PROFESSIONAL PRACTICE GUIDELINES

CIVIL AND TRANSPORTATION INFRASTRUCTURE

SEISMIC ASSESSMENT AND SEISMIC DESIGN OF DIKES IN BRITISH COLUMBIA

VERSION 1.0
PUBLISHED OCTOBER 7, 2021

ENGINEERS & GEOSCIENTISTS
BRITISH COLUMBIA

FUNDING PROVIDED BY:

Ministry of Forests, Lands, Natural Resource Operations and Rural Development (British Columbia)

Emergency Management BC (British Columbia)

SUPPORTED BY:

Fraser Basin Council

FIRST PUBLISHED: VERSION 1.0, OCTOBER 7, 2021

PREFACE

These *Professional Practice Guidelines – Seismic Assessment and Seismic Design of Dikes in British Columbia* were developed by Engineers and Geoscientists British Columbia to guide professional practice related to seismic assessment and seismic design of Dikes in British Columbia (BC).

In 2014, the Ministry of Forests, Lands, Natural Resource Operations and Rural Development (MFLNRORD) published the *Seismic Design Guidelines for Dikes, 2nd Edition* (referred to in this document as the "Ministry Guidelines"), which outline the technical requirements related to seismic assessment and seismic design of Dikes under the *Dike Maintenance Act*. However, since then, the Ministry has identified areas for improvement in how Engineering Professionals are applying the Ministry Guidelines to this work, and requested that Engineers and Geoscientists BC develop practice guidelines to assist.

These guidelines were first published in 2021 to supplement the Ministry Guidelines and outline the professional practice considerations that must be undertaken when Engineering Professionals perform this work. The MFLNRORD provided funding as well as input throughout the development of these guidelines, which provide an overview of the roles and responsibilities of the various parties involved in seismic assessment and seismic design of Dikes in BC. In particular, the concept of the Coordinating Engineering Professional is introduced to facilitate coordination between the various disciplines.

The section on professional practice provides background information on the Ministry Guidelines; discusses developments in this area of practice since the Ministry Guidelines were published in 2014; and presents considerations for professionals when implementing the Ministry Guidelines. A list of the required input data for seismic Dike projects is included, along with a discussion on climate change and future considerations. An outline of both the performance-based design approach and the probabilistic-based design approach follows, and includes discussion of the process for applying each approach. Finally, appropriate documentation of decision making throughout the assessment and design is discussed, and an outline of reporting requirements is provided.

These guidelines describe expectations and obligations of professional practice in relation to seismic assessment and seismic design of Dikes in BC to be followed at the time they were prepared. However, this is a living document that is to be revised and updated as required in the future, to reflect the developing state of practice.

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ABBREVIATIONS

ABBREVIATION	TERM
AEP	annual exceedance probability
BC	British Columbia
iBPT	instrumented Becker penetration test
km	kilometre(s)
m	metre(s)
FS	factor of safety
MFLNRORD	Ministry of Forests, Lands, Natural Resource Operations and Rural Development
MICP	microbially induced calcite precipitation
NBC	*National Building Code of Canada*
ReMi	Refraction microtremor
SCPT	seismic cone penetration test
SPT	standard penetration test
UHS	uniform hazard spectrum
USACE	United States Army Corps of Engineers

DEFINED TERMS

The following definitions are specific to these guidelines. These words and terms are capitalized throughout the document.

TERM	DEFINITION
Act	*Professional Governance Act* [SBC 2018], Chapter 47.
Bylaws	The Bylaws of Engineers and Geoscientists BC made under the *Act*.
Coordinating Engineering Professional	The Engineering Professional undertaking multi-discipline coordination of all design and field reviews for a project that includes seismic assessment and seismic design of Dikes.
Design Team	The Professionals of Record representing the various applicable disciplines on a Dike assessment and Dike design project.
Dike	Defined in the *Dike Maintenance Act* as: "an embankment, wall, fill, piling, pump, gate, floodbox, pipe, sluice, culvert, canal, ditch, drain, or any other thing that is constructed, assembled, or installed to prevent the flooding of land." In some cases, Dikes are located near or along riverbanks, lakes, or coastal waters; in other cases, they are set back some distance from the source of potential flooding. Dikes are designed and constructed to meet engineering standards, taking into account the design flood level.
Dike Reach	Dike systems are often divided into reaches that may be a few hundred metres to a few kilometres in length. A Dike Reach (Zimmaro et al. 2017) is defined herein as a continuous length of Dike of similar distribution of geotechnical materials, hydrological demand, consequences of failure, and potentially other parameters relevant to a flood hazard assessment.
Dike Segment	A short segment within a Dike Reach for which the soil properties and seismic vulnerability can be considered uniform.
Dike System	A structure providing flood protection for a specific region, which often consists of many kilometres of contiguous Dike and appurtenance structures or a series of Dikes.
Document(s)	Includes any physical or electronic record, including but not limited to a report, certificate, memo, specification, drawing, map, or plan, that conveys a design, direction, estimate, calculation, opinion, interpretation, observation, model, or simulation that relates to engineering or geoscience.
Engineering/Geoscience Professional(s)	Professional engineers, professional geoscientists, professional licensees engineering, professional licensees geoscience, and any other individuals registered or licensed by Engineers and Geoscientists BC as a "professional registrant" as defined in Part 1 of the Bylaws.
Engineers and Geoscientists BC	The Association of Professional Engineers and Geoscientists of the Province of British Columbia, also operating as Engineers and Geoscientists BC.

