further reduced by a factor of 0.7 for Q-1000 and 0.8 for PMF.

Reservoir water levels
The reservoir water levels are calculated by considering attenuation as for other types of floods making allowance for reductions in flood capacity as set out above.

3 Calculation of Discharge Floods

The calculation of the discharge floods is carried out in the same way as described for the reservoir water levels, but with the hydraulic assumptions for tunnel/shaft spillways as shown under point 4, and without using the reduction factor for the flood discharge capacity.

The calculated discharge floods are used in erosion studies in the spillway itself, and for flood calculations further downstream.

4 Assumptions Behind the Calculation

The assumptions behind the calculations shall be established on the basis of the existing information and shall be selected conservatively on the basis of the uncertainties within that information.

In the study of existing installations, these must always be visited by the person responsible for the calculations, and profiles of the completed installation should be available or some other evidence that shows that the true cross-section is similar to the theoretical one.

Many of the parameters in an installation can be uncertain but the selection of favorable and unfavorable assumptions should be limited.

Friction loss: Cross section and Manning's friction coefficient

Singular loss: Cross-section and loss coefficient

The uncertainties in the other parameters must be taken account of in the selection process for the chosen parameters.

Air should be able to be conducted through the shaft/tunnel system in a mixture with water, and separately in the system's upper cross-section.

An estimate of the quantities of air should be made because of the assessments of cross-section capacity, but investigations should also be made of the flood system's operation with regard to air in more normal situations with the flow of water under design flood conditions.

Basis: Working drawings

■ Friction loss

In establishing values for Manning's friction coefficient M and the tunnel/shaft cross-section F, it is recommended that the data already assembled on this in Norway be used as a starting point.

It should be assumed that friction conditions in flood tunnels are worse than in operating tunnels.

The selection of values for M and F should be regarded as a selection which, on the whole, will give an estimated loss of head which clearly will be on the side wanted (i.e. either conservative or unconservative).

For a tunnel F_{theor} = 25m² is recommended

Conservative:	F = 25m²,	M = 28
Optimistic:	F = 31m²,	M = 35

For tunnel with F_{theor} = 50m² is recommended

Conservative:	F = 50m²,	M = 28
Optimistic:	F = 58m²,	M = 35

For a shaft with F_{theor} = 15m² is recommended

Conservative:	F = 15m²,	M = 26
Optimistic:	F = 18m²,	M = 35

For a shaft with F_{theor} = 30m² is recommended

Conservative:	F = 30m²,	M = 26
Optimistic:	F = 35m²,	M = 35

■ Singular loss

In calculating singular loss, the theoretical cross-section and the energy loss formula found in the hydraulic literature are used. It has to be recognized that these formula give probable values and one should expect 10% lower values when one is using optimistic assumptions and 10% higher when one is using conservative assumptions.

When one is using optimistic assumptions, one also has to assume a larger cross-section than the theoretical one, as when one is determining friction loss.

Typical singular loss coefficients to be found in the hydraulic literature are as follows:

Bend: $K = 1.1\ (\alpha/90)^2$

Rough transition: $K = (1 - A1/A2)^2$

Singular loss at the shaft entrance itself will vary considerably depending on the shape of the entrance itself.

In normal situations the flow of water in front of the shaft entrance will be in roughly the same direction as the orientation of the shaft itself. In these cases the value of K will be 0.1 to 0.3.

But if flows are coming from several directions, then higher values should be expected e.g. K = 0.2 to 0.5.

Under particularly unfavorable hydraulic conditions, the value of K should be fixed conservatively at 1.0.

Basis: Measured profiles and site inspection

■ **Friction loss**

The cross-section can be determined from measured profiles. The value F = estimated average cross-section can be used for both the conservative and optimistic assumptions.

Where the tunnel length is greater than 200 m, the loss of head co-efficient is determined on the basis of measured profiles. It is recommended that the basis for the "conservative" assumption should be 0.95 times the estimated M-value whilst the basis for the "optimistic" assumption should be 1.05 times the estimated M-value.

Where the tunnel length is less than 200 m, it is recommended using M values determined on the basis of working drawings.

Model testing

By using model tests it will be possible to obtain a better basis for determining water current characteristics, water loss at the shaft entrance and in the areas between the shaft entrance and the dam crest.

