Report

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From	Habib Ahsan	**Project No.**	12642468
Project Name	PNCC Stormwater Support Services 2024/25		
Subject	Design and construction considerations for dams additional to the PNCC ESLD requirements		

Dear Stuart,

1. Introduction

The Palmerston North City Council (PNCC) has developed Engineering Standards for Land Development (ESLD) to "state the technical standards necessary to comply with the objectives and policies set out in Section 7 of the PNCC's District Plan". Further, the ESLD states that the ESLD "contain all relevant criteria to ensure Developers provide all the information necessary when seeking engineering approval for land development". The most recent version of this document is dated March 2023.

The ESLD focuses on land development and provides limited reference to dams. Where dams are required as a part of land development projects, incorporation of supplementary guidance specific to dam design and construction is considered necessary.

1.1 Purpose of this report

The purpose of this report is to provide high level guidance to PNCC and developers engineering representatives in relation to the design and construction of embankment dams (constructed from earthfill materials) that do not meet the threshold for classification as a 'large dam'. This includes highlighting aspects of dam design and construction that may differ from land development works as foreseen in the ESLD.

This guidance is not intended to be exhaustive and given that conditions related to each dam site differ, the land developer is recommended to engage suitably qualified professionals in relation to such works.

Direction is required to reference documentation commonly used within the dam industry that, when applied by a suitably qualified professional, may form the basis for substantiating an alternative solution for dam design in relation to the Building Regulations 1992 (Building Code).

2. Scope and limitations

2.1 Scope of work

This report provides a high-level guidance to be considered by the PNCC when reviewing design documentation submitted for dams that are not classified in the Building Act 2004 as large dams. This report may be included as an appendix to the PNCC Engineering Standards for Land Development.

2.2 Limitations

This report has been prepared by GHD for Palmerston North City Council and may only be used and relied on by Palmerston North City Council for the purpose agreed between GHD and Palmerston North City Council as set out in section 1.1 of this report.

GHD otherwise disclaims responsibility to any person other than Palmerston North City Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

GHD has prepared this report on the basis of information provided by Palmerston North City Council and others who provided information to GHD (including Government authorities), which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer section 3 of this report). GHD disclaims liability arising from any of the assumptions being incorrect.

3. Assumptions

The following assumptions are integral to the guidance provided herein:

- These guidelines will not be read in isolation and must be read in conjunction with other industry guidance.
- Dams being assessed are not classified as large dams and their consequence category is no greater than Low as defined in NZSOLD 2023 Guidelines.
- Professionals suitably qualified and experienced in dam engineering are responsible for the design and review of dams.
- Advances in dam engineering practice and legislation are incorporated as appropriate.

4. Legislative requirements

Legislation for the design of dams in New Zealand is provided for within the Building Act 2004 and the Building Regulations (the Building Code) 1992. Table 1 below indicatively shows the relationship of these as well as the various means of demonstrating compliance with the Building Code.

The following sub-sections provide a selected summary of aspects from legislation in New Zealand related to dams.