TERM	DEFINITION
High Consequence Dike	A flood protection Dike where the economic and/or life safety consequences of failure during a major flood are very high. High Consequence Dikes typically protect urban or urbanizing areas, and failure could result in large economic losses and/or significant loss of life. Dike consequence categories are determined by the Province of British Columbia and are subject to change at the discretion of the Ministry of Forests, Lands, Natural Resource Operations and Rural Development. A list of consequence categories is available on the Province's website for Dike Management, under the heading "Dike Consequence Classification."
Inspector(s)	Public officials, including the Inspector of Dikes and any acting, deputy, or assistant Inspector of Dikes, who have general supervision of Dikes and oversee the operation of diking authorities relative to the construction and maintenance of Dikes, as per the *Dike Maintenance Act*.
Liquefaction	A phenomenon whereby a saturated soil loses a significant portion of strength and stiffness in response to a sudden change in stress and/or pore pressure condition that causes the soil to behave like a viscous fluid.
Liquefaction Potential	The resistance of a deposit to liquefaction as a result of a sudden change in stress level and/or pore pressure condition due to cyclic loading.
Liquefaction Susceptibility	The ability of the soil deposit to liquefy, which depends on the soil type. For example, a dry or unsaturated granular deposit does not have the ability to liquefy due to the absence of saturated conditions. Cohesive deposits are also not susceptible due to the particle structure of the deposits and the interstitial forces that hold the clay molecules together (cohesion).
Ministry Guidelines	*Seismic Design Guidelines for Dikes, 2nd Edition* (MFLNRORD 2014). The Ministry Guidelines provide technical requirements related to seismic assessment and seismic design of Dikes under the *Dike Maintenance Act*.
Moment Magnitude	A measure of the amount of energy released during an earthquake, which is not dependent on ground shaking levels or level of damage (Wood and Neumann 1931), but reflects factors that are characteristic to the rupture of the fault that produces the earthquake.
Professional Letter of Commitment	A letter outlining the commitment for Engineering Professionals related to the design and/or field review of Dike works subject to approval under the *Dike Maintenance Act*.
Professional of Record	The Engineering Professional who is professionally responsible for professional work, professional activities, or Documents related to the engineering practice.
Registrant	Means the same as defined in Schedule 1, section 5 of the *Professional Governance Act*.
Seismic Dike Report	Report written by the Professional(s) of Record on the Design Team to outline the results of the seismic Dike assessment or seismic Dike design work that was completed. This can be a stand-alone document or part of a larger document.

VERSION HISTORY

VERSION NUMBER	PUBLISHED DATE	DESCRIPTION OF CHANGES
1.0	October 7, 2021	Initial version.

1.0 INTRODUCTION

Engineers and Geoscientists British Columbia is the regulatory and licensing body for the engineering and geoscience professions in British Columbia (BC). To protect the public, Engineers and Geoscientists BC establishes, monitors, and enforces standards for the qualifications and practice of its Registrants.

Engineers and Geoscientists BC provides various practice resources to its Registrants to assist them in meeting their professional and ethical obligations under the *Professional Governance Act* (the *Act*) and Engineers and Geoscientists BC Bylaws (Bylaws). Those practice resources include professional practice guidelines, which are produced under the authority of Section 7.3.1 of the Bylaws and are aligned with Principle 4 of the Code of Ethics.

Each professional practice guideline establishes expectations and obligations of professional practice that all Engineering Professionals are expected to have regard for in relation to specific professional activities. Engineers and Geoscientists BC publishes professional practice guidelines on specific professional activities where additional guidance is deemed necessary. Professional practice guidelines are written by subject matter experts and reviewed by stakeholders before publication.

These *Professional Practice Guidelines – Seismic Assessment and Seismic Design of Dikes in British Columbia* provide guidance on professional practice for Engineering Professionals who carry out seismic assessment or seismic design of Dikes in BC and are following the *Seismic Design Guidelines for Dikes, 2nd Edition*, published by the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (BC MFLNRORD 2014). (In these guidelines, the *Seismic Design Guidelines for Dikes, 2nd Edition* are referred to as simply the "Ministry Guidelines.")

The Ministry Guidelines provide technical requirements related to seismic assessment and seismic design of Dikes under the *Dike Maintenance Act*. These guidelines are intended to be a supplement to the Ministry Guidelines, and help clarify how Engineering Professionals can meet the intent of the Ministry Guidelines while fulfilling their professional practice obligations.