For the determination of singular loss in shaft/tunnel systems, model tests will give more reliable results.

In the case of friction loss, model tests do not give more reliable results than calculations. Determination of friction loss has to be undertaken on the basis of recommendations on the values of F and M used in the calculations. In addition, in using model tests, one has to compensate for any special uncertainties associated with model testing methods.

Loss at the inflow point and other singular loss can be determined on the basis of model test results. Values which are on the safe side of the uncertainty picture should be used.

Calculated capacities have to be adjusted using the recommended reduction factors.

Capacities which assume negative pressures in the pipe flow should not be used. The inflow should also be modelled without a shaft and tunnel below.

5 Flow Conditions

The flow conditions in the shaft/tunnel will change depending on the water-flow and the level of water in the reservoir, and the determination of capacity will take as a starting point the real or actual situation to-day.

In the calculations the capacities under different flow conditions will be estimated and the least capacity will be selected.

In the calculations and the model tests account will not normally be taken of capacities where negative pressure in parts of the pipe have an effect upon the capacity itself.

The various flow conditions that can occur may be largely summed up as follows:

1. Pipe flow in the entire shaft and tunnel.
   Water level in downstream channel or river channel determines total head of pipe flow.

2. Pipe flow in the entire shaft and tunnel.
   - Level of dip at tunnel outlet determines total head of pipe flow.

2a. Pipe flow in the entire shaft and most of the tunnel.
   - Critical depth at tunnel outlet determines total head.
   - This condition may be regarded approximately as condition 2.

3. Pipe flow in the shaft.
   - Open channel flow in the tunnel.
   - Dip level at shaft outlet determines total head of pipe flow.

4. Submerged shaft inlet.
   - Open channel flow in shaft and tunnel
   - Dip level at shaft inlet determines total head.
   - For inlet with varying cross section the condition must be checked at several sections.
   - In reality the flow condition may be unstable and alternate with open channel flow at the inlet.

5. Open channel flow at shaft inlet.
   - Critical section at shaft inlet is the determining factor.

6. Open channel flow at shaft inlet.
   - Critical section at spillway edge to shaft inlet is the determining factor.

In particular it should be considered whether the shaft inlet or the length of the spillway determines the capacity (condition 4,5or 6). It seems likely that in several of our existing installations this is the case without it having been used as the basis for capacity determination.

At situations 4,5 and 6 it is also important to consider the head loss in the spillway chute.

In order to establish the connection between water flow and reservoir water level, the losses between spillway crest and reservoir must be estimated. These losses consist of losses in the spillway and over the crest.

For installations with side channel only, the flow conditions may be the same with the exception of nos. 3 and 6. Also for such type of installations we would like to point out that the inlet controlled capacity situations (4 and 5) are not considered in capacity determination.

APPENDIX 5

Investigations into the Capacities of Existing Shaft/ Tunnel Spillways

The Dam Safety Project has undertaken a review of new flood calculations performed after 1981 and of previous flood calculations and spillway capacities at a selection of facilities.

■ Flood magnitudes (Q-1000 and PMF) calculated for the period after 1985 are greater than those calculated before 1985.

This emerges from Tables 1 and 2. The reason for this is that to-day's methods for calculating flood dimensions had not been worked out in detail during the early 1980s. This was particularly true for the PMF calculations.

Table 1
K_1 = Q-1000/original design flood

	Calculations undertaken	
	BEFORE 1985	**AFTER 1985**
Maximum value:	**1.58**	**1.94**
75% percentile:	**1.30**	**1.55**
Median:	**1.05**	**1.35**
25% percentile:	**1.00**	**0.90**
Minimum value:	**0.90**	**0.78**
Average value:	**1.14**	**1.31**
No. of facilities:	**11**	**10**

Table 2:
K_2 = PMF/original design flood

	Calculations undertaken	
	BEFORE 1985	**AFTER 1985**
Maximum value:	**2.00**	**3.64**
75% percentile:	**1.7**	**1.8**
Median:	**1.4**	**2.3**
25% percentile:	**1.3**	**1.8**
Minimum value:	**1.27**	**1.33**
Average value:	**1.58**	**2.33**
No. of facilities:	**11**	**10**

■ For flood analyses undertaken in accordance with today's practice it emerges that the PMF amounts to 1.5 to 2 times the value of Q-1000 (discharge flood). However in extreme cases this can be as high as 2.5 times. This is illustrated in Tables 3 and 4.

