dam safety guidelines

Part 3: Performance guidelines for low, significant and high hazard dams

Introduction

This part of the guideline aims to promote appropriate levels of investigation, design and monitoring are being applied to dams within the Auckland region, in order to ensure dams in the region are built to and operate within acceptable safety margins. Part 3 is not intended as a design manual, but rather a guideline by which the Auckland Regional Council, as a regulator, can determine whether adequate dam safety standards are being achieved.

While this document is predominantly concerned with earth fill structures, similar principles can be applied to dams made of other materials.

The performance standards in this guideline are mainly based on the New Zealand Society of Large Dams (NZSOLD): Dam Safety Guidelines (Nov 1995), which provide excellent background information on dam safety requirements and standards.

The principal topics covered in this part of the guideline are:

1 appropriate levels of investigation
2 appropriate levels of design input
3 construction monitoring and testing external design reviews
4 monitoring and surveillance.

Monitoring procedures, performance monitoring and external reviews of existing dams are dealt with more extensively in Parts 4 and 5 of this guideline.

1.0 Dam hazard and risk

For a proposed dam, its hazard largely determines the appropriate level of input into dam investigation, design or construction monitoring. The hazard category for a particular dam provides the best indication of this.

Dam hazard categories for use in the Auckland region are outlined in Part 1 of this guideline. As well as dam safety, the categories include historical and environmental considerations.

Users of Part 3 of the guideline must use Part 1 to determine the hazard category of a proposed dam.

2.0 Dam risk

The hazard category dictates the level of design input needed to ensure that the structure has an appropriately low risk of failure. A dam with a higher hazard category must be designed and constructed in a way so as to ensure a lower risk of failure than a dam with a lower hazard category. The concept of risk is discussed in Part 1 of this document.

3.0 Dam ownership and liability

Few dam owners are technically qualified in dam engineering. Owners often play a minor role in project development, but play a very important role, being the holder of permits and consents needed to build and operate the dam.

The owner is legally responsible for maintaining the dam and its associated structures in a safe condition and for operating the dam safely.

The owner usually needs help from technical advisers about dam design, construction, and operation. These advisers have the responsibility to meet the owner's requirements and also to ensure the owner is made aware of the operational and safety limitations of the structure.

In the event of an incident, attention will first be focussed on the owner. The owner is legally liable for damage after a dam failure and may be culpable in the event of loss of life.

4.0 Dam failures worldwide

A study undertaken by the International Commission on Large Dams (ICOLD) 1983 examined 14,700 large dams of over 15m around the world and found that 0.7% had failed, and 0.83% of embankment dams had failed. Failure was defined as damage sufficient to lead to breaching of the reservoir, or its abandonment or temporary removal from operation.

Numerous studies have been conducted on dam failure statistics. The main conclusions from these studies are:

1 earth and rockfill dams make up the greatest percentage of failures, but also form the largest proportion of dams overall

2 most failures occur during reservoir filling or shortly afterwards

3 the most frequent consequence of failure is scheme abandonment.

Some of the statistics presented in these studies are shown in Figures 3.1, 3.2 and 3.3.

Figure 3.1 shows that earth and rock fill dams make up a slightly higher percentage of the number of failures than would be expected from the proportion of dams they represent.

Examination of earth dam failures in more detail is thus warranted, given that they make up the greatest proportion of dams.

Figure 3.2 shows the proportions of embankment dams that fail and the reason for failure. Also shown is the time in the dam's history when failure occurred. These figures highlight the vulnerability of embankment dams during construction and first filling.

Figure 3.3 examines 65 embankment dam incidents, including 15 failures, according to embankment type. It highlights the value of taking a more sophisticated approach to embankment dam design than just a simple earthfill structure.

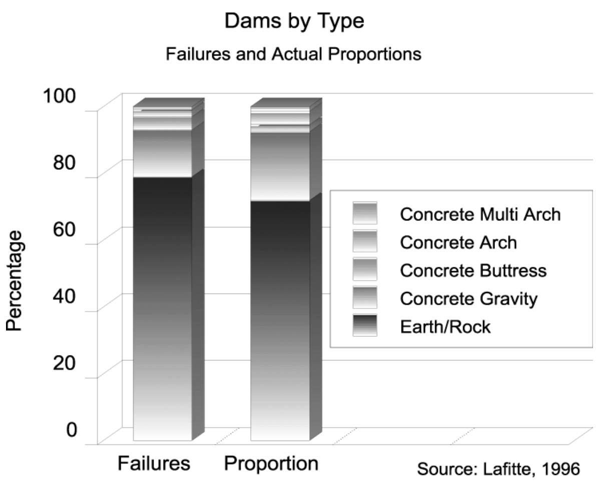


Figure 3.1: Failures and Actual Proportions

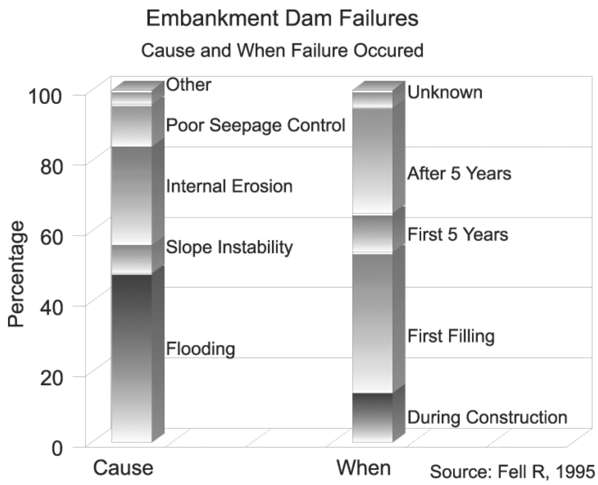


Figure 3.2: Embankment Dam Incidents

Although the statistics shown in Figure 3.3 would suggest that drainage should be incorporated into dam design as a matter of course, most homogeneous earthfill dams are relatively small structures. The hazard posed by these structures is less, so the acceptable risk of failure is often higher.

Larger structures have a lower acceptable risk of failure and constitute a greater investment. Design necessities such as drainage and zoned construction are therefore justified for larger dams.

5.0 Dam failures in New Zealand

New Zealand dam failures follow a similar pattern as overseas ones, also being most likely to fail during construction or within the first few months of completion. Failures at the Ruahihi and Wheao schemes shortly after construction and the recent damage to the Opuha dam during construction are some well known examples.

Natural factors that have a large influence on dam construction method in New Zealand include the volcanic and seismological setting, complex soil and foundation conditions and hydrological issues. The complex geology associated with volcanic areas has influenced over half the recorded incidents in New Zealand. Poor foundation conditions were a factor in over 75% of the more serious recorded incidents.

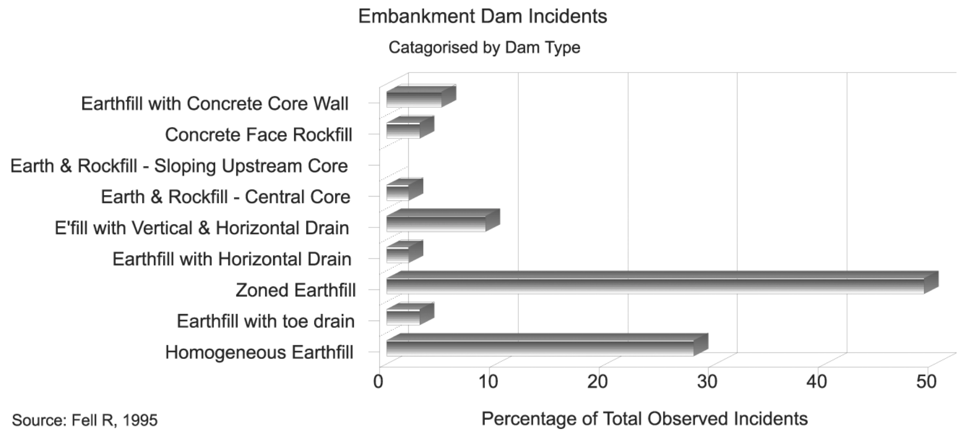


Figure 3.3: Embankment Dam Incidents

Of paramount importance to dam design, construction and operation in New Zealand is the adequate selection and use of materials and drainage. Inadequate attention to drainage has been a factor in 86% of serious dam incidents in New Zealand. This includes poor drainage a-Found conduits through dams, which introduces a weak point in the dam's construction. Poor understanding or insufficient consideration of difficult materials was a factor in nearly two thirds of serious incidents. Structural deficiencies influenced 50% of minor incidents. The main factors influencing incidents in New Zealand are shown in Figure 3.4.