1.1 PURPOSE OF THESE GUIDELINES

This document provides guidance on professional practice to Engineering Professionals who perform seismic assessment and seismic design of Dikes in BC under the *Dike Maintenance Act*, which therefore requires adherence to the Ministry Guidelines. This document also provides assistance to others involved in designing and planning flood protection systems. The purpose of these guidelines is to provide a common approach for carrying out a range of professional activities related to this work, while meeting the intent of the Ministry Guidelines.

Following are the specific objectives of these guidelines:

1. Describe expectations and obligations of professional practice that Engineering Professionals are expected to have regard for in relation to the specific professional activity outlined in these guidelines by:
   - specifying tasks and/or services that Engineering Professionals should complete;
   - referring to professional obligations under the *Act*, the Bylaws, and other regulations/legislation, including the primary obligation to protect the safety, health, and welfare of the public and the environment; and

   - describing the established norms of practice in this area.
2. Describe the roles and responsibilities of the various participants/stakeholders involved in these professional activities. The document should assist in delineating the roles and responsibilities of the various participants/stakeholders, which may include the Professional of Record, owner, Coordinating Engineering Professional, and Inspector.
3. Define the skill sets that are consistent with the training and experience required to carry out these professional activities.
4. Provide guidance on the use of assurance documents, so the appropriate considerations have been addressed (both regulatory and technical) for the specific professional activities that were carried out.
5. Provide guidance on how to meet the quality management requirements under the *Act* and the Bylaws when carrying out the professional activities identified in these professional practice guidelines.

1.2 ROLE OF ENGINEERS AND GEOSCIENTISTS BC

These guidelines form part of Engineers and Geoscientists BC's ongoing commitment to maintaining the quality of professional services that Engineering Professionals provide to their clients and the public.

Engineers and Geoscientists BC has the statutory duty to serve and protect the public interest as it relates to the practice of professional engineering and professional geoscience, including regulating the conduct of Engineering Professionals and Geoscience Professionals. Engineers and Geoscientists BC is responsible for establishing, monitoring, and enforcing the standards of practice, conduct, and competence for Engineering Professionals. One way that Engineers and Geoscientists BC exercises these responsibilities is by publishing and enforcing the use of professional practice guidelines, as per Section 7.3.1 of the Bylaws.

Guidelines are meant to assist Engineering Professionals in meeting their professional obligations. As such, Engineering Professionals are required to be knowledgeable of, competent in, and meet the intent of professional practice guidelines that are relevant to their area of practice.

The writing, review, and publishing process for professional practice guidelines at Engineers and Geoscientists BC is comprehensive. These guidelines were prepared by subject matter experts and reviewed at various stages by a formal review group, and the final draft underwent a thorough consultation process with various advisory groups and divisions of Engineers and Geoscientists BC. These guidelines were then approved by Council and, prior to publication, underwent final editorial and legal reviews.

Engineers and Geoscientists BC supports the principle that appropriate financial, professional, and technical resources should be provided (i.e., by the client and/or the employer) to support Engineering Professionals who are responsible for carrying out professional activities, so they can comply with the professional practice expectations and obligations provided in these guidelines.

These guidelines may be used to assist in the level of service and terms of reference of an agreement between an Engineering Professional and a client.

1.3 INTRODUCTION OF TERMS

For the purposes of these guidelines, the Professional of Record is the Engineering Professional who is professionally responsible for professional work, professional activities, or Documents related to the engineering practice.

The term Design Team is used to refer to the Professionals of Record representing the various applicable disciplines on a Dike assessment and Dike design project. The makeup of the Design Team will depend on the specific requirements of the project.

The term Coordinating Engineering Professional refers to the Engineering Professional who takes on the role of providing coordination between the various disciplines on a project involving the seismic assessment and seismic design of Dikes.

See the Defined Terms section at the front of the document for a full list of definitions specific to these guidelines.

1.4 SCOPE AND APPLICABILITY OF THESE GUIDELINES

These guidelines provide guidance on professional practice for Engineering Professionals who carry out seismic assessment and seismic design of Dikes in BC in accordance with the *Dike Maintenance Act*, and also provide guidance to others involved in overall flood protection management.

For minor repairs and routine maintenance of Dikes, seismic work is not generally required; however whether and/or how the Ministry Guidelines and these guidelines apply to a particular Dike project should be discussed with the Inspector prior to undertaking any work.

It is recognized that not all Dikes in BC deemed vulnerable to seismic impacts fall under the *Dike Maintenance Act*, such as Dikes on federal land; however, even in the absence of other legislation or guidance, Engineering Professionals should consider the guidance in these guidelines, and the local authority may still require that the guidance on professional practice presented in these guidelines be followed.

These guidelines are not intended to provide technical or systematic instructions for how to carry out seismic assessment and seismic design of Dikes; rather, these guidelines outline considerations to be aware of when carrying out these activities. Engineering Professionals must exercise professional judgment when providing professional services; as such, application of these guidelines will vary depending on the circumstances.

An Engineering Professional's decision not to follow one or more aspects of these guidelines does not necessarily represent a failure to meet professional obligations. For information on how to appropriately depart from the practice guidance within these guidelines, refer to the *Quality Management Guides – Guide to the Standard for the Use of Professional Practice Guidelines* (Engineers and Geoscientists BC 2021a), Section 3.4.2.