Table 3:
K_3 = PMF/Q-1000

	Calculations undertaken BEFORE 1985	AFTER 1985
Maximum value:	1.75	2.42
75% percentile:	1.5	1.9
Median:	1.3	1.7
25% percentile:	1.2	1.6
Minimum value:	1.16	1.52
Average value:	1.39	1.78
No. of facilities:	14	11

Table 4:
K_5 = PMF/Q-1000 (inflow flood);
K_6 = Q-1000/QM
QM = Average largest annual flood

	QM $L/S.km^2$	K_6	K_5
Maximum value:	1250	4.2	3.2
75% percentile:	530	3.2	2.3
Median:	440	3.0	2.0
25% percentile:	280	2.5	1.8
Minimum value:	110	2.0	1.2
Average value:		2.95	2.06

■ The original theoretical capacity of the closed spillway varies between and 1.75 times the original design flood and has an average value of 1.2(times the original design flood. 35% of the facilities were constructed withou extra capacity in the shaft/tunnel systems, that is to say the capacity wa: equal to the originally calculated design flood. Reference is made to Table 5.

Table 5:
K_4 = Theoretical capacity of the shaft-tunnel/original design flood

Maximum value:	1.74
75% percentile:	1.4
Median:	1.2
25% percentile:	1.0
Minimum value:	1.00
Average value:	1.26
No. of facilities:	11

The data for tables 1,2,3 and 5 are derived from facilities with shaft-tunne spillways. Comparisons are made for discharge floods without narrowing c the shaft-tunnel. Data for Table 4 is derived from 49 flood analyses carrie out after 1985.

APPENDIX 6

International Dam Failure Statistics

Dam failure statistics are collected in connection with current work in the International Committee Of Large Dams (ICOLD) and in the various national committees.

Basic material and the interpretation of this can be found in the references (1), (2) and (3).

In the ICOLD dam safety committee, work is presently going on on revised dam failure statistics, and a preliminary excerpt of this work is presented in (4).

In this project, international dam failure statistics have been examined to find out what they can tell us about the risk level of dams in Norway.

1 What the Statistics Include

ICOLD statistics mainly include dams higher than 15m, but dams higher than 10m and with reservoir capacity larger than 1 million m^3 may also be included.

In the ICOLD statistics two main categories of accidents have been dealt with.

- Dam failure
  In cases where the dam collapses and the water from the reservoir flows out.

- Serious accident
  In cases where dam failure probably would have occurred had the reservoir not been drawn down or other precautions taken.

Approximately half of the world's ICOLD dams are to be found in China, but in our assessments we have not included material on dam failures in China. The reason is that very little material is available on dam failures in China. What is termed `world statistics´ does therefore not include China.

2 The Level of Risk in History

Lists of dam failures and dams show that the frequency of dam failures have depended on the following factors:

The year of construction of the dam
The failure frequency of modern dams is around 1/10 of the failure frequency of dams built around 1900 (table 1 and 4)

The geographic location of the dam
The failure frequency is consistently lower in Europe than in the world at large.

This applies largely to all periods of construction and to both embankment dams and concrete dams. The exception is concrete dams built after 1950. For the variety of dams prevalent in Norway, the registered dam failure frequency in Europe is around 50% of corresponding failures for th whole world.

Of other geographical areas USA is an area with high failure frequenc and Japan an area with low failure frequency (lower than Europe).

Dam type

Frequency of failures has been higher for embankment dams than for concret dams (table 1 and 4).

Of concrete dam types, the *gravity* dam type has had the least failur frequency.

It is also worth noting that a relatively large number of "concrete dam failures" are in actual fact failures of masonry dams.

The age of the dam

A very large number of the dam failures have occurred during the dam's firs five years. For embankment dams the anticipated share is 42%, while fc concrete dams the anticipated share is 65% of the anticipated failures in th course of the dam's first 100 years (table 2 and 3).