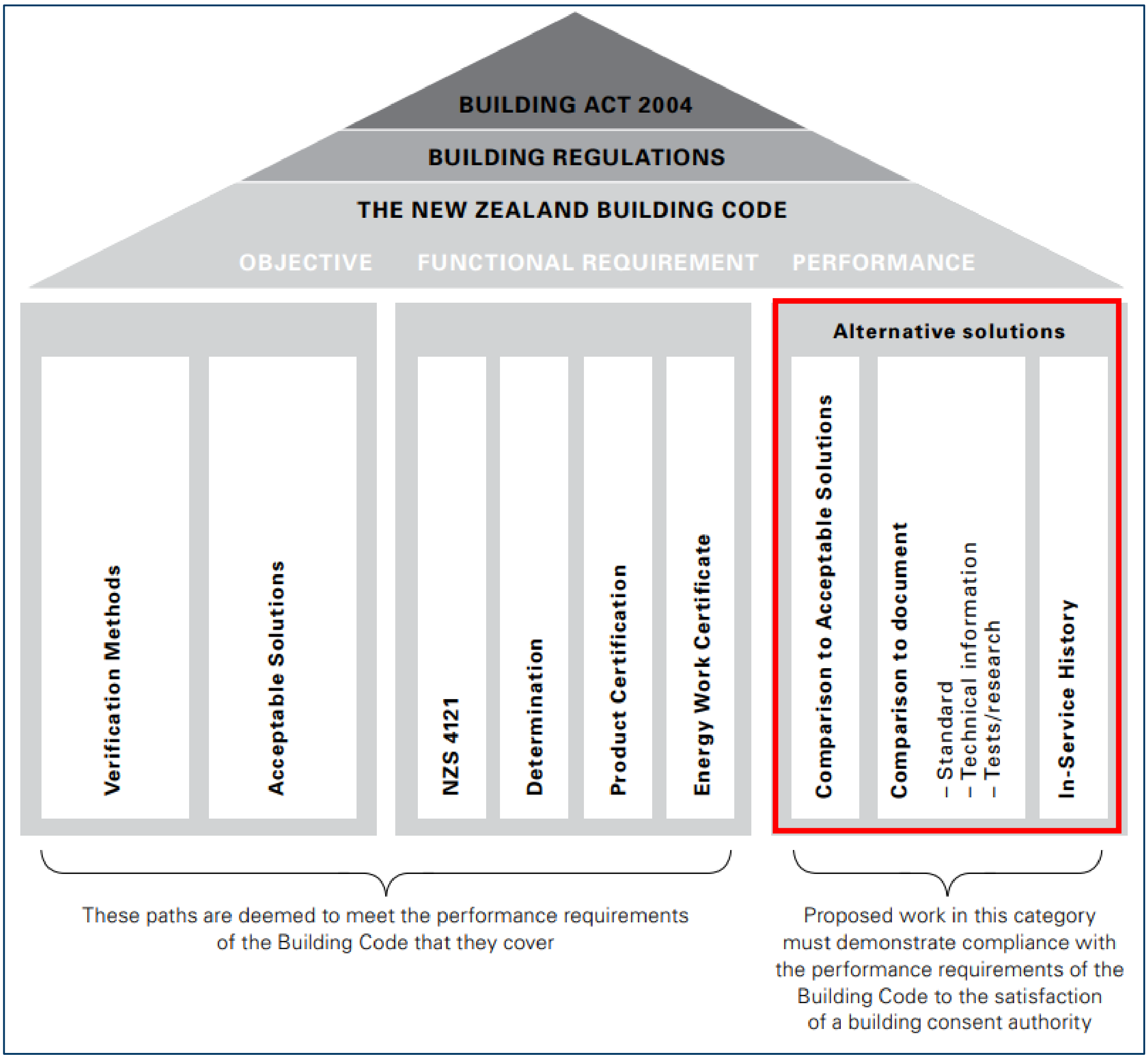

Figure 1 New Zealand Building Control Framework, adapted from (Building and Housing, 2011)[1]

4.1 Definition of Dam as per Building Act (2004)

Section 7 of the Building Act 2004 defines a dam as follows:

(a) an artificial barrier and its appurtenant structure that:

- (i) Is constructed to hold back water or other fluid under constant pressure so as to form a reservoir; and
- (ii) Is used for storage, control, or diversion of water or fluid; and

(b) Includes:

- (i) A flood control dam; and
- (ii) A natural feature that has been significantly modified to function as a dam; and
- (iii) A canal; but

(c) does not include a stopbank designed to control floodwaters.

[1] Department of Building and Housing (2011) New Zealand Building Code Handbook, Wellington, New Zealand. Ministry of Business, Innovation & Employment

4.2 Large Dams and Exempted building work

The New Zealand Building (Dam Safety) Regulations 2022 that came into effect on 13th May 2024 affect dam owners with classifiable dams. The regulations describe the classifiable dam as:

Dam that has a height of 4 or more metres and stores 20,000 or more cubic metres volume of water or other fluid.

A building consent is required for dam known as large dam satisfying the above criteria.

Exempted building work for which a building consent is not required includes building work in connection with a dam that is not a large dam.

However, all building work in New Zealand must comply with the building code to the extent required by the Building Act 2004, whether or not a building consent is required. This is stated in Section 17 of the Building Act 2004.

Even where a building consent is not required, it is required that:

- Plans and Specifications are sufficient to result in Building Work that, if built to those Plans and Specifications, complies with the Building Code.
- Building Work for which a Building Consent is not required complies with the Building Code.

4.3 Dam Height

As per the Building (Dam Safety) Regulations 2022, effective on 13th May 2024, the height of a dam is the vertical distance from the crest of the dam and must be measured:

(a) in the case of a dam across a stream, from the natural bed of the stream at the lowest downstream outside limit of the dam; and

(b) in the case of a dam not across a stream, from the lowest elevation at the outside limit of the dam; and

(c) in the case of a canal, from the invert of the canal.

4.4 Building Regulations 1992 (Building code)

A Large Dam is a defined in the Building Code as a Dam that is greater than 4 m in height and has the potential to retain more than 20,000 m^3 of fluid.

For dams, compliance with the Building Regulations 1992 (the building code) is typically by demonstration of an acceptable alternative solution. An alternative solution that is commonly adopted for the design of dams is citing of the New Zealand Dam Safety Guidelines NZSOLD 2023 Guidelines.

4.5 Dam safety regulations (2022)

The Dam Safety Regulations 2022 that came into effect on the 13th of May 2024. These Regulations require that the owners of dams that meet the height and volume requirements as defined in Section 4.4 above will need to confirm the potential risk their dam poses in the event of a dam failure, put in place a Dam Safety Assurance Programme (DSAP) and undertaking yearly Intermediate Dam Safety Review (IDSR) and Comprehensive Dam Safety Review (CDSR) at every five year interval for Medium and High PIC (Potential Impact Classification). A dam with Low PIC, DSAP, IDSR and CDSR are not required. PIC is a system of classifying dams according to the incremental consequences of dam failure so that appropriate dam safety criteria can be applied to reduce adverse impacts on people and properties. A dam can be classified as Low, Medium and High PIC dam depending on the severity of the impacts in the event of potential failure as set in NZSOLD 2023 Guidelines.

However, dams that do not meet the minimum size and volume thresholds as stated in Section 4.4 above are excluded from the regulatory framework.

The Regulations will apply to dams that are[2]:

[2] https://www.legislation.govt.nz/regulation/public/2022/0133/latest/whole.html

- 4 or more meters higher and stores 20,000 m³ or more cubic metres volume of water or other fluid.

4.6 Regional Council plan

New and existing small dams are a permitted activity in the Horizons Regional Council Regional Plan[3] provided that:

(a) Any new dam must not be located in a river prohibited by Rule 17-1 or regulated under Rule 17-3.

(b) For a dam in a river, the catchment area above the dam must be no greater than 50 ha.

(c) The maximum water depth must be less than 3 m (measured from natural ground level at the upstream toe of the dam structure).