It should be noted that just because an Engineering Professional follows these practice guidelines, approval of an application under the *Dike Maintenance Act* is not guaranteed.

1.5 ACKNOWLEDGEMENTS

This document was reviewed by a group of technical experts, as well as by various advisory groups and divisions of Engineers and Geoscientists BC. Authorship and review of these guidelines does not necessarily indicate the individuals and/or their employers endorse everything in these guidelines.

Engineers and Geoscientists BC thanks the authors and reviewers for their time and effort in sharing their knowledge and experience

Engineers and Geoscientists BC would also like to thank the Fraser Basin Council for their input and support, and the Ministry of Forests, Lands, Natural Resource Operations, and Rural Development for their input. We gratefully acknowledge the financial support of the Province of British Columbia through the Ministry of Forests, Lands, Natural Resource Operations and Rural Development and Emergency Management BC.

See Appendix A: Authors and Reviewers for a list of contributors.

2.0 ROLES AND RESPONSIBILITIES

2.1 REGULATORY CONTEXT

The principal legislation in British Columbia (BC) pertinent to the operation and maintenance of flood protection works is the *Dike Maintenance Act*. The *Dike Maintenance Act* establishes the authority of public officials known as Inspectors, specifically the Inspector of Dikes and any acting, deputy, or assistant Inspector of Dikes.

These Inspectors have general oversight and authority over all Dikes under the *Dike Maintenance Act*, and over the operation of all diking authorities relative to the construction and maintenance of these Dikes.

Furthermore, applications involving the seismic design and seismic assessment of Dikes are reviewed and must be accepted by an Inspector as part of the *Dike Maintenance Act* approval process. Construction cannot proceed without approval under the *Dike Maintenance Act*.

See Section 2.3.4 Inspector for more information on the role of Inspectors.

2.2 COMMON FORMS OF PROJECT ORGANIZATION

Project organization and the makeup of the Design Team for seismic assessment and seismic design of Dikes will vary according to the needs of the project and the parties involved. Typical projects have a Design Team comprising Engineering Professionals in the geotechnical engineering, coastal engineering, seismic engineering, hydrotechnical engineering, and civil engineering disciplines; however, this does not preclude other disciplines and expertise from being involved, including Geoscience Professionals or others.

It is recommended that a Coordinating Engineering Professional be engaged for any multi-disciplinary project, in order to adequately coordinate between disciplines (see Section 2.3.3 Coordinating Engineering Professional). Coordination includes confirming that the various professionals are using the same design parameters and assumptions; the appropriate disciplines are communicating with each other; and any projects with utilities or other structures within, or in proximity to, the Dike are given appropriate oversight (see Section 3.4.3 Utilities and Other Structures).

Project types can generally be split into two categories:

- an existing Dike; or
- a new Dike.

In both instances, seismic work is generally a component of a scope of work on a Dike, except possibly for minor repairs and routine maintenance, as discussed in Section 1.4 Scope and Applicability of These Guidelines.

Both project types can be split into the following stages, and any given project may include some or all of these stages:

- High-level feasibility study
- Preliminary design
- Detailed design
- Construction or implementation

Regardless of the type or stage of a project, these guidelines provide context for how to apply the Ministry Guidelines.

When a *Dike Maintenance Act* approval is required, applications to the Inspector must be accompanied by a Professional Letter of Commitment. High-level feasibility and planning studies may not require *Dike Maintenance Act* approval.

Many projects have multiple disciplines involved in the application process. In these cases, each Engineering Professional taking responsibility for a specific discipline on a project is considered a Professional of Record for that discipline (see Section 2.3.2 Professional of Record). All of the Professionals of Record combined are referred to as the Design Team.

Each Professional of Record must sign and seal a Professional Letter of Commitment for their discipline to confirm that they will:

- undertake design and field review within their area of expertise;
- obtain approval prior to modifying a project already approved; and
- provide documentation as required by the Inspector, including appropriately authenticated (sealed with signature and date) completion reports and drawings for the area of work prepared by them or by someone under their direct supervision.

When each Professional of Record authenticates the Professional Letter of Commitment, they are confirming that seismic considerations are included within their scope of work on the project, as appropriate.

The role of the Coordinating Engineering Professional is to confirm that all Professional Letters of Commitment are submitted, and if there is a change of professional during a project, that a new Professional Letter of Commitment from the incoming Professional of Record is submitted in support of the *Dike Maintenance Act* approval application.

2.2.1 COMMUNICATION AND COORDINATION

Communication between all disciplines on the Design Team is essential for the successful completion of a seismic assessment and seismic design of a Dike. The various Professionals of Record must communicate and coordinate with each other appropriately, as well as with other technical specialists, to ensure both project needs and appropriate professional practice requirements are being met. The role of the Coordinating Engineering Professional is key to confirming effective and efficient communication and coordination is taking place on a project.