3 Dam Failure Frequency in Norway

Based on the registered dam failures in Europe (table 1) the anticipate number of dam failures in Norway for the period 1890 to 1986 has bee calculated and resulted in 0.73 dam failures (table 5).

In ICOLD statistics serious accidents are also recorded, and for every dar failure an average of 2.3 serious accidents occur. Anticipated failures an serious accidents in Norway should therefore amount to 2.3 x 0.73 = 1.68.

In Norway 0 dam failures and 0 serious accidents have been recorded.

With an anticipated figure of 1.68 it is 19% probability of recording 0 a is the experience in Norway, and the statistical probability that there is lower average probability of failure of Norwegian dams in relation to Europ is 81%. It is further 50% more probable that the probability of failure i Norway is lower than 50% of the probability in Europe.

Anticipated annual probability of dam failures in Norway

On the basis of recorded cases of dam failure it is possible to calculate a annual probability of dam failure today or in the future.

Such a calculation is based on an estimated total probability subject t dam type and year of construction (table 4) and an annual apportioning c the probability (table 5).

Such a calculation of today's probability of dam failure in our dams i Norway has been undertaken and the result is $p=1.2x10^{-2}$ per annum prov ded that the risk level in Norway is the same as in the rest of Europe (tabl 6). The probability level in Norway is most likely lower than in the rest c Europe.

It should be emphasised that the assessments are only based on statistic material, and that no assessment of the safety of dams in Norway in relation t Europe or the rest of the world based on comparisons of natural condition quality of dam construction or differences in regulations, design etc. has bee undertaken.

With 0 registered dam failures and with a total of more than 300 ICOLD dams, Norway has a very good dam failure record (table 7).

4 Causes of Dam Failure

The most active construction period for dams in Norway is past and it may therefore be interesting to examine which causes of failures are most common for dams that are a few years old. Dam failure statistics indicate that failures in connection with dams older than 15 years have two main causes:

- Overtopping (concrete and embankment dams)
- Leakages (embankment dams)

Foundation failure is also a very common cause of failure, but this type of failure occurs mainly in concrete dams before they are 5 years old, and in embankment dams before they are 15.

5 References

(1) Lessons from dam incidents (ICOLD 1974)
(2) Lessons from dam incidents, USA (ASCE/USCOLD 1975)
(3) Safety of Existing Dams (National Academy press 1983)
(4) Statistics of dam failures, a preliminary report (Water Power and Dam Construction, April 1989)

6 Tables

	The world except China			Europe		
CONSTRUCTION PERIOD	**BEFORE 1900**	**1900–1950**	**AFTER 1950**	**BEFORE 1900**	**1900–1950**	**AFTER 1950**
DAM TYPE						
Embankments Dams	7.9	1.69	0.32	2.9	1.05	0.24
Concrete Dams	3.9	0.95	0.14	2.4	0.52	0.21
ALL DAMS	6.4	1.41	0.28	2.6	0.63	0.22

Table 1:
Recorded dam failures in percentage of constructed dams

	Embankment Dams			Concrete dam		
	BEFORE 1900	**1900–1950**	**AFTER 1950**	**BEFORE 1900**	**1900–1950**	**AFTER 1950**
0-5 years	32%	50%	71%	57%	73%	100%
5-20 years	24%	25%	29%	29%	7%	0
20-50 years	24%	13%	0	14%	13%	0
50-100 years	20%	12%	0	0	7%	0

Table 2:
Recorded dam failures according to the age of the dam

	Concrete Dams		Embankment Dams	
	PER PERIOD	PER YEAR	PER PERIOD	PER YEAR
0-5 years	65.0%	13.0%	42.0%	8.4%
5-20 years	19.0%	1.3%	23.0%	1.5%
20-50 years	10.0%	0.3%	20.0%	0.7%
50-100 years	6.0%	0.1%	15.0%	0.3%

Table 3:
Anticipated dam failures.
Anticipated distribution according to the age of the dam

	THE WORLD EXCEPT CHINA			EUROPE		
CONSTRUCTION PERIOD	Before 1900	1900-1950	After 1950	Before 1900	1900-1950	After 1950
DAM TYPE						
Embankment dams	7.9	1.99	0.49	2.9	1.24	0.37
Concrete dams	3.9	1.01	0.17	2.4	0.55	0.25
All dams	2.6	1.62	0.42	2.6	0.69	0.29