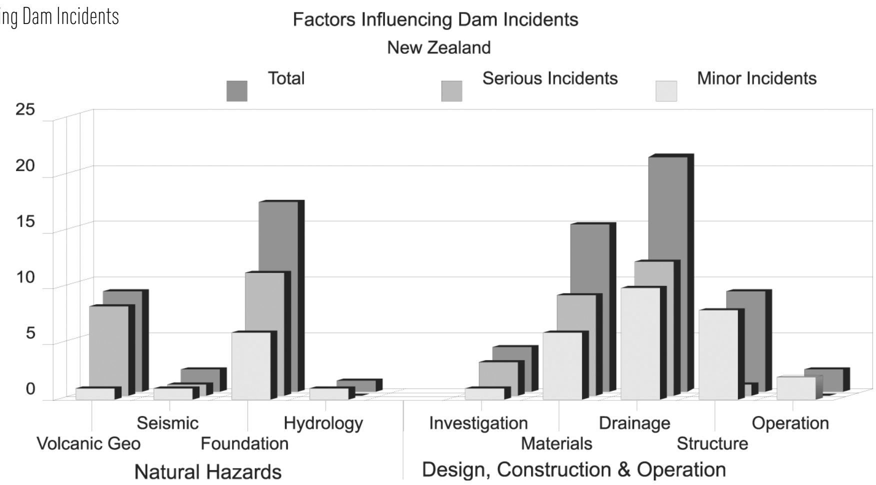
In the Auckland and Northland regions difficult soil and foundation conditions pose a major challenge to dam design and construction. The moist maritime climate has produced deep, often uneven, weathering of soils. This has in turn provided a setting for widespread land instability and erosion.

Deposition of eroded or landslide material has in-filled valleys with deep soft alluvial soils which are often inter-bedded with organic peats, gravels and weak clay seams.

The successive weathering and infilling of materials, coupled with localised volcanic influences, mean foundation conditions can change over very short distances, even within the area of a dam's footprint. A dam design may need to cope with varying foundation conditions over relatively short distances. Several recent failures of irrigation dams in the Northland region have been mainly due to inattention to foundation conditions.

Attention to details such as compaction and seepage control around conduits within and under the dam is also of crucial importance. Poor attention to conduit design and drainage around conduits has contributed to dam incidences in New Zealand.

Figure 3.4: Factors Influencing Dam Incidents



The Auckland Region is also subjected to more challenging hydrological conditions than much of the country. The predominance of small steep catchments gives rise to high peak flood flows. Diversion planning during construction and spillway design are therefore of utmost importance.

6.0 Proposed vs existing dams

Part 3 of the guideline should mainly be used to assess the performance of proposed structures. Investigating, designing and assessing construction standards of proposed dams is relatively straight forward: the critical components of the dam which safeguard its existence and operation can be observed and reviewed before construction. While this does not necessarily mean that a proposed or newly constructed dam has a lower risk of failure than an existing comparative structure, it does reduce the level of uncertainty about its risk of failure.

Part 3 is generally applicable to existing structures, but it is often impractical to assess the adequacy of a dam's design and construction once it is built. Risk assessment of existing dams therefore needs to be treated in a slightly different manner, relying more on the monitoring, surveillance and past performance of the structure. Many of the components critical to safe dam operation are permanently hidden, with monitoring being the only means of determining performance.

Monitoring levels, which are too low to give an adequate assurance of safe operation, create possible uncertainty about the risk of particular components or the structure as a whole. If there is any uncertainty, performance monitoring procedures for existing dams dictate that a conservative approach to dam safety must be adopted. Monitoring and surveillance are discussed in Part 4.

7.0 Key dam components and safety considerations

The term 'dam' can describe more than just a barrier across a stream or river. Dams include a number of key components and their nature and function can vary depending on a dam's purpose. The principal components discussed in this document and their related safety considerations are discussed below:

1 **Reservoir** – The most common purpose of a dam is to form a storage or holding area behind it. This storage is one of the main determinants of a dam's hazard category. The changes in water levels caused by the reservoir can induce slope instability and affect groundwater in surrounding areas. There is also a range of environmental and ecological issues associated with the formation of a reservoir.

2 **Dam Structure** – The main dam structure is required to provide a barrier behind which the storage is retained. Safe performance depends on a number of components.

- A dam cannot exist in isolation from its foundation and abutments. Sufficient investigation needs to be undertaken to determine foundation conditions and an appropriate type of dam structure must then be selected to match these conditions. Systems may also be required within the dam structure to control load stresses, seepage flows and/or potential movements.

3 **Spillways** – Flood flows are the most visually obvious, and for most dams, the most frequent threat to dam safety. These flows are nearly always controlled by means of one or more spillways. The level of protection provided by these spillways must be appropriate to the dam's hazard category.

- Spillways come in a variety of forms and configurations. The selection of the most appropriate spillway or spillways depends on the characterisation of the site, proposed uses for the dam and economic constraints.

4 **Conduits** – Most dams have one or more conduits passing through the main dam structure or adjacent abutment. Conduits are the most common method used during construction to divert streams while the dam is being built. They are also used for spillways, draw-off systems and power conduits for hydroelectric schemes.

- Conduits are often a potential line of weakness through the dam, connecting the storage behind the dam with the downstream toe. Care must always be exercised in the design and construction of conduits to ensure they do not cause safety problems.

5 **Construction** – A dam is usually at its most vulnerable during construction. Flood control facilities, performance monitoring and external protection are often significantly less than for a completed structure. The level of risk accepted during construction is typically much higher than during operation, creating a greater potential for an incident.

- Careful consideration needs to be given to the tolerable level of risk during construction and whether it is consistent with the hazard category of the structure at various critical stages during its construction.

6 **Other** – Many dams include other structures which, although they may not represent significant safety issues in their own right, may have importance and require a high level of protection.

Such structures could include:-

- access roading to the dam or local communities
- powerstations supplying the local area
- water supply to local communities

These issues can influence the required level of design or monitoring input for a given dam.

8.0 Technical advisors and contractors

Technical advisors and contractors will be required during most stages of dam design and construction for all but the smallest dams. For larger structures, teams of specialists will probably be required to investigate, design, supervise and monitor key components of the development.

The appropriate level of specialist input and design competence depends on the dam's hazard category.

Typical skills that may be called upon and their respective roles include:-

1 **Engineering geology** – for investigating and assessing foundation conditions, and in the case of embankment dams, the properties of the proposed fill material.

2 **Geotechnical engineering** – for assessing the strength and stability of the foundation and dam. Particular attention will be placed on the interface and interaction between man made components and natural materials, and between components formed from differing materials.

- Specific assessment of reservoir slope stability may also be required.

3 **Hydrological engineering** – to assess if there is enough water available to make the scheme viable, and to assess the size and means of passing flood events.

4 **Hydraulic engineering** – to design spillways and associated structures.

5 **Seismological engineering** – will be required in areas where earthquakes represent a possible threat (this includes most of New Zealand).