As discussed in Section 3.0 Guidelines for Professional Practice, a two-tiered approach for seismic design of Dikes in BC is introduced in these guidelines and should be used to meet the intent of the Ministry Guidelines:

- Tier 1 is a performance-based design approach, as outlined in Section 3.6 Performance-Based Design; and
- Tier 2 is a probabilistic-based design approach, as outlined in Section 3.7 Probabilistic-Based Design.

Tier 1 must be undertaken and approval received from the Inspector before moving to Tier 2, as outlined in Section 3.1.2 Design Approach Summary. The makeup of the Design Team may change throughout this process, as the expertise required for a probabilistic-based design is specialized. Communication with the Inspector regarding the design approach and subsequent approvals is key to ensuring a project continues to move ahead in a timely manner.

2.3 RESPONSIBILITIES

The following is a description of the typical responsibilities of various project participants in the seismic assessment and seismic design of a Dike.

2.3.1 OWNER

The owner of a Dike is often a “diking authority,” which is defined under the *Dike Maintenance Act* as:

> “(a) the commissioners of a district to which Part 2 of the *Drainage, Ditch and Dike Act* applies,
>
> (b) a person owning or controlling a dike other than a private dike,
>
> (b.1) if the final agreement of a treaty first nation so provides, the treaty first nation in relation to dikes on its treaty lands,

(c) a public authority designated by the minister as having any responsibility for maintenance of a dike other than a private dike, or

(d) a regional district, a municipality or an improvement district"

Per the Memorandum of Understanding (MOU) between the Province of BC and the City of Vancouver, the City of Vancouver is considered the owner of any Dikes built within the City's boundaries, as defined under the Vancouver Charter. This MOU also addresses the roles of the Province and the City beyond Dike ownership.

Regardless of who owns a Dike, the owner's responsibilities outlined in this section remain the same.

Before undertaking a seismic assessment or seismic design of a Dike, the owner should be knowledgeable about and gather the following information:

- Inspector requirements, as well as any processes or procedures within the area of jurisdiction.
- The legal description of the property on which the Dike is located or proposed to be located.
- A survey of the alignment or proposed alignment of the Dike.
- Foundation soil characteristics.
- For work on an existing Dike
  - material types and degree of compaction of the Dike;
  - methods used to construct the Dike;
  - alterations that may have been undertaken on the Dike; and
  - changes that may have happened over time, including scouring, vegetation, animal burrows, and adjacent land use changes, and how they may impact reliability and performance.
- Information regarding accessibility and any restrictions to accessibility at the Dike location.
- Information on water levels adjacent to the Dike.

As indicated in Section 2.2 Common Forms of Project Organization, the seismic aspect of Dike works is typically one aspect of the overall project scope, although it could also be a stand-alone scope of work. Either way, the owner should enter into professional services agreements with the appropriate Professionals of Record, as required, to complete the scope of the entire project, prior to undertaking work on the project. The owner may rely on the Coordinating Engineering Professional to confirm the appropriate disciplines required for the project. If work proceeds to a probabilistic-based approach, as per Section 3.7 Probabilistic-Based Design, the owner should exercise additional caution when selecting design professionals, since this approach requires special expertise. (See Section 5.0 Professional Registration & Education, Training, and Experience for information related to who is appropriately qualified to undertake this work.)

The owner may consider basing the professional services agreement on a proven standard agreement such as the Master Municipal Construction Documents Client-Consultant Agreement (MMCDA 2021), or the Canadian Construction Documents Committee document CDC 31 – 2020 Service Contract Between Owner and Consultant (CCDC 2020). It would be prudent for the owner to confirm that the Professionals of Record for the project are aware of and will meet the intent of the Ministry Guidelines and the *Dike Maintenance Act* in their professional work.

The professional services agreement should:

- confirm the scope of services to the extent known at the time of agreement, including all commitments required under the Ministry Guidelines, the *Dike Maintenance Act*, and the Professional Letter of Commitment;
- establish a budget estimate, either for hourly services, lump sum, or otherwise (recognizing that modifications to scope will typically impact the budget); and

- confirm the budget reflects the need for an independent review, as outlined in Section 4.1.8 Documented Independent Review of High-Risk Professional Activities or Work (see also Section 3.1.2 Design Approach Summary).

After receiving the Seismic Dike Report outlining the results of the work from the Design Team, the owner should:

- review the Seismic Dike Report and understand the limitations and qualifications that apply;
- discuss the Seismic Dike Report with the Design Team and seek clarification, if desired; and
- discuss the findings of the Seismic Dike Report with the Inspector for acceptance prior to proceeding to the detailed design phase.

If the owner is applying for *Dike Maintenance Act* approval, the owner should submit the Seismic Dike Report as part of the application. If the Design Team is submitting the application for *Dike Maintenance Act* approval on behalf of the owner, the owner may consider reviewing the Seismic Dike Report with the Inspector prior to the Design Team moving forward with the application.

If the Design Team has been retained by a developer, prior to submitting the Seismic Dike Report for *Dike Maintenance Act* approval, the developer should obtain approval from the appropriate diking authority.