(d) A spillway must be constructed enable passage of a 200-year flood without the dam being overtopped.

(e) Water impounded by the dam must not encroach onto adjoining properties.

(f) Dams in permanently flowing rivers must maintain a residual flow out of the dam at all times including during filling of the dam.

(g) For a dam located in a river, the activity must comply with the general conditions listed in Section 17.3.

(h) For a dam located in an artificial watercourse, the activity must comply with general conditions (a) to (k) of section 17.3 as if these conditions applied to an artificial watercourse.

(i) The activity must not take place in any rare habitat, threatened habitat or at-risk habitat.

5. NZSOLD Guidelines

The New Zealand Society on Large Dams Guidelines 2023[4], (NZSOLD 2023) provide generally accepted industry guidance in relation to dam design, construction, commissioning, assessment, rehabilitation and operation. Citing of the guidance provided in NZSOLD 2023 Guidelines is commonly used as an alternative solution to demonstrate compliance with the performance requirements of the Building Code.

The primary focus of NZSOLD 2023 Guidelines is to provide recommended practices for the investigation, design, construction, commissioning, assessment, rehabilitation and operation of large dams in New Zealand that are 4 m or more in height and impound 20,000 m^3 or more of water or other fluid. All of the principals and recommended practices in NZSOLD 2023 Guidelines are applicable to dams where the consequences of dam failure would be unacceptable to the public. In addition, all of the principals and many of the recommended practices are applicable to dams that do not meet the large dam threshold.

The guidelines are not intended to use in the investigation, design, construction, commissioning, assessment or operations manual, and reference must be made to appropriate technical publications, and appropriately qualified and experienced technical personnel during the development or safety evaluation of any dam project. The Guidelines do not cover every conceivable situation and the Owner and Technical Advisors to the dam Owner must decide what is appropriate to a particular project.

It is acknowledged that portions of the guidelines will be amended from time to time to reflect changes in industry knowledge and practice, or changes in the regulations. The latest update to the NZSOLD Guidelines were made in December 2023 and it is recommended that most recent revision of the guidelines be followed.

6. Literature

The commonly referenced literature related to the investigation, design, construction, and operation of dams includes:

- Geotechnical engineering of dams, 2nd edition, 2015 Fell, R; MacGregor, P; Stapledon, D; Bell, G; Foster, M

[3] https://www.horizons.govt.nz/publications-feedback/one-plan/part-2-regional-plan/chapter-17/17-6-rules-dams-and-damming
[4] https://nzsold.org.nz/wp-content/uploads/2024/01/nzsold_dam_safety_guidelines2023.pdf

- United States Bureau of Reclamation (USBR) Design Standards[5]
- United States Army Corps of Engineers Engineer (USACE) Manuals[6]
- Federal Emergency Management Agency (FEMA) Dam Safety Federal Guidelines[7]
- International Commission on Large Dams (ICOLD) Bulletins[8]
- Australian Commission of Large Dams (ANCOLD) Bulletins[9]

The Designer must decide what literature is appropriate to a particular project.

7. Design and construction considerations

The following aspects provide a non-exhaustive list of aspects that differ significantly between works related to land development and dams.

7.1 Potential Failure modes

A potential failure mode is a mechanism or set of circumstances that could result in the uncontrolled release of all or part of the contents of a reservoir. Potential failure modes of an embankment dam include:

- Overtopping
- Internal Erosion of embankment materials
- Suffusion of embankment materials
- Internal erosion of embankment materials into foundation materials
- Instability of downstream shoulder
- Instability of upstream shoulder
- Loss of freeboard, overtopping and subsequent erosion
- Erosion along embankment/structure interfaces
- Contaminated seepage
- Instability
- Structural failure

A potential failure mode of an embankment dam is a sequence of events starting from an initiating mechanism, such as a defect, flaw or seepage path in the dam or its foundation, and which may lead to an uncontrolled release of the reservoir. Potential failure modes are broadly characterised into four phases:

- Initiation
- Continuation
- Progression
- Breach.

The identification and evaluation of the failure modes for concrete gravity and buttress dams are similar to that of the embankment dams.

Each dam is unique and therefore it is not possible to provide a complete listing of potential failure modes for a type of dam. The Designer should consider all possible potential failure modes based on site-specific conditions

[5] https://www.usbr.gov/tsc/techreferences/designstandards-datacollectionguides/designstandards.html
[6] https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/u43544q/44414D/udt_43544_param_orderby/Pub_x0020_Number/udt_43544_param_direction/descending/
[7] https://www.fema.gov/emergency-managers/risk-management/dam-safety/federal-guidelines
[8] https://www.icold-cigb.org/GB/publications/bulletins.asp
[9] https://www.ancold.org.au/?page_id=19476

and the specific characteristics of the dam including:

- Loading conditions
- Foundation characterisation
- Material characterisation
- Design details
- Construction details

While identification of potential failure modes for a dam should be based on site-specific conditions and the specific characteristics of the dam, Table 1 summarises more common potential failure modes in relation to embankment dams and their foundations (NZSOLD Guidelines 2023).