6 **Volcanological engineering** – in areas when volcanic activity could represent a threat to the dam or associated structures.

7 **Environmental engineering** – to identify issues and effects and design any necessary mitigation measures.

8 **Structural engineering** – to design structural components.

9 **Project management** – for larger projects, specialist project management skills are required to ensure smooth operation and integration of various components of the development.

10 **Construction competence** – a level of construction competence appropriate for dam size is required. This means skill in construction procedures and in programming and design interpretation. Larger projects will usually have several contractors undertaking a range of different tasks. The NZSOLD guidelines discuss construction competence.

In addition to the various technical advisors and contractors, a peer reviewer or review panel is needed for larger projects in order to provide an independent overview of concepts, design issues and construction.

9.0 New dams: conception to completion

The investigation and design process needs to address both physical and intangible considerations. As well as ensuring the structure can be built and operated safely, it also must be shown that the dam will not have adverse effects on the environment or the public.

The Resource Management Act 1991 (RMA) requires that the impacts from a development be kept to a practical minimum and that mitigation measures be undertaken to remedy adverse effects. Consideration of practical alternatives will typically be required to ensure the best overall development option is adopted. This subsection looks at:

- investigation
- design
- construction
- commissioning.

9.1 Investigations

For the purpose of this guideline the term 'investigation' includes studies into both physical (geology, hydrology etc) and intangible (environmental, historical) issues in three phases:

- preliminary
- Pre-design
- Design.

Smaller structures may not have multiple stages although some preliminary investigation is almost always undertaken before more in-depth investigations.

Preliminary investigations

In the first stages of a project's development, the actual scheme configuration and size is normally poorly defined, and a potential hazard category would not be assigned. Initial investigations aim to define the physical viability of the scheme and will mainly be based on existing information.

Objectives:

- define physical limits and viability of scheme
- define scheme concept or range of concepts, and probable limitations
- define environmental issues and concerns.

Methods:

- desktop study using geological/ topographical maps etc
- walkover survey/site appraisal to assess need for on-site controls
- search of historical data on hydrology, climate, and values.

Following these, a preliminary scheme design concept or concepts would typically be produced in order to assess what level and type of further investigation is required. For larger developments, these design concepts will often be used to begin the consultation process required under the Resource Management Act.

Pre-design investigation

Pre-design investigations would be undertaken before full design stage. Pre-design can be considered the main investigation phase.

Objectives

- accurately define physical limits and scheme viability
- assess geological, geotechnical and hydrological controls
- define level of hazard and identify risks
- undertake hazard assessment including seismological studies
- define and examine environmental, sociological and cultural issues
- define scheme concept and probable design restrictions
- obtain cost-effective design solution

Methods

- topographic and geological surveys and mapping
- surface and subsurface investigation
- laboratory testing etc.
- installation of specific monitoring equipment

The investigations should be adequate to allow full design of the main scheme components. Some additional investigations, identified during the design process, may be required for specific components. In addition to the investigations examining the area in the vicinity of the dam, consideration must also be given to the area around and within the reservoir. Slope stability around the reservoir perimeter can, on occasion, dominate project feasibility.

Design investigations

For larger projects it is normal for the design process to highlight potential difficulties that may result in modifications to the design concept. Often this process may require additional investigations for new design elements or design optimisation.

9.2 Design

Dam design, as with most complex developments, involves an iterative process. Numerous design options and modifications will be required before a solution is found that meets the client's expectations, required safety standards, environmental constraints, public considerations and budgetary limitations.

For large dam projects involving many specialist disciplines, this iterative process will involve a series of intertwined feedback loops.

The design process for dams is complex and varies depending on dam type and purpose. It is not practical in this document to cover the design processes involved, but an understanding of the main safety issues that must be addressed in the dam design phase is necessary. These are:

1 Evaluation of the hazard and associated risks. This needs to be undertaken at a early stage as it determines the appropriate levels of investigation, design and design conservatism.

2 Qualifications of the design team must be adequate for the level of project complexity. The Project Manager fulfils the most important role of ensuring that incompatibilities do not arise between different design components and technical advisors.

3 Appropriate analyses and design methods should be adopted. While most dams are unique in their setting and design, the design procedures used to derive the designs are well established. New technology and knowledge may allow better scheme optimisation and cheaper solutions, but the process is very similar from site to site.

4 A 'what if' approach is required for engineering critical components or in areas of greatest risk. A backup control for a spillway gate may cost several thousand dollars but a multi-million dollar spillway may end up being useless in the event of failure of a $5 switch to open the gates.

This conservative approach is often termed *defensive failsafe engineering.*

5 Construction specifications, based on the design must be clear and understandable. The contractor must be made aware of design parameters, assumptions and concepts and have an understanding of design limitations.

- The design must also be able to withstand construction. The loadings and risk present during construction are amongst the greatest the structure will ever face and consideration of how the dam will be built is often influential on and sometime dictates the overall design concept.

6 A degree of flexibility must be maintained in the design to allow for modifications that will almost certainly be required during construction to meet unforeseen conditions.

7 Careful consideration must be given to any stream diversion during construction and the construction sequence as a whole. The level of risk associated with the adopted diversion during construction concept must be assessed.

Once the final design solution is obtained, a check needs to be made that the parameters on which the initial design concept was based are still valid. Many failures have occurred due to a sequence of very minor design changes which when accumulated together produce a design solution well outside the initial design envelope on which important design assumptions were based.

9.3 Construction

Dam construction involves the conversion of the design in to an actual physical structure. While this may seem obvious, this link between design and realisation of the design is crucial to the establishment of a safe dam. Many dam incidents have resulted from lack of communication between construction and design personnel. Whereever possible, key members of the design team should be involved in construction.

Key issues associated with the construction process to consider:

1 The contractor should be suitably experienced in dam construction and in communication with specialist design staff.

2 The level of supervision and quality assurance both from the contractor and the owner's representatives should be appropriate to the scale of the project.

3 The owner must be made aware that modifications during construction will nearly always be required and that an allowance should be made for this when funding the scheme.

4 Design changes should not be made without the original designer's approval. A dam is a combination of interdependent components. A change to one component will frequently have flow-on effects on others.

5 Observations, monitoring and design changes during construction should be recorded and brought together in an as-built document. This record could be crucial in the event of problems that may arise later.

It is the role of Auckland Regional Council to ensure compliance with the consents issued for the development and the construction phase. Consents granted for dams effectively give permission for a 'hazard' to be constructed. Council staff must ensure they do not mistakenly assume liability for unsafe structures. External reviews are essential and are discussed in detail in Part 5 of this guideline.

9.4 Commissioning

Commissioning a dam involves the gradual application of design loadings. Formal commissioning is usually conducted only on higher hazard category dams. The purpose of commissioning is to test the dam and its associated structures under a range of loadings. Many design loadings, such as seismic and extreme floods, can not be tested. However if expectations are realised for normal load cases, confidence is gained for more extreme events.

Figure 3.2, shown previously, shows many failures and incidents occur during initial dam filling, highlighting the importance of careful commissioning.

Key components of the commissioning process include:

1 Carry out testing of all key components to a pre-arranged schedule

2 Give staff 'on the job' training for monitoring systems, safety, and incident response

3 Repair and/or modify any components that do not meet required performance specifications

4 Prepare a commissioning report detailing tests undertaken, results, modifications made and warning levels on monitoring equipment.

Preparation of an emergency action plan for higher hazard dams will typically be required.

The commissioning period should continue until the dam and all the associated components have met the required performance standards. Some items such as spillways may require review at a later date if their full design loading cannot be tested.

10.0 Minimum guidelines for building new dams

Standards for the investigation, design and construction of a new dam must be based on its hazard category. Definition of an appropriate hazard category as outlined in Part 1 of this guideline is fundamental for establishing the required level of design input.