2.3.2 PROFESSIONAL OF RECORD

Professionals of Record in the context of these guidelines are Engineering Professionals who take overall responsibility for the seismic assessment and seismic design of a Dike within their respective disciplines. By signing the Professional Letter of Commitment, each Professional of Record confirms that they are taking into consideration the seismic aspects of the work associated with the Dike project and committing to undertake field reviews related to that work, as appropriate. Professionals of Record are responsible for writing a Seismic Dike Report outlining the results of the seismic Dike assessment or seismic Dike design work that was completed.

For Dikes that are not subject to *Dike Maintenance Act* approval, each Professional of Record should consider the professional practice considerations outlined in these guidelines. Refer to Section 1.4 Scope and Applicability of These Guidelines for more information.

A Professional of Record should refer to expectations and obligations outlined in Section 3.0 Guidelines for Professional Practice when undertaking seismic assessment and seismic design of a Dike. Each Professional of Record on a project must ensure that the requirement for independent review, as outlined in Section 4.1.8 Documented Independent Review of High-Risk Activities or Work, has been completed before their work is submitted to those who will be relying on it.

2.3.3 COORDINATING ENGINEERING PROFESSIONAL

The Coordinating Engineering Professional is one of the Engineering Professionals working on a seismic Dike project who agrees to coordinate the various disciplines on the project. The decision about which Engineering Professional should take on this role is generally determined through discussion and agreement amongst the Design Team.

To enable the Professionals of Record to perform their duties properly, the Coordinating Engineering Professional should:

- confirm that the appropriate disciplines requiring Professionals of Record are included on the Design Team;
- if the scope of the project changes at any time, and additional disciplines are required, obtain new Professionals of Record to fill those gaps;
- coordinate the communication between disciplines to ensure the same design parameters and assumptions are being used by all Design Team participants;
- facilitate communication between Design Team participants;

- provide oversight and facilitate coordination in relation to any utilities or other structures within or in proximity to the Dike;
- coordinate the writing of a Seismic Dike Report;
- if a project is being submitted for *Dike Maintenance Act* approval, confirm that each Professional of Record has signed the Professional Letter of Commitment for their discipline; and
- if there is a change of Professional of Record, coordinate the submission of a new Professional Letter of Commitment from the new Professional of Record.

2.3.4 INSPECTOR

The Inspector, under the powers conferred by the *Dike Maintenance Act*, is responsible for establishing provincial standards for the design, construction, operation, and maintenance of Dikes through the provincial Dike safety program. The Dike safety program is delivered through the Inspector in each region. Provincial responsibilities include:

- approving all works in and about Dikes;
- monitoring and auditing the owner's Dike management program;
- issuing orders to protect public safety (where necessary); and
- regulating diking authorities.

Section 2(4) of the *Dike Maintenance Act* requires that works occurring in and about flood protection Dikes are subject to written approval by the Inspector. This includes:

- anything that may lower or decrease the size and/or integrity of the cross-section of a Dike;
- installations of flood boxes, culverts, pipes, or any structure through a Dike;
- construction of works over or on a Dike right of way;
- alterations to the foreshore or stream channel adjacent to a Dike; and
- construction of a new Dike.

This list is not exhaustive, and the Inspector may include other works in and about flood protection. The *Dike Maintenance Act* empowers the Inspector to make orders under the *Dike Maintenance Act*, and take measures in the interests of public safety if there is failure to comply with regulations.

In relation to these practice guidelines, the Inspector receives the Seismic Dike Report as part of the *Dike Maintenance Act* application, and determines if the report is accepted. It should be noted that acceptance of the Seismic Dike Report is only one part of the application and does not guarantee approval of the application as a whole.

3.0 GUIDELINES FOR PROFESSIONAL PRACTICE

3.1 OVERVIEW

This section sets out the professional responsibilities of Engineering Professionals who undertake seismic assessment and seismic design of Dikes in British Columbia (BC).

Certain Dike construction activities could be considered nominal, such as minor repairs and routine maintenance, and could be exempt from the requirements of the Ministry Guidelines. However, any exemption is subject to Inspector approval; therefore, possible exemptions should be discussed with the Inspector prior to undertaking the work.

It is also recognized that not all Dikes in BC that are deemed vulnerable to seismic impacts fall under the *Dike Maintenance Act*, such as Dikes on federal land; however, in the absence of other legislation or guidance, Engineering Professionals should consider the guidance in these guidelines, and the local authority may still require that the guidance on professional practice presented in these guidelines be followed.

The intent of this section is not to provide detailed technical procedures for conducting the various components of seismic assessment and seismic design of Dikes, but to outline considerations for the technical work. It is up to each Engineering Professional to be proficient in any technical work they undertake, including keeping informed of advances in their area of practice.

See Section 1.4 Scope and Applicability of These Guidelines for more information.

3.1.1 DIFFERENCE BETWEEN SEISMIC ASSESSMENT AND SEISMIC DESIGN

Note that starting in Section 3.2 Overview of Seismic Design Guidelines for Dikes, the term "seismic design" will be used to refer collectively to both "seismic assessment" and "seismic design," to avoid repetition and improve readability.