Table 1 Potential failure modes for embankment dams[10]

Potential failure mode	Common causes
Overtopping	Insufficient freeboard to accommodate storms and flood events
Internal erosion of embankment materials	Presence of defect or crack, cohesionless core material or core material with a Plasticity Index less than 7, dispersive soils, lack of adequate filter protection
Suffusion of embankment materials	Cohesionless core material or core material with a Plasticity Index less than 7, gap graded embankment materials
Internal erosion of embankment materials into foundation materials	Open joints at interfaces, lack of adequate filter protection, lock of or inappropriate foundation treatment
Internal erosion of foundation materials	Foundation material has a Plasticity Index less than 7, dispersive foundation materials, lack of or inappropriate foundation treatment
Instability of downstream shoulder	Weak foundation, weak shallow seam in foundation, poor conditioning and compaction, lack of effective drainage and saturation of downstream shoulder, insufficient shear strength, strong earthquake shaking
Instability of upstream shoulder	Weak foundation, poor conditioning and compaction, rapid drawdown of reservoir, insufficient shear strength, strong earthquake shaking
Loss of freeboard, overtopping and subsequent erosion	Insufficient freeboard to accommodate foundation and embankment settlement, settlement following seismic loading, liquefaction of embankment and/or foundation materials, seiches generated by earthquakes, uplift of the reservoir due to fault displacement, reservoir landslides
Erosion along embankment/structure interfaces	Inappropriate design details, lack of filter and drainage protection, poor compaction adjacent to structure

7.2 Loading Conditions

Loading conditions for the design and rehabilitation of embankment dams are presented and discussed in various ANCOLD guidelines, Canadian Dam Association (2007), and various USACE and USBR engineering manuals. Loading conditions that should be considered in the design or rehabilitation of an embankment dam are:

- Normal loading conditions - Normal loading conditions are those which the dam is expected to continuously withstand during normal operation such as steady state seepage, embankment stability with normal maximum reservoir operating level and embankment stability with no reservoir for flood detention dam.
- Unusual loading conditions - Unusual loading conditions occur on an infrequent basis such as severe wave action, rapid drawdown of reservoir and end of construction condition with high pore water pressure that can exist in core and foundation materials.

[10] Adapted from (NZSOLD 2023), Table 6.2

- Extreme loading conditions - Extreme loads are those associated with low probability events such as flood at or above IDF (Inflow Design Flood), Earthquake at or near SEE (Safety Evaluation Earthquake) and post SEE loading condition.
- The Designer should consider whether each identified potential failure mode is credible or non-credible. Each potential failure mode should be documented including the foreseen path from initiation to breach along with rationale for inclusion or exclusion from further consideration. Potential failure modes considered credible should then be addressed in the design.

7.3 Performance criteria

The potential consequences of dam failure may include loss of life, injury, damage to infrastructure and property, damage to environmental values, and economic and social impacts. Based on damage levels (damage to the community buildings (residential dwellings, commercial, industrial and community facilities such as schools, hospitals, childcare facilities, places of worship, swimming pools, etc.), cultural sites, critical or major infrastructure, time to restore operation of critical or major structures, damage to natural environment), number of populations at risk at the above affected facilities and number of potential loss life at the effected facilities, NZSOLD 2023) guidelines define performance of a dam as low, medium and high PIC dam. These criteria are given for large dams however can be applied likewise for dams which do not meet the threshold classification for large dams.

Flood and earthquake hazard performance criteria for low PIC dams given in NZSOLD 2023 Guideline are reproduced below:

Table 2 Low PIC flood and earthquake hazard performance criteria

Hazard	Performance criteria	Low PIC guidance
Flood	Inflow Design Flood (IDF)	1 in 100 AEP to 1 in 1,000 AEP[12]
Earthquake	Operating Basis Earthquake (OBE)	1 in 150 AEP
	Safety Evaluation Earthquake (SEE)	50th percentile level for the CME if developed by a deterministic approach, and if developed by a probabilistic approach then at least a 1 in 500 AEP ground motion but need not exceed the 1 in 1,000 AEP ground motion.

Notes

[12] A condition of being a permitted activity under the Horizons Regional Council Regional Plan is that the spillway must be capable of passing the 1 in 200 annual recurrence interval (ARI) rainfall event.

Definitions as given in NZSOLD 2023 Guidelines:

AEP, Annual Exceedance Probability: The estimated probability that an event of specified magnitude will be equalled or exceeded in any year.

CME, Controlling Maximum Earthquake: The maximum earthquake on a seismic source that is capable of inducing the largest seismic demand on a dam.

OBE, Operating Basis Earthquake: The earthquake for which a dam, appurtenant structure and mechanical and electrical equipment that fulfils a dam safety function is designed to remain operational, with any damage being minor or readily repairable following the event.

PIC, Potential Impact Classification. A system of classifying dams according to the incremental consequences of dam failure, so that appropriate dam safety criteria can be applied.

SEE, Safety Evaluation Earthquake: The earthquake that would result in the most severe ground motion which a dam mut be able to endure without uncontrolled release of the reservoir, and for which the dam should be designed or analysed.

The IDF for Medium PIC dam is 1 in 1,000 AEP to 1 in 10,000 AEP while that for the High PIC dam is 1 in 10,000 AEP to PMF (Probable Maximum Flood). The OBE for both Medium and High PIC is same as that of the Low PIC dam i.e. 1 in 150 AEP. The SEE for Medium PIC dam is 50th to the 84th percentile level for the CME if developed by a deterministic approach and need not exceed the 1 in 2,500 AEP ground motion developed by a probabilistic approach. The SEE for High PIC dam is 84th percentile level for the CME if developed by a deterministic approach and need not exceed the 1 in 10,000 AEP ground motion developed by a probabilistic approach.