For example, it could be argued that a 7m high dam (with a low hazard category) on soft foundations would need more than simple test pits as a means of site investigation. Given the potential foundation problems, an appropriate hazard category for this structure may well be significant, in which case a more intense investigation is needed. This simple example highlights the importance of defining an appropriate hazard category for a dam.

The minimum standards outlined in the four flow charts that follow describe minimum investigation, design and construction performance levels that could be expected for proposed dams in four hazard categories. These are not the only appropriate methods or the maximum level of input required. A level of interpretation will be required from the personnel assessing a new dam proposal as to the appropriateness of the proposed methods. A performance assessment sheet is provided in Figure 3.11.

More detailed information on specific areas of investigation and design is given in Section 12 of this Part 3. A brief checklist sub-divided by hazard category is provided in Figures 3.12 – 3.14 for different hazard categories.

11.0 Specific design details

Dam structures and their impounded materials place a load on their foundations and surroundings. This loading needs to be transferred to the surrounding natural materials. The dam also needs to control seepages, not settle significantly, and serve the purpose for which it was built.

Most dams, especially embankment dams, consist of three main parts, in terms of loadings:

- the foundation which must provide support to the structure above and not allow excessive leakage. The connection between the dam and foundation must also be adequate
- the **upstream portion** or part of the upstream portion of the dam which must provide a seal against excessive leakage from the storage
- the **downstream portion** of the embankment which must provide support to the upstream portion.

The dam must be protected from natural events that may add extra loading onto the structure or threaten damage to it.

This section is mainly aimed at earthfill embankment dams, but most of the broad principles also apply to other forms of dam construction. For construction methods other than earthfill, designs are typically more complex and need more specialist input. For this reason, alternative construction types are most often associated with larger structures.

11.1 Dam foundations

The foundation of a dam, or the zone in which the engineered structure meets the natural ground, is crucial to the integrity of the dam. The adage that a 'structure is only as secure as the foundations on which it rests' applies to dams. Common problems associated with foundations include:

- bearing capacity failures
- foundation settlement
- piping and leakage.

Ways of over coming these problems are outlined below:

Foundation profile and bearing capacity

The dam must be founded on material strong enough to bear the vertical loads imposed on it. It must also be able to resist the shearing force produced by the structure. Assessing the soil strength profile of the foundation is the main purpose of the sub-surface investigations in the vicinity of the dam.

The soil profile beneath the dam, and the properties of this profile have the greatest influence on the selection of dam type and profile. Some typical foundation profiles and the effect these may have on embankment dam design are shown in Figure 3.5.

Foundation conditions have a major influence on the stability of the embankment.

Earth dams must be analysed for stability of the embankment itself, while concrete structures are more prone to sliding on the foundations or toppling.

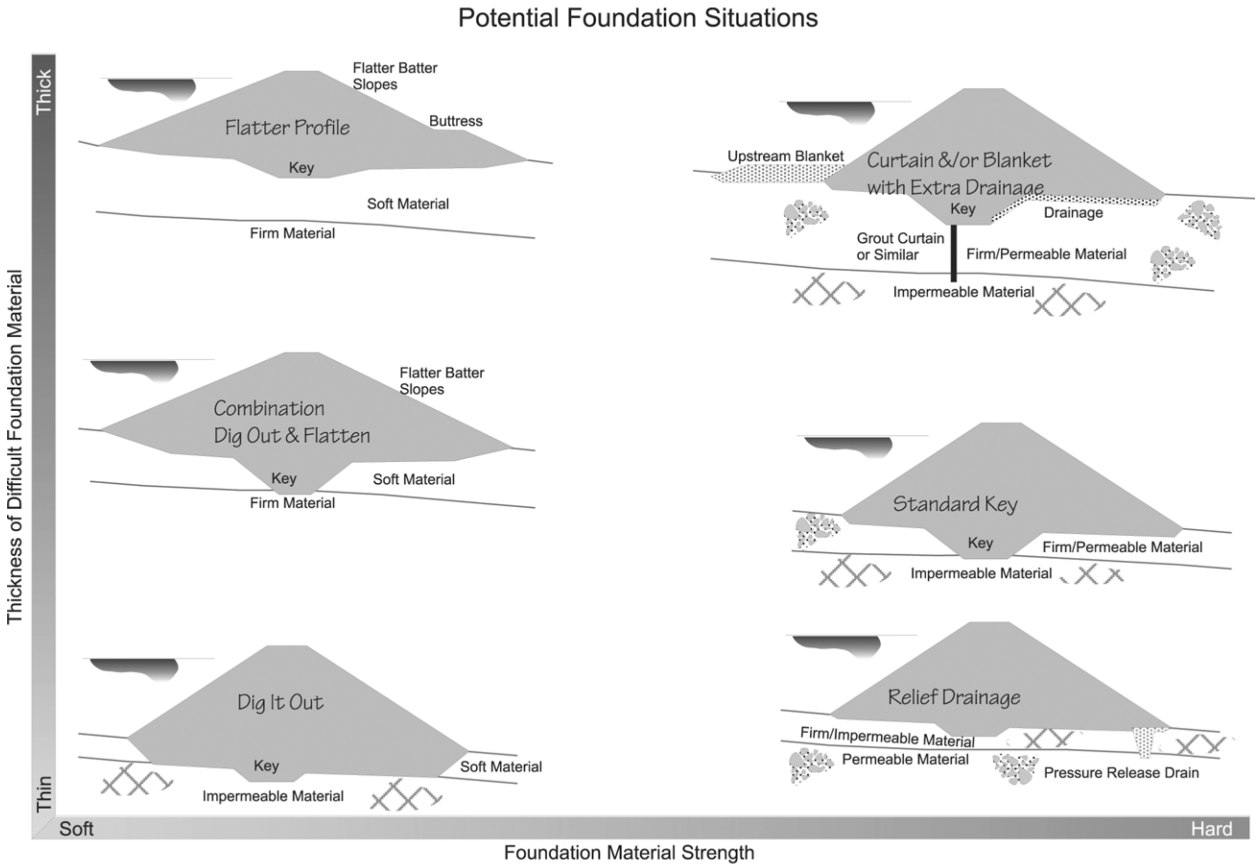


Figure 3.5: Potential Foundation Situations

Foundation settlement

Some settlement of the foundation materials, in addition to settlement of the embankment fill (in the case of earthfill dams) is likely to occur. This settlement can cause cracking in the fill and stress or even dislocate conduits that pass through the embankment or foundations. Differential settlement, which occurs when material properties change over the site or if the valley has an unusual profile, is of particular concern. Some examples of this are given in Figure 3.6.

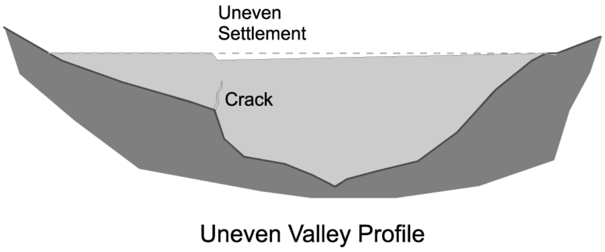
Potential settlement is another reason why softer foundation materials need to be either removed or designed for. Where settlement is likely to be a problem, additional drainage measures are warranted to control seepages that may occur through settlement cracks.

11.2 Piping and seepage control

All dams leak. Classical dam engineering focussed on trying to stop seepage flows completely. Not only were these attempts almost always unsuccessful, but they occasionally worsened the destabilising effects of seepage and water pressure. The modern approach is to limit seepages to a practical minimum, and then control the remaining flows by extensive targeted drainage.

Losses due to seepage can be economically and environmentally costly and can have safety implications, as most dams, especially earthfill dams, can be detrimentally affected by excessive or uncontrolled seepage flows. Reducing seepage and lowering the probability of piping failures can also reduce uplift pressures under the dam.

Seepage must therefore be reduced to a practicable minimum.