A brief explanation of the differences between seismic assessment and seismic design of Dikes follows:

- **Seismic assessment**:
  - An assessment is usually carried out to evaluate the expected performance of an existing Dike in its current conditions under seismic and hydraulic loads.
  - The potential behaviour of an existing Dike is determined by the geometry, material types, and degree of compaction of the Dike as it was originally constructed, along with any alterations that were made to the Dike since construction (including the effects of deterioration over time).
  - In an assessment, the performance expectations in the Ministry Guidelines may not be met, so upgrades or improvements could be required.
  - Understanding of the expected mode of failure and physical consequences of failure are important considerations for an assessment.
  - An assessment requires the characterization of material properties and the expected seismic behaviour of an existing Dike.

- **Seismic design**:
  - A design uses a set of engineering analyses for the construction of a new Dike or for modifying or adding components to an existing Dike to achieve a given level of performance.
  - Unlike during an assessment, a designer can, within reason, modify the behaviour of a Dike during design with the intent to meet provisions in the Ministry Guidelines and confirm that the performance objectives of a Dike will be achieved across all expected levels of loading.
  - In contrast to an assessment, design procedures for new Dikes, or alterations of an existing Dike, aim to deliver Dikes that can be expected to meet or exceed the performance expectations outlined in the Ministry Guidelines.

In both assessments and design, Engineering Professionals should not assume that any Dike works that predate current design standards will perform adequately, or that the codes in place during the original construction were complied with or interpreted as intended, as historically, many Dikes in BC were constructed without any engineering design input.

3.1.2 DESIGN APPROACH SUMMARY

These guidelines aim to provide a common approach for carrying out a range of professional activities related to seismic assessment and seismic design of Dikes, while meeting the intent of the Ministry Guidelines, as outlined in Section 1.1 Purpose of These Guidelines.

Accordingly, a two-tiered approach should be used for seismic assessment and seismic design of Dikes in BC.

- **Tier 1: Performance-based approach**
  - See Section 3.6 Performance-Based Design.
  - If a thorough performance-based analysis shows that the performance-based criteria in the Ministry Guidelines cannot practicably be met, and after discussing the results with the owner and obtaining approval from the Inspector, then the Engineering Professionals may proceed to Tier 2.
- **Tier 2: Probabilistic-based approach**
  - See Section 3.7 Probabilistic-Based Design.
  - Engineering practice has evolved over the years, and evaluating the flood hazard of a Dike using a probabilistic-based framework is a newer approach to seismic assessment and seismic design.

Note that both the performance-based and probabilistic-based analyses outlined in these guidelines require that documented independent reviews be undertaken, and that these independent reviews be Type 2 independent reviews. This means that individuals undertaking these types of independent reviews cannot be employed in the same firm as the Engineering Professional undertaking the work (see Section 4.1.8 Documented Independent Review of High-Risk Professional Activities or Work).

The requirement for independent review is in addition to the regular documented checking process required of all engineering activities (see Section 4.1.5 Documented Checks of Engineering and Geoscience Work).

3.1.3 CONSIDERATION OF UNCERTAINTY AND ASSOCIATED RISK

Engineering Professionals have a professional responsibility to uphold the principles outlined in the Engineers and Geoscientists BC Code of Ethics, including protection of public safety and the environment. As such, Engineering Professionals must use a documented approach to identify, assess, and mitigate risks that may impact public safety or the environment when providing professional services.

In relation to seismic assessment and seismic design of Dikes, Engineering Professionals should consider risks that arise from project uncertainty. This includes, but is not limited, to sources of uncertainty, such as:

- input data;
- analysis methods; and

- prediction of future conditions including those from climate change, channel changes, and land use changes.

Additionally, Engineering Professionals should consider potential impacts to:

- society, such as impacts to public safety, the environment, social and cultural valued assets, infrastructure, and the economy; and
- clients, such as project costs, schedule, and quality.

See Section 3.5 Climate Change and Future Considerations for further discussion on this issue in relation to seismic assessment and seismic design of Dikes.

3.2 OVERVIEW OF SEISMIC DESIGN GUIDELINES FOR DIKES

This section provides an overview of the Ministry Guidelines, which were released in 2014; developments since 2014 that impact seismic design of Dikes; and considerations for the implementation of the Ministry Guidelines that have been established through discussions and workshops with practitioners and municipalities. Guidance is also provided on supplementary practice requirements for the designs to be consistent with the new developments.

Note that starting in this section, the term "seismic design" will be used to refer collectively to both "seismic assessment" and "seismic design," to avoid repetition and improve readability. See Section 3.1.1 Difference Between Seismic Assessment and Seismic Design for more information.

3.2.1 OVERVIEW OF THE MINISTRY GUIDELINES

The first edition of the *Seismic Design Guidelines for Dikes* was issued by the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (MFLNRORD) in 2011. Based on feedback received from practitioners and owners, and following an external peer review, the MFLNRORD issued the second edition of the document in 2014, referred to in these guidelines as the Ministry Guidelines (BC MFLNRORD 2014).

In the Ministry Guidelines, the MFLNRORD adopted the performance-based design framework for seismic design of Dikes. The intent was to specify measurable or predictable performance indicators, such as Dike crest displacements under different levels of ground shaking, to achieve a satisfactory design of the Dike for flood protection during and following an earthquake.