Table 4:
Anticipated probability of dam failures (in percentage of constructed dams) in the course of a hundred years effective life.
(table 1 is adjusted)

DAM TYPE AND CONSTRUCTION PERIOD	NUMBER OF DAMS > 15 M	HISTORIC EUROPEAN FAILURE FREQUENCY	ANTICIPATED NO OF FAILURES
Concrete dam before 1900	1	2.4%	0.024
Embankment dam before 1900	0	2.9%	0
Concrete dam 1900-1950	42	0.52%	0.218
Embankment dam1900-1950	3	1.05%	0.031
Concrete dam 1950-1986	70	0.21%	0.147
Embankment dam1950-1986	129	0.24%	0.310
Total	245		0.730

Table 5:
Anticipated dam failures in Norway 1890-1986

DAM TYPE AND CONSTRUCTION PERIOD	FAILURE FREQUENCY IN 100 YEARS. %	ANNUAL SHARE OF FAILURES (1990) %	NUMBER OF DAMS	ANNUAL PROBABILITY x 10^{-4}
Concrete Dam before 1900	2.40	0.1	1	0.2
Embankment Dams before 1900	2.90	0.3	0	0
Concrete Dam 1900-1950	0.55	0.1	42	2.3
Embankment Dams 1900-1950	1.24	0.3	3	1.1
Concrete Dam 1950-1970	0.25	0.3	61	4.6
Embankment Dams 1950-1970	0.37	0.7	53	13.7
Concrete Dam 1970-1985	0.25	1.3	12	3.9
Embankment Dams 1970-1985	0.37	1.5	70	38.9
Concrete Dam after 1985	0.25	13.0	5	16.2
Embankment Dams after 1985	0.37	8.4	12	37.3
Total			259	116.2

Table 6:
Calculation of annual probability of dam failure in Norway (1990)

Annual probability equal to 1,2 x 10^{-2} or dam failure in Norway (>15m) presupposes a probability level in Norway equal to European average. It is likely that the probability level in Norway is lower.

LAND	ALL DAMS Number of dams	Number of failures	Frequency	DAMS BUILT AFTER 1950 Number dams	Number of failures	Frequency
Spain	737	7	1.0%	532	3	0.6%
Great Britain	535	6	1.1%	157	0	–
France	468	2	0.4%	304	1	0.3%
Italy	440	3	0.7%	241	1	0.4%
Norway	245	0	–	199	0	–
Germany (West)	191	0	–	126	0	–
Czechoslovakia	146	1	0.7%	99	0	–
Switzerland	144	0	–	104	0	–
Sweden	141	2	1.4%	110	1	0.9%
Romania	133	0	0	128	0	–
Austria	123	0	–	93	0	–
Yugoslavia	123	1	0.8%	111	1	0.9%
Europe	4215	22	0.5%	2892	7	0.2%
USA	5459	81	1.5%	3908	12	0.3%
Japan	2228	4	0.2%	1055	1	0.1%
Rest of the world ex. China	5513	27	0.5%	4300	18	0.4%
The world ex. China	17415	134	0.8%	12155	38	0.3%

Table 7:
Dam failures in some European countries and areas of the world (ICOLD-dams)

LIST OF SUBSIDIARY REPORTS

Report no 1: Ageing and Safety of Concrete Dams

Report no 2: Emergency Planning for Abnormal Situations

Report no 3: Safety of Embankment Dams Towards Piping?

Report no 4: Obstruction of Spillways

Report no 5: Overtopping of the Impervious Core in Embankment Dams

Report no 6: Functional Safety of Flood Gates

Report no 7: Alkali Aggregate Reactions in Concrete Dams

Norwegian Water Resources and
Energy Administration

P.O. Box 5091, Maj
N-0301 Oslo Norway

Telephone: + 47 22 95 95 95
Telefax: + 47 22 95 90 00

Water System Management Association

P.O. Box 274
N-1324 Lysaker Norway

Telephone: + 47 67 11 91 00
Telefax: + 47 67 11 91 10