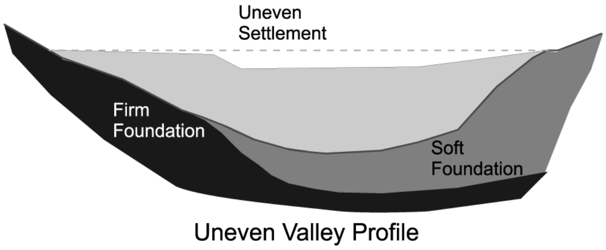


Figure 3.6: Differential Foundation Settlement

Seepage control focuses on two critical aspects:

- foundation and embankment seepage
- seepage along conduits.

Pressurised conduits, a special case, are also discussed.

Foundation and embankment seepage control

As shown embankment dams without drainage make up a disproportionate number of the observed incidents. The use of homogeneous earthfill dams without drainage is only acceptable for minimal hazard dams in uncomplicated situations.

The design of appropriate seepage control measures is site and material specific, and is therefore beyond the scope of this guideline to describe in depth. Some typical examples of drainage control measures are given in Figure 3.7.

The most common means of reducing seepage losses through dam foundations and abutments is by means of a cut-off or key. The purpose of the key is to replace a segment of the potentially permeable or variable foundations with engineered materials. The type, location and extent of the key reflects the foundation materials, dam type and likely seepage rates and pressures involved.

Part of the seepage control in Figure 3.7 is a key. The size and location of the key, if one is required, will depend on the nature of the foundation materials and the dam design. While a cutoff key will typically be incorporated into the design of an earthfill dam it should not be assumed that this is normal. (refer to Figure 3.5 and Section 11.1 of this part of the guideline).

Seepage reduction and control

The purpose of most dams is to retain fluids for use or treatment. Losses due to seepage can be economically and environmentally costly, and can have safety implications most dams, especially earthfill dams, can be detrimentally affected by excessive or uncontrolled seepage flows. Seepages must therefore be reduced to a practical minimum

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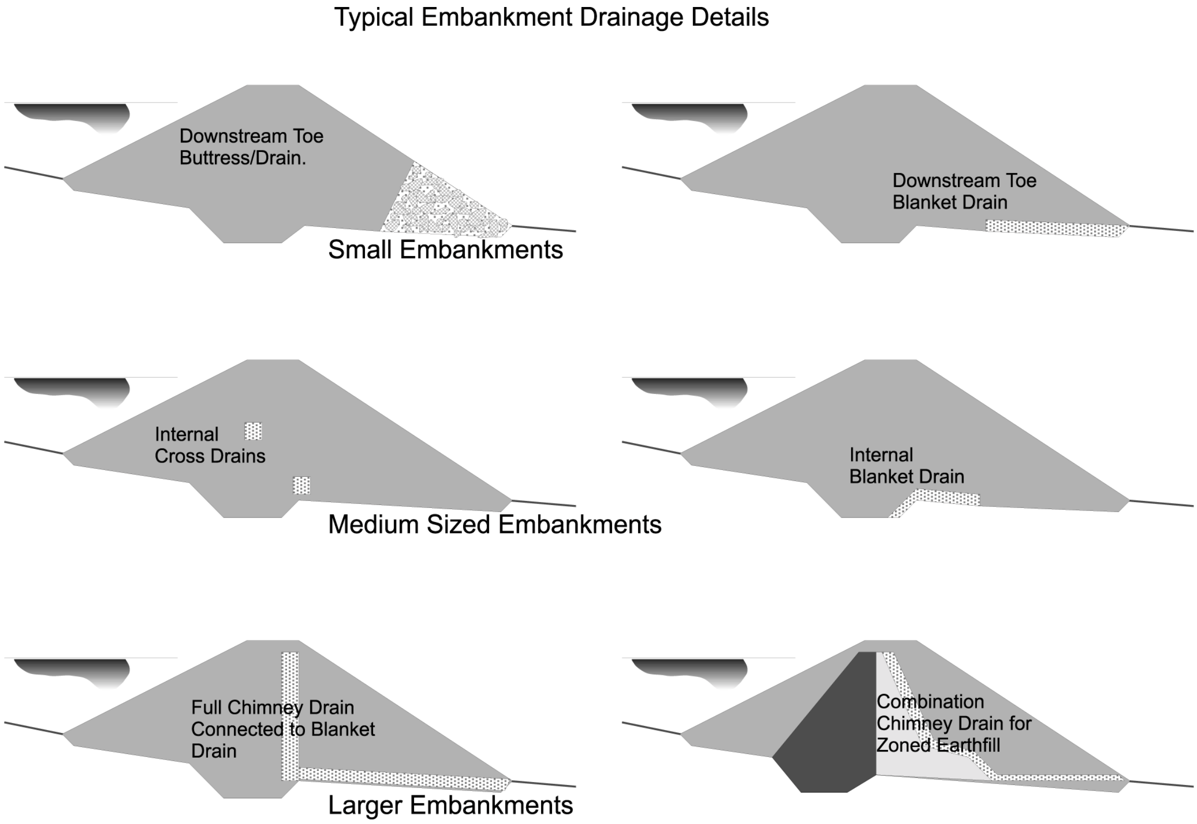

Figure 3.7: Typical Embankment Drainage Detail

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Seepage along conduits

Conduits through dams, especially embankment dams, produce a discontinuity in materials. These different material properties between the conduit and the surrounding fill can result in differential settlement. This will produce potential leakage paths along the line of the conduit, which in the worst case will enlarge with time, leading to failure. In addition, it is very difficult to adequately compact around conduits, exacerbating the problem.

Again, the classical approach was to try and stop seepage along conduits, typically with the use of cut-off collars. Cut-off collars along the upstream portion of the conduit will retard flow and provide a degree of support for the conduit, but the same problem of adequate compaction remains for material either side of the collars. For this reason cut-off collars should not be relied on as the only means of controlling seepage, though they are still applicable in many situations. In many situations alternative measures are more applicable such as the use of concrete encasement or bedding. Another alternative for smaller dams would be compacted soil / bentonite mixes. The downstream section should however always be drained in a controlled manner. This ensures these seepage flows that will occur do not erode the fill material around the conduit. A typical detail using collars is shown in Figure 3.8.

Pressurised conduits

The use of pressurised conduits through dams should be avoided whenever possible. If their use is unavoidable, their design and construction must be considered very carefully. Because settlement of the dam fill or underlying foundations can cause stress or dislocations to conduits passing through the dam, in the case of pressurised conduits high water pressures, equivalent to the water level in the reservoir, could be released into the sensitive dam interior. For this reason pressurised conduits are seldom used for large dams.

There is no definitive rule for when pressurised conduits pose a significant risk. The strength of the foundations, type of conduit and conduit purpose all influence the suitability of pressurised conduits.

11.3 Flood magnitude and control

Floods pose one of the greatest threats to dams. Adequate control of floods is required to reduce the risk that potential hazard is realised.