7.4 Foundation classification

Regional and site-specific geological studies should be completed for all dams, regardless of their Potential Impact Classification (PIC). The extent of the studies necessary will vary according to the quality of the existing information that is available (e.g. regional geological maps, aerial photographs), the complexity of the site, composition of foundation, the type of dam and its PIC.

7.4.1 Foundation characterisation – Low PIC dams

Investigation activities should include (Modified from NZSOLD 2023):

- Examination of published geological maps.
- Canvassing of local knowledge.
- Inspection of the dam site and reservoir area for signs of surface instability, faults, dormant or ancient landslides (particularly if they form the abutments) and other adverse geological features.
- Site investigations considering site-specific requirements.

Testing of the foundation materials to determine their characteristics and the extent of any necessary foundation excavation is recommended. Depending on the nature of the materials and potential failure modes identified, these could include:

- Water content
- In situ strengths
- Atterberg limits
- Dispersivity tests
- Particle Size Distribution (PSD)
- Permeability

7.4.2 Construction material characterisation

The identification and investigation of potential construction material sources is a key component of any investigation programme for a new dam and can be important for the rehabilitation of an existing dam. Haul distances between the borrow areas and dam site, the characteristics of the available materials (e.g. suitability for concrete or embankment construction, material quality, variability in the borrow area), and the scope of the completed investigation programme can all significantly affect the dam type and the final cost of a new dam or rehabilitated dam.

The scope of any borrow material investigation will vary with the dam type, the characteristics of the rehabilitation project and the stage of the investigation. In comparison to a concrete dam and concrete appurtenant structures, which require durable, fine and coarse, non-reactive concrete aggregates, an embankment dam requires a wide range of materials including earthfill (core and shoulder materials), rockfill, transition, filter and drainage materials. The Designer should therefore be looking for materials that:

- Have sufficient strength when placed in the dam.
- Do not deteriorate during placement, unless this is a desired characteristic that can be achieved with an appropriate level of quality assurance
- Do not have high rates of weathering where weathering could compromise their design performance or function.
- Do not have expansive properties (e.g. alkali-silica reactive properties in concrete aggregates).
- Do not have dispersive characteristics unsuitable for the cores of embankment dams.
- Have fines contents appropriate for their purpose (e.g. low permeability core, filter function, drainage function).
- Have good plasticity for use in the cores of embankment dams. Low plasticity materials can be used in dam cores but materials with good plasticity should be used if they are available.
- Lack plasticity and cannot hold an open crack for use as filter and drainage materials.

- Are not gap-graded. • Are not prone to segregation

A pre-feasibility investigation should include the completion of sufficient geological mapping to identify potential borrow material sources and enable the scoping of a later feasibility investigation. In comparison, a feasibility investigation for any dam project, including a dam rehabilitation project, should include sufficient work to:

- Identify preferred borrow areas.
- Prove that sufficient volumes of the material are available from the preferred borrow areas.
- Establish that the preferred materials are suitable for their intended design use.
- Ascertain what likely processing requirements and construction methods will be necessary during the construction of the dam or rehabilitation project.
- Select the appropriate dam type(s), or rehabilitation works, with respect to the foundation and available construction materials.
- Provide assurance that the materials will meet the design specification.

Material testing to characterise materials proposed for use within the dam and present within the foundation is required. Development of a material testing program will be site-specific and should consider the identified potential failure modes.

To satisfactorily address the above questions, a feasibility investigation normally includes:

Borrow area

- An exploration programme (test pits, shafts and/ or boreholes) to log the available borrow materials.
- Recover samples for laboratory testing
- Estimation of borrow area volumes.

A laboratory testing programme to establish the characteristics of the materials and the suitability of the materials for their intended use. Laboratory testing requirements will vary according to the dam type and borrow material, but would typically include:

Fine grained embankment materials

- Gradation
- Water content
- Atterberg limit
- Standard compaction and optimum moisture content
- Permeability
- Strength tests
- Dispersion tests

Filter and drainage materials

- PSD
- Permeability
- Soundness
- Durability
- Petrographic analysis

Riprap and rockfill materials

- PSD
- Gradation
- Petrographic analysis

Geotextiles

Where geosynthetic materials are incorporated into a design, product specifications should be obtained including:

- Shear strength

- Peel strength
- CBR burst strength
- Permeability
- Filtration compatibility
- Hydraulic transmissivity

Construction Trials

- Construction trials to demonstrate appropriate fill placement, conditioning and compaction methods, to determine the properties of the placed fill, and to confirm quality control methods.

Assessment of Investigation Results

- An assessment of the investigation results to confirm the suitability of the materials for dam construction, establish likely processing requirements and estimate the cost of the embankment or concrete placement.

7.5 Stability analyses

7.5.1 Static stability analyses

For embankment dams, the dam, foundation and abutments must be stable during construction and under all operating conditions, including full or partial drawdown. Recommended minimum factors of safety for static slope stability are provided in Table 6.3 of NZSOLD 2023 Guidelines. These are reproduced below:

Table 3 Recommended minimum factor of safety for slope stability – Static assessment

Loading condition	Slope	Minimum factor of safety[1, 2, 4]
End of construction before reservoir filling	Upstream and downstream	1.3
Long-term (steady state seepage, normal reservoir level)	Downstream	1.5
Full or partial rapid drawdown.	Upstream	1.2 or 1.3[3]

[1] The factor of safety is a representation of the factor required to reduce operational shear strength parameters, or increase the loading, in order to bring a potential sliding mass into a state of limit equilibrium, using generally accepted methods of analysis.

[2] Higher factors of safety may be necessary if there are high levels of uncertainty in the inputs to the stability analysis.

[3] Higher factors of safety may be required if drawdown occurs relatively frequently during normal operation.

[4] The above factors of safety are appropriate for the design of new dams on high strength foundations with low permeability zones constructed of soil which is not strain weakening, using reasonable conservative shear strengths and pore pressures developed from extensive geotechnical investigations of borrow areas, laboratory testing and analysis of the results. Fell et al (2005) provides guidance for adjusting the above minimum factors of safety for other conditions such as an existing dam, soil or weak rock foundation materials, strain weakening soils, and limited strength investigation and testing.

7.5.2 Dynamic stability analyses

Dynamic stability analyses should consider the earthquake loading performance criteria guidance as provided in Section 7.3 above.

The recommended minimum requirements for slope stability – seismic assessment adapted from (NZSOLD 2023) are shown in Table 4 below.

Table 4 Recommended minimum requirements for slope stability – Seismic assessment

Loading condition	Slope	Minimum factor of safety or acceptable deformation
OBE (consider embankment response)	Upstream and downstream	Minor deformations are acceptable provided that the dam remains functional and the resulting damage is easily repairable.

Loading condition	Slope	Minimum factor of safety or acceptable deformation
SEE (consider embankment response)	Upstream and downstream	Deformations are acceptable provided they do not lead to an uncontrolled release of the impounded contents.
Post earthquake	Upstream and downstream	1.2 to 1.3

NZSOLD 2023 Guidelines provide guidance on methodologies for assessment of embankment performance that Designers may find useful for earthfill embankment dams. These include:

- (Fell et all 2005)11
- (Swaisgood 2014)12*
- (Fong and Bennett 1995)13
- (Bray and Macedo 2019)14*, (Bray, Macedo and Travasarou 2018)15

Notes:

*Updated from (NZSOLD 2023) to reflect more recent revisions.

7.5.3 Defensive design details

In addition to meeting the recommended performance criteria, successful embankment dam design relies on the adoption of good defensive design details. Based on NZSOLD 2023 Guidelines these include:

- Providing ample freeboard and appropriate crest details.
- Using the best available materials in the more critical areas of the embankment.
- Providing well designed and constructed filter and transition zones to ensure compatibility between adjacent materials.
- Providing ample drainage zones for the interception and control of seepage flows.
- Providing good design details (e.g., flaring or widening the filter and transition zones) at all interfaces between the embankment and its foundation and at all interface between the embankment and concrete structures (e.g., spillway and diversion culverts).
- Providing adequate protection against erosion by wave action and runoff.

7.6 Specification of earthfill

Specification of earthfill for embankment dams will differ from the requirements of the ESLD.

The Designer is required to specify aspects of earthfill including:

➢ The source and Unified Soil Classification.

➢ Maximum size and particle size distribution.

- Typically, a maximum particle size of 75 mm or less. Larger cobbles will make compaction more difficult.
- Have sufficient fines content to give the required permeability.
- Be compatible with gradient requirements assumed during the design of adjacent filters and drainage zones.
- Be internally stable.

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[11] Fell et al (2005).Geotechnical Engineering of Dams. R Fell, P MacGregor, D Stapledon, G Bell, published by A.A. Balkema, ISBN 04-1536-440-x.

[12] Swaisgood, J, Behavior of embankment dams during earthquake. Published in Association of State Dam Safety Officials, “The Journey of Dam Safety (V12 n2, 2014)

[13] Fong, F & Bennett, W. (1995). Transverse Cracking in Embankment Dams due to Earthquakes. ASDSO Western Regional Conference.

[14] Bray, J.D., and Macedo, J. (2019) “Procedure for Estimating Shear-Induced Seismic Slope Displacement for Shallow Crustal Earthquakes,” J. of Geotechnical and Geoenvironmental Engineering, ASCE, V. 145(12), doi: 10.1061/(ASCE)GT.1943-5606.0002143.

[15] Bray, J.D., Macedo, J., and Travasarou, T. (2018) “Simplified Procedure for Estimating Seismic Slope Displacements for Subduction Zone Earthquakes,” J. of Geotechnical and Geoenvironmental Engineering, ASCE, V. 144(3): 04017124, DOI: 10.1061/(ASCE)GT.1943-5606.0001833.

- The Atterberg limits
- Density ratio and water content
    - Typical to specify a density ratio ≥98% of standard maximum dry density with water content between Optimum Water Content (OWC) and OWC +2%. The water content at which the maximum dry unit weight of soils occurs is called OWC and typically varies from 75-90% saturation.

7.7 Earthfill construction considerations

- Oversize materials
    - Remove prior to compaction.
- Segregation
    - Ensure that segregation of materials does not occur during placement and spreading. Rework placed material where segregation is observed.
- Surface preparation between layers
    - The surface of the previously compacted layer should be scarified prior to placing the next layer of fill to ensure good bond and to remove any cracks which may have formed at the surface between placing layers.
- Roller type
    - It is common for specification of a tamping foot ('sheep's foot') roller for earthfill. The Designer should consider the proposed embankment fill material and specify an appropriate roller type for the fill available.
- Fill adjacent to foundation.
    - Where earthfill is placed adjacent (within 0.6 m) of a dam foundation on rock, the earthfill should be comprised on finer more plastic soil available from within the borrow area and be compacted at a higher water content (e.g., OWC +2% or OWC +3%) with rubber tyred construction equipment or rollers. This is to facilitate squeezing the soil into irregularities in the foundation.
- Compaction of edges of fill
    - under normal operations the outer 1 m to 1.5 m (measured horizontally) of an earthfill embankment will not be adequately compacted by rollers. It is recommended to over-place fill and trim back to the design line following compaction.
- Compaction trials
    - Compaction trails prior to construction may be carried out to determine the number of passes required to achieve the target density for a particular roller, layer thickness and earthfill (Method Specification). Alternatively, a performance specification can be specified by the Designer setting out requirements for the density ratio and water content (refer Section 7.6) and confirmed during construction by Nuclear Densometer Testing (NDM) or other suitable testing method as determined by the Designer.
- Testing frequencies
    - Testing frequencies should be determined by the Designer based on the site-specific requirements. Minimum guidance provided in (Fell et al 2015)[16] is summarised below for Zone 1 (low permeability zone). This is also considered applicable for homogenous embankments. Testing frequencies for other embankment zones and filters should be defined by the Designer based on the criticality of the material property, variability of the material and volume of the material to be placed.