Flood magnitude

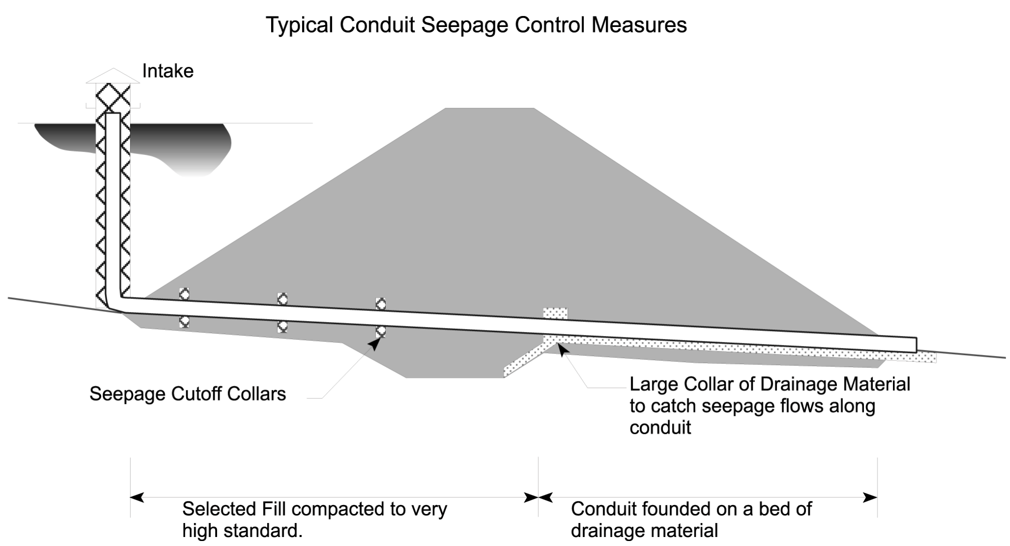
The design flood is selected on the basis of the dam's hazard category, the significance of components that may be damaged in a flood and the level of understanding of the area's hydrology. Of the series of terms used to describe different types and level of design floods, the most common are:

Diversion design flood – the magnitude of the event for which the dam is protected during construction.

Operation base flood (OBF) – a moderate sized event for which no specific flood control measures would be required and following which the structure could be expected to return immediately to full operation.

Maximum design flood (MDF) – the maximum event that the structure has been designed to safely pass. Normal operation of the structure would probably not be possible following the event until a full systems check was undertaken.

Figure 3.8: Typical Conduit Seepage Control Measures



Bank/crest full flood (CFF) – an event which causes the reservoir to rise to the level of the dam crest to the extent that there is no freeboard. In some situations this may be equivalent to the MDF.

Probable maximum flood (PMF) – the largest probable flood event that could occur at the site, or the theoretical upper limit to flood magnitude.

Appropriate standards for design floods

Flood standards suggested by this guideline are compared with some from overseas organisations shown in Figure 3.9. The figures shown should not always be considered minimum standards, as in some instances a lower design flood may be appropriate, particularly for dams at the lower end of their hazard category. In these situations the designer must prove that a lower level is appropriate. Design floods must be adopted on a case by case basis.

The differences in design floods selected by various organisations, reflect these different hydrological conditions. The conservative design floods specified in the ANCOLD guidelines would not necessarily be practical in New Zealand.

The standard suggested by the Auckland Regional Council is not an immovable standard. Flexibility should be maintained to allow the applicant the opportunity to present an alternative to the design flood suggested. Use of external peer reviews would be an important consideration in the acceptance of alternative design standards.

Consideration of diversion floods

The selection of appropriate diversion design flood needs at least as much careful consideration as finished dam design floods. The applicant must justify the diversion flood standard to be adopted.

When selecting the diversion design flood, the applicant must consider interim hazard categories for the structure for the various key stages of its development. Diversion flood capacity may well also change during the period of construction. For larger dams, where construction may take several seasons, consideration should also be given to programming construction to avoid the dams more vulnerable stages that coincide with seasons when floods are more prevalent.

Seasonal flood frequency analysis is used to identify critical times during the year. Care must

Figure 3.9: Flood Design Standards

Organisation	**Hazard category**		
	Low	Significant	High
	Diversion design flood return period		
ICOLD	1 : 5 to 1 : 50 year return period event for earthfill dams		
ANCOLD	up to 1: 50	1:10 - 1:100 * Construction time (yrs)	1:100 * Construction time (yrs)
Suggested by this guideline	1 : 5	1 : 5 * Construction time (yrs)	1 : 10 * Construction time (yrs)
	Operation Base Flood (OBF) return period		
Suggested by this guideline	1 : 5	1 : 20	1 : 100
	Maximum Design Flood (MDF) return period		
ANCOLD	1:100 - 1:1000	1:1000 - 1:10,000	1:10,000 to PMF
US Corps	1:50 - PMF	1:100 - PMF	½ PMF - PMF
Suggested by this guideline	1 in 100	1 in 1000	1:1000 - PMF

ANCOLD – Australian National Committee on Large Dams
US Corps – US Corps of Engineers

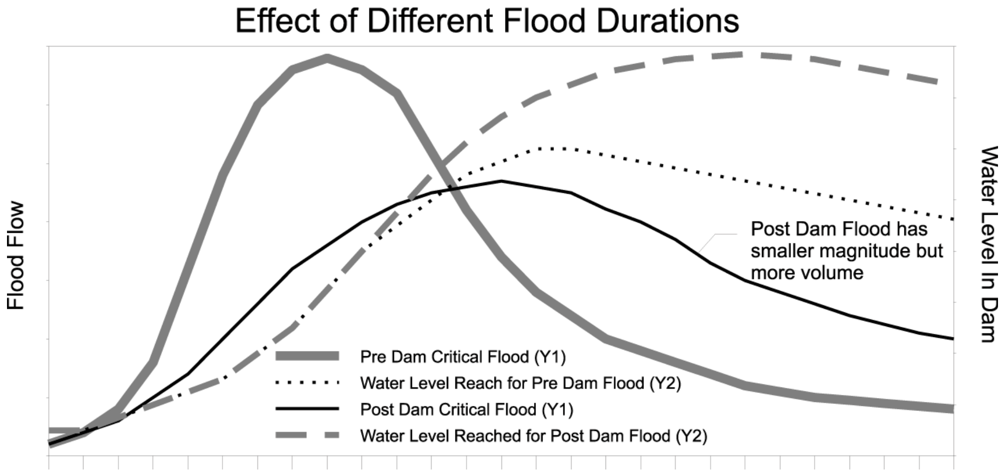


Figure 3.10: Effect of Different Flood Durations

be exercised to ensure that a consistent level of protection is obtained. For instance a 1 in 10 year seasonal design flood will not give the same level of protection as a 1 in 10 year annual design flood.

For smaller structures where construction may only take a few months, selection of a smaller diversion flood may be appropriate.

Consideration of flood volume

The introduction of a dam changes the flood regime of a river. The storage behind the dam will slow down, attenuate the flood, reducing the peak flood magnitude downstream. It is very important to consider the impact of flood events of different duration when designing spillways. The critical flood event for a dam will not be the same as that for the river in its natural state. Longer duration events that contain a greater volume of water are typically more critical. This effect is shown in Figure 3.10.

Freeboard and wave run-up

When determining the height of a dam, allowance needs to be made for flood rises. Additional height should be added to allow for wave run-up and to give the dam a freeboard, or safety margin, against flood rise.

Freeboard is somewhat independent of hazard category, as the level of risk will already have been set by selecting appropriate design floods.

In many cases the maximum design flood will produce a water level in the storage close to crest full, with an allowance for wave run-up.

Wave run-up is dependent on reservoir size, orientation and location. Wave action is unlikely to be significant in reservoirs with open water lengths of less than 200m.

Spillway configuration

Many different spillway configurations are used for flood control. The type, number and operating method of spillways reflect the dam's size and site conditions. The main criteria for spillways or flood passing systems are:

- controlled, safe passing of the operational base flood with no damage to the dam or associated structures
- safe passing of the maximum design flood without risk of dam failure or significant damage.

It is often impractical to meet both of these requirements with a single spillway or bypass system. Reliance on a single spillway passing flows in an extreme event is not appropriate for any except the smallest dams. If the spillway suffers damage during a maximum design flood and needs extensive repairs, an alternative means of passing smaller events should be available for use while repairs are undertaken.

In many situations the second flow-passing system may not be a spillway, but a low level outlet, turbine or similar.

Two spillways are the most common configuration for earth dams; a service spillway and an extreme event spillway. The next most common configuration is a single highly engineered spillway, with a backup means of passing flow such as a low level outlet, or a turbine.