      For dams with small fill volumes, the testing frequency should be adjusted to achieve at least the minimum number of tests as per Note 2 below for PSD, Atterberg limits, permeability (in-situ), and dispersivity. Water content and density ratio should be measured each layer with a frequency of not less than one test per 100 m^2. The PNCC may opt to develop a database of materials testing results from particular material sources to reduce the overall testing requirements required for specific developments constructed from materials obtained from these sources. Project specific testing would still be required to demonstrate that the properties of the materials sourced are consistent with the database values. Any

[16] Fell et al (2005).Geotechnical Engineering of Dams. R Fell, P MacGregor, D Stapledon, G Bell, published by A.A. Balkema, ISBN 04-1536-440-x.

reduction in testing requirements would need to be considered on a case-by-case basis considering the structure to be constructed, material source and relevance of test results within the database.

Further relevant guidance on Earthworks for Dams can be found in

- NZS 4431: Engineered Fill, and
- NZGS Specification_0510 Earthworks (**NZGS Specification**)

Zone	Fill volume m^3	Particle size distribution (2, 3)	Atterberg limits (2, 3)	Permeability in situ (2, 3)	Dispersivity (2, 3)	Water content (4)	Density ratio (4)
Zone 1	< 100,000	500 m^3 to 2,000 m^3	4,000 m^3 to 10,000 m^3	5,000 m^3 to 20,000 m^3	4,000 m^3 to 10,000 m^3	Each layer, or 100 m^3 to 500 m^3	Each layer, or 100 m^3 to 500 m^3
	100,000 to 1,000,000	2000 m^3 to 5,000 m^3	4,000 m^3 to 10,000 m^3	10,000 m^3 to 40,000 m^3	4,000 m^3 to 10,000 m^3	Each layer, or 250 m^3 to 1000 m^3	Each layer, or 250 m^3 to 1000 m^3
	> 1,000,000	2000 m^3 to 5,000 m^3	4,000 m^3 to 20,000 m^3	40,000 m^3 to 100,000 m^3	4,000 m^3 to 20,000 m^3	Each layer, or 500 m^3 to 2,000 m^3	Each layer, or 500 m^3 to 2,000 m^3

Figure 2 Suggesting minimum required frequency of construction testing – Zone 1.

Notes:

[1] Lower volumes to apply to smaller volumes and more variable soils

[2] Zone 1; A minimum of 10 tests for each property for uniform soils, 20 to 50 tests for variable soils

[3] Not used.

[4] Whichever gives the greater number of tests.

7.8 Pipe details

Concrete collars such as those provided for in the ESLD for steep slopes (ref Plan no 4.2) are not considered suitable for use within dam embankments. Where possible, pipes through an erodible dam embankment or foundation should be avoided.

Where a pipe through a dam embankment or foundation is required, granular filters, compatible with the adjacent embankment zones should be used. Figure 3 provides a typical detail for provision of such a filter for a pipe penetration. How the specified compaction is achieved in materials present in the haunch zone of pipes should be provided for in the design.

Use of geotextiles as a filter should be avoided where possible and where used should consider accessibility should they become clogged and require maintenance / replacement.