For concrete dams where overtopping of the dam is less perilous a single spillway may be appropriate.

Service spillway

The service spillway is required to take the smaller, more frequent events without damage. It must also be able to be shut off or take its share of the flow during extreme events and still be useable afterwards. The capacity of the service spillway is typically up to the operation base flood event as described in Table 3.9.

Common types of service spillway used include:

- piped spillways
- flume or chute spillways
- conduit spillways such as bellmouth spillways

Flood spillway

The flood spillway must operate safely when required, but may sustain some damage during extreme flood events. The capacity of the flood spillway must be sufficient to pass the maximum design flood as described in Figure 3.9.

For simplicity and safety reasons, spillways without gates are preferable, although for economic and practical reasons, gates are often used. Additional care is required with gated spillways to ensure that the gates will open when most needed. They therefore need good design with regular inspection and maintenance when required (see Part 4 of this guideline).

Common types of flood spillway include:

- overflow chute spillways
- fuse plug spillways.

Energy dissipation

Flowing water contains energy. The more pressure or head that drives the flow, the more energy contained within it. This energy needs to be removed before the flow exits the engineered environment of the spillway or conduit.

If not enough energy is dissipated by the spillway design, damage can occur to the river downstream of the dam, to the spillway and to associated structures near the toe of the dam. In the worst case this damage may progress back upstream until the dam itself is compromised.

There are many ways of dissipating the energy from spillway flows. Care must be exercised to ensure a system is used that is compatible with the spillway type, energy in the flow and the downstream environment.

12.0 Existing dams

A dam's hazard category is independent of whether the structure is new or has been in existence for many years. In many cases the hazard category changes over the period of a dam's life due to increased at-risk population or changes in dam use. This can result in the dam becoming under-designed for the level of hazard it has come to pose as a result of these changes.

The safety and performance of existing dams must therefore be gauged in terms of current standards and design methods. This can cast some existing structures, particularly older dams, in a poor light. There are a number of reasons why an existing dam may not meet the required level of low risk appropriate to its hazard category. The main reasons are:

- changes in design and construction technology - the state of the art
- changes in hazard category due to demographic changes downstream
- modifications to the structure, its use or operation
- deterioration of all or parts of the dam
- changes in required standards
- uncertainty about the dam's structural integrity.

In most cases there is likely to be a combination of the above. Uncertainty is one of the most common reasons why a dam may be perceived as not meeting current criteria. For this reason adequate levels of monitoring are critical to ensure confidence can be maintained in a structure's performance.

12.1 Safety reviews

The issues listed above mean that larger dams are generally subjected to periodic performance and safety reviews. These reviews range from frequent internal reviews of monitoring and surveillance data to full external reviews.

Internal reviews generally focus on the performance of the dam and its associated structures against a set of guidelines and criteria developed by the original designer or peer reviewer. Should observed results fall outside the prescribed original limits there should be procedures set in place to take appropriate action.

External reviews are conducted to obtain a fresh, unbiased view of the scheme's performance. The review will generally include examination of monitoring and surveillance results and a comparison of its design and operation against current dam criteria.

Dam reviews are discussed in detail in Part 5 of these guidelines.

12.2 Meeting current criteria for existing dams

In an ideal world it would be desirable to upgrade all existing dams and associated structures to current standards. In the real world, however, there are several reasons why this is not always practical.

Dam owners are very reluctant to commit finances to upgrades, particularly when there is no guarantee that the standards won't change again in the near future, forcing further upgrades. Public perception of hazard is also often less for existing structures than new dams.

More positively however, several alternatives offer better options than upgrading many existing dams:

1 **Alter operations** – If the dam is not meeting the required safety level appropriate for its hazard control in just one or two specific areas (eg flood protection), changes to the dams operation may offset the safety deficit. For example by maintaining a lower operating level to increase flood freeboard.

2 **Monitoring** – Often dams do not meet current safety criteria because of lack of understanding of uncertainties about how the structure is performing. Enhanced monitoring, often in conjunction with exploratory investigations, may well show that the structure does meet required safety standards.

3 **Decommission** – In some cases it may be more appropriate and economically viable to decommission the structure. While this removes the hazard posed by the dam and reservoir, consideration must be given to the changes this will have to the downstream environment.

   For example, the reduced occurrence of floods downstream the dam may have induced, will no longer be enjoyed. This may have implications for communities or infrastructure that have developed since the dam was built.

The type and extent of modifications to an existing dam that will enable it to meet current safety criteria are very site and structure-specific and cannot be addressed in detail in this guideline. The information in Sections 9, 10 and 11 was aimed at new dams but is still applicable for assessing existing structures. The performance assessment checklist at the end of this part (Figure 3.11) can be used to assess potential safety deficiencies in a dam and when further information is needed.

Auckland Regional Council
Performance Standards for Dams

Performance Assessment Sheet for New Dams

Items Shown in *Italics* are more applicable to Significant and High Hazard Structures.

Dam Details			Hazard Cat.
Dam Name	Ref	Assessed	L S H
Owner	Purpose	Date	

Assessment

Design Team

Designer — Experience
Specialist Input
Geotechnical
Hydrological
Hydraulic — Comments
Mech/Elec
Other

Adequate / Uncertain / Inadequate

Q. Assurance

System
Internal Review — *External Reviewer*
Concept Yes No Who — *Concept Yes No Who*
Design Yes No Who — *Design Yes No Who*
Construction Yes No Who — *Construction* Yes *No Who*
Commissioning Yes No *Who* — *Commissioning* Yes *No Who*

Adequate / Uncertain / Inadequate

Investigations

Geotechnical Y N Type & Extent
Hydrological Y N Type & Extent
Environmental Y N Type & Extent
Other Y N Type & Extent

Adequate / Uncertain / Inadequate

Design

Floods & Spillways
Operational Base Flood 1 in Flow m3/sec Duration hr Freeboard m
Maximum Design Flood 1 in Flow m3/sec Duration hr Freeboard m
Service Spillway Type Design Flood 1 in
Flood Spillway Type Design Flood 1 in
Other Outlets Type

Adequate / Uncertain / Inadequate

Dam Embankment
Type
Foundation
Drainage

Adequate / Uncertain / Inadequate

Conduits
Type
Foundation
Drainage

Adequate / Uncertain / Inadequate

Construction

Contractor(s)
Name — Experience
Supervision
Name — Component(s)
Completion
Monitoring and Surveillance Installed Y N Type & Extent
Separate M&S Schedule Y N
Report / As Built Y N

Adequate / Uncertain / Inadequate

Comm'g

Commissioning Procedure Undertaken Y N — *Commissioning Report Y N*
Components Tested
Spillway Y N Comments
Conduits Y N Comments
Other

Adequate / Uncertain / Inadequate

Op. & P.