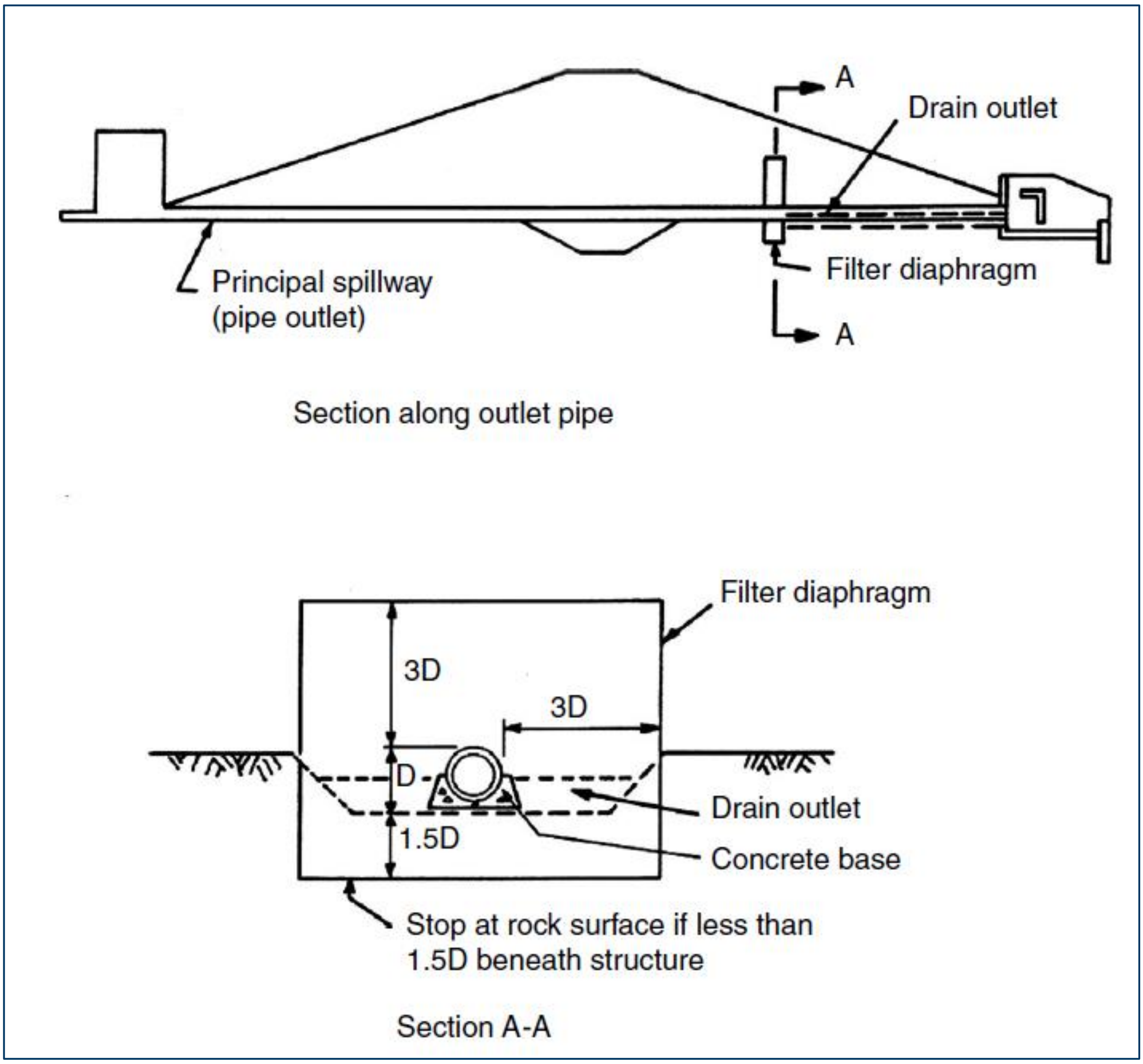

Figure 3 Filter diaphragm for seepage and piping control around outlet pipe[17]

7.9 Vegetation

Vegetation of dam embankment crests and slopes is recommended to be limited to short grass cover. This is to:

- Aid identification of seepage and slope instability to enable timely intervention.
- Limit the influence of vegetation roots on seepage path lengths.
- Limit the influence of vegetation instability on crest height/width.

Where vegetation other than grass is specified on the embankment crest and slopes, the Design should make an assessment of the influence that this may have on dam safety.

7.10 Freeboard

Provided dry freeboard (above the maximum flood water level) should be not less than 0.9 m. This should include consideration of long-term embankment settlement and provide camber as necessary to achieve a design dry freeboard over the design life of the dam. The freeboard for the embankment dams should be the largest of the following three freeboard requirements:

- Freeboard at Maximum Normal Reservoir Level - Wind set up and wave run up for the highest 10% of

[17] Geotechnical engineering of dams, 2nd edition, 2015 Fell, R; MacGregor, P: Bell, G; Foster, M

waves caused by a sustained wind speed, which is dependent on the fetch, with an AEP of greater than 1 in 100.

- Freeboard at Intermediate Flood Levels - Freeboard should be determined so that it has a remote probability of being exceeded by any combination of wind generated waves, wind set up and reservoir level occurring simultaneously.
- Freeboard at Maximum Reservoir Level during the Inflow Design Flood (IDF) - The greater of (a) 0.9 m or (b) the sum of the wind set up and wave run up for the highest 10% of waves caused by a sustained wind speed, which is dependent on the fetch, with an AEP of 1 in 10.

7.11 Spillways

Spillways should be provided at all facilities to manage flood flows and intake. These should be capable of passing the routed design flood without encroachment into the provided dry freeboard. The following should be taken into consideration for the design of the spillways:

- Spillway design should consider potential for blockage.
- Spillways should be ungated where possible to minimise operational and maintenance requirements.
- Erosion and scour protection of spillways will need to be designed on a case-by-case basis.
- Where possible, spillways should be located over rock abutments.

7.12 Concrete structures

The interfaces between embankment dams and concrete structures are potential sources of internal erosion. All concrete surfaces adjacent to embankment materials, particularly core materials, should be smooth and free of construction defects (e.g. horizontal offsets along construction joints). Where concrete structures (such as headwalls) are incorporated in the works, a slope should be provided on all concrete surfaces against which the embankment is to be compacted to facilitate compaction. Slope should be 8H:1V or flatter to encourage positive contact pressures along the interface.

7.13 Maintenance / access

To provide for maintenance access over the life of the facility, a crest width of not less than 4.0 m should be provided.

Where grassed embankments that require mowing are provided, slopes should typically be no greater than 1V:4H or as otherwise specified by PNCC.

Where embankment slopes >5 m vertical are required, berms at intermediary levels should be considered to provide maintenance access. Actual benching requirements should consider foreseen maintenance, access and PNCC requirements.

The Designer should consider all aspects of the facility and the respective maintenance requirements and provide for these within the Design.

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