Operation & Performance Manual Prepared Y N
Emergency Preparedness Plan Prepared Y N
Comments

Adequate / Uncertain / Inadequate

Figure 3.11: Performance Assessment Sheet for New Dams

Auckland Regional Council
Performance Standards for Dams

Minimum Guideline for the Development of New Dams

	(Minimal) Low Hazard Catagory		
	Minimum Input Required	Suggested Appropriate Method/Standard	Dams Approaching 'Significant' HC
Proficiency of Design Team	➢ prior dam design experience an advantage ➢ good all round civil engineering experience ➢ specialist support for electrical/mechanical aspects.		Specialist geotechnical input may be required.
Quality Assurance	➢ appropriate in-house systems		
Investigations	➢ general appraisal of local land forms with respect to slope stability and groundwater seepage. Explore local knowledge.	walkover survey	
	➢ foundation investigation over dam footprint.	test-pits, auger drills holes and/or hand-augers boreholes.	
	➢ hydrological assessment using general regional methods.		Use of local data if availiable.
Design Procedures	➢ empirical design procedures and profiles will generally be appropriate.	embankment profile of 3h:1v or similar for earthfill	Specific attention to drainage of the foundations and embankment
	➢ embankment stability should be considered	FOS > 1.5 under worst static load case.	Specific stability analyses may be required for range of load situations
	➢ standard procedures for design of hydraulic structures	Spillway Capacity: refer later. Conduit Detail: refer later.	Specific design of conduits through dam may be necessary
	➢ design report detailing concepts, assuptions and details should be produced in conjuction with uncomplicated design drawings.		Simple construction specification
Construction	➢ contractor has prior relevant experience in similar type of work. Particular experience required in the area of interpretation of design drawings.		In-Situ testing of foundation and fill materials Sub-contractors may be warrented for specific components (eg pipe work)
	➢ Intermittent inspections by responsible technical staff. Key inspection times include: - following foundation preparation but prior to any fill placement. - periodically during embankment construction - during constrution of any conduits through the dam - during installation of key safety components (eg spillways) - final completion	Visual Inspections Simple in-situ testing (eg shear vane, clegg hammer)	
	➢ brief construction completion report.		A more extensive report including 'as-built' details may be warranted.
Commissioning	➢ specific commissioning procedures unlikely to be required although owner should undertake frequent visual inspections and maintain contact with designer.		

Figure 3.12: Minimum Guideline for the Development of Minimal and Low Hazard Dams

Auckland Regional Council
Performance Standards for Dams

Minimum Guideline for the Development of New Dams

Significant Hazard Catagory

	Minimum Input Required	Suggested Appropriate Method/Standard	Dams Approaching 'High' HC
Proficiency of Design Team	➢ prior dam design experience in similar dam projects either as team leader or in major design role. ➢ specialist geotechnical input for foundation and materials aspects. ➢ specialist input on electrical, mechanical and hydraulic design. ➢ formal quality assurance system		Other specialist input such as geological and seismological may be warranted.
Quality Assurance	➢ peer review of design concepts and key components		
Investigations	➢ geotechnical apprasials should include - examination of aerial photos if available - geological appraisal of local and - regional aspects including seismicity sub-surface investigation of entire dam footprint and beyond. - materials investigation of borrow areas - in-situ and laboratory testing of foundation and construction material properties.	walkover survey, research existing data test-pits, auger drills holes machine boreholes. shear vane, penetrometer. fill compaction testing, moisture content atterburg limits.	Consideration should be given to obtainig new aerial photos. SPT, CPT testing may be appropriate Triaxial, consolidation, permeability testing.
	➢ hydrological apprasials should include - examination of local data and characteristics. - consideration of local groundwater regime.	local rainfall gauge information published rainfall intensity data	Installation of hydrological monitoring may be appropriate. Flow gauging especially for streams with a year round flow.
Design Procedures	➢ empirical design procedures are only appropriate for smaller dams without foundation difficulties.	embankment profile of 3h:1v or similar for smaller earthfill dams	Specific design solution required
	➢ specific detailing of remedial measures to address problems highlighted during the investigation		Additional investigation could be required to check design issues
	➢ stability analysis for all main load cases including rapid drawdown.		Computer modelling of dam and foundations may be undertaken
	➢ specific attention to hydraulic components (eg conduits)	Conduit Detail: refer later.	
	➢ flood analyses should include allowance for storage effects.	Spillway Capacity: refer later.	Storage modelling and flood routing will be necessary
	➢ special attention should be given to how the dam will be built (eg river diversion)	Diversion Considerations: refer later.	
	➢ specific attention given to seepage and groundwater control measures	seepage flow nets.	Specific seepage and groundwater modelling may be appropriate
	➢ full design report detailing investigation results, analyses, design assuption and concepts.		Peer reviewer report and endorsements.
	➢ specifications and construction drawings.		

Figure 3.13: Minimum Guideline for the Development of Significant Hazard Dams

Auckland Regional Council
Performance Standards for Dams

Minimum Guideline for the Development of New Dams

Significant Hazard Catagory

	Minimum Input Required	Suggested Appropriate Method/Standard	Dams Approaching 'High HC'
Construction	➢ prior experience in directly applicable work and have existing personel with relevant experience in dam construction		
	➢ intermittent inspections for smaller dams, up to full time supervision for larger dams.		
	➢ supervision undertaken by responsible technical staff. Different personel may be required to supervise different components. Key inspection times include: - following foundation preparation but prior to any fill placement. - any foundation drainage systems or seepage control measures - periodically during embankment construction - internal drainage systems - during construction of any conduits through the dam - during installation of key safety components (eg spillways) - during installation erosion control measures (eg riprap) - final completion	visual inspection backed up with in-situ testing (eg shear vane, clegg hammer, scala penetrometer etc).	Laboratory testing of fill compaction standards, material suitability. Multiple inspections will be required for many components. Installation of hydrological monitoring may be appropriate. Flow gauging especially for streams with a year round flow.
	➢ construction completion report with details of, and reasons for, any alteration to the design. As-built details.		Construction coments from the external reviewer may also be availiable.
Commissioning	➢ a specific list of items to observe during the commisioning process should be prepared.		Some specific tests may be programme for key components.
	➢ acceptable limits for monitoring equiptment should be defined.		Alarm levels may be set for key instruments for the purpose of incident management. Storage modelling and flood routing will be necessary
	➢ a short commissioning report should be prepared with specific details of any problems encountered and remedial measures required.		

Auckland Regional Council
Performance Standards for Dams

Minimum Guideline for the Development of New Dams

High Hazard Catagory

	Minimum Input Required	Suggested Appropriate Method/Standard
Proficiency of Design Team	➢ team leader should have specific experience in 'High' hazard dam projects of a similar type either as team leader or major contributing role. ➢ specialist personel with appropriate levels of previous experience in all major disciplines involved. ➢ specialist input on electrical, mechanical and hydraulic design.	
Quality Assurance	➢ formal, fully integrated quality assurance system across entire project. ➢ peer review of design, construction and commissioning. More than one reviewer will probably be required to cover different disciplines.	
Investigations	➢ geotechnical apprasials should include - examination of all existing material. - geological appraisal of local and regional aspects including seismicity, volcanism etc. - comprehensive investigation of the dam site, abutments and sensitive areas of the reservoir perimeter. - full materials investigation of borrow areas and sources for imported materials	walkover survey, topographical survey, research existing data, examination of similar schemes. testpits, auger drillholes, machine borehole exploratory tunnels and trenching, geophysical testing full range of in-situ and laboritory testing
	➢ hydrological apprasials should include - examination of local data and characteristics. - installation of hydrological monitoring equipment - consideration of local and regional groundwater regime.	flow gauging with correlation with long term records from nearest appropriate flow record(s).
Design Procedures	➢ state of the art specific design of all components. ➢ specific attention paid to the interation and interconnection between different components. flood analyses using atleast two recognised mothods	
	➢ full consideration of 'during construction' case especially with respect to diversion design and short term foundation loading groundwater modelling or indepth seepage analyses.	interim Hazard and Risk evaluation for during construction case.
	➢ full design report plus supporting documentation. Peer review report(s)	
Construction	➢ prior experience in large dam with existing personnel with relevant experience in dam construction ➢ designer should be represented onsite full time by adequately qualified personnel. full time supervision and performance testing ➢ peer reviewers should be retained and kept up to date with project and alterations. ➢ comprehensive instrumentation installed and monitored during construction. ➢ thorough construction completion report, as-built drawings and performance records.	
Commissioning	➢ pre-defined scope and procedure for commissioning each main component. ➢ pre-defined performance limits and acceptable tolerances ➢ alert and warning levels on monitoring installations for commissioning period and beyond. ➢ full commissioning report with details of any problems encountered review comments and ongoing monitoring recomendations.	

Figure 3.14: Minimum Guideline for Development of High Hazard Dams