The Ministry Guidelines provide Dike design and remediation guidance on specific aspects of this work, including:

- seismic ground motions to be considered for the analysis and design of Dikes, along with corresponding performance expectations established in terms of Dike crest displacements;
- suitable geotechnical investigation methods, to characterize and obtain engineering properties of the site soils for input into the seismic analyses;
- commonly used methods for seismic analyses considered appropriate for Dikes;
- seismic rehabilitation and strengthening measures;
- threshold seismic events that should trigger a post-event evaluation of the integrity of the Dike System; and
- post-earthquake temporary emergency repair and permanent remediation measures.

When the Ministry Guidelines were developed in 2014, a province-wide consequence classification system for the flood protection Dikes did not exist. As a result, and in the interim, the MFLNRORD focused its attention primarily on High Consequence Dikes, which were qualitatively classified as:

> "flood protection Dikes where the economic and/or life safety consequences of failure during a major flood are very high. These Dikes typically protect urban or urbanizing areas, and failure could result in large economic losses and/or significant loss of life. The majority of the Dikes reconstructed under the 1968 to 1994 Fraser River Flood Control Program would be considered High Consequence Dikes" (BC MFLNRORD 2014).

In 2019, the province-wide *BC Dike Consequence Classification Study, Final Report* was published, which presents five consequence categories (BC MFLNRORD 2019). See Section 3.2.2.1 Dike Classification System for discussion of the province-wide consequence classification.

3.2.1.1 General Principles

The Ministry Guidelines focus on preserving Dike integrity under seismic loading conditions to minimize the potential for flooding. As such, Dike performance is anticipated for three different industry-accepted levels of ground shaking (100-year, 475-year, and 2,475-year return periods) in terms of vertical and horizontal permanent Dike crest displacements.

The Ministry Guidelines require that the Dike design must not exceed the displacements prescribed for all three levels of ground shaking, and Dike crest displacements must be quantified for Dike cross sections developed at horizontal distances of less than or equal to 300 m along the Dike alignment. At this maximum specified spacing along the Dike, it is implied that differential Dike core displacements resulting from varying subsurface conditions would be sufficiently small, resulting in a low potential for a Dike breach.

The intent of the Ministry Guidelines is to achieve a consistent assessment among Engineering Professionals of Dike integrity and performance under seismic conditions. Accordingly, prescriptive seismic loading criteria and analysis methods, including reporting requirements, were identified.

Although the Ministry Guidelines generally only apply to Dikes classified as High Consequence Dikes, the Inspector may require that the Ministry Guidelines be applied to Dikes of lower consequence, when it is suspected or known that future development or other alterations to the protected floodplain would increase the classification level. Note that the Inspector has the authority to apply the Ministry Guidelines to any Dike, regardless of classification level.

3.2.1.2 Seismic Design Process

The seismic design process outlined in the Ministry Guidelines starts by collecting data on soil stratigraphy and the characteristic design properties of different soil types required for both static and seismic analyses; establishing location-specific seismic ground motion parameters; and quantifying mean annual and 10-year water levels for the site. The process also involves compiling and reviewing historical data such as air photos; data on buried or abandoned streams and channels in the general area; surficial geology data; and available Liquefaction Susceptibility, landslide, and flood hazard maps.

Both inertial loads and Liquefaction-induced permanent Dike displacements impact the stability of Dike slopes, and damage to the Dike core, so both should be considered in Dike design. The Liquefaction Potential of soils within and underlying the Dike, and the resulting permanent displacements, have a fundamental impact on Dike performance and its flood-protection capability. The Liquefaction Potential of soils can be established using simplified or wave propagation analysis methods.

The Ministry Guidelines outline:

- the selection of appropriate shaking levels and corresponding representative earthquake magnitudes for Liquefaction analysis for each of the three return periods for simplified analysis; and
- selection and use of time-history input motions for wave propagation analyses.

Once zones of soil Liquefaction have been identified, the anticipated permanent Dike displacements should be assessed. If the estimated Dike crest displacements are larger than the acceptable (or prescribed) displacements, then reconfiguring the Dike geometry and/or implementing ground improvement measures, or constructing a new Dike Segment along a less vulnerable alignment, should be considered. This process may require one or more iterations, and may require undertaking rigorous analyses using continuum-based numerical models, in order to provide better insight on both the magnitude and pattern of Dike displacements. This process also requires the examination of zones of shear strain concentrations and/or potential failure modes of the Dike core.

Flow charts outlining the seismic design process for Dikes underlain by liquefiable soils (classified using a Liquefaction index varying from L0 to L3, with L0 representing no Liquefaction and L3 representing complete Liquefaction) are available in the Ministry Guidelines (BC MFLNRORD 2014).

The example in Figure 1: Typical Analysis Flowchart for Dike Sites With Zones of Soil Liquefaction of Limited Thickness outlines the design process (applicable for a site where Liquefaction of soils is expected to occur in zones of limited thickness, or with a Liquefaction index of L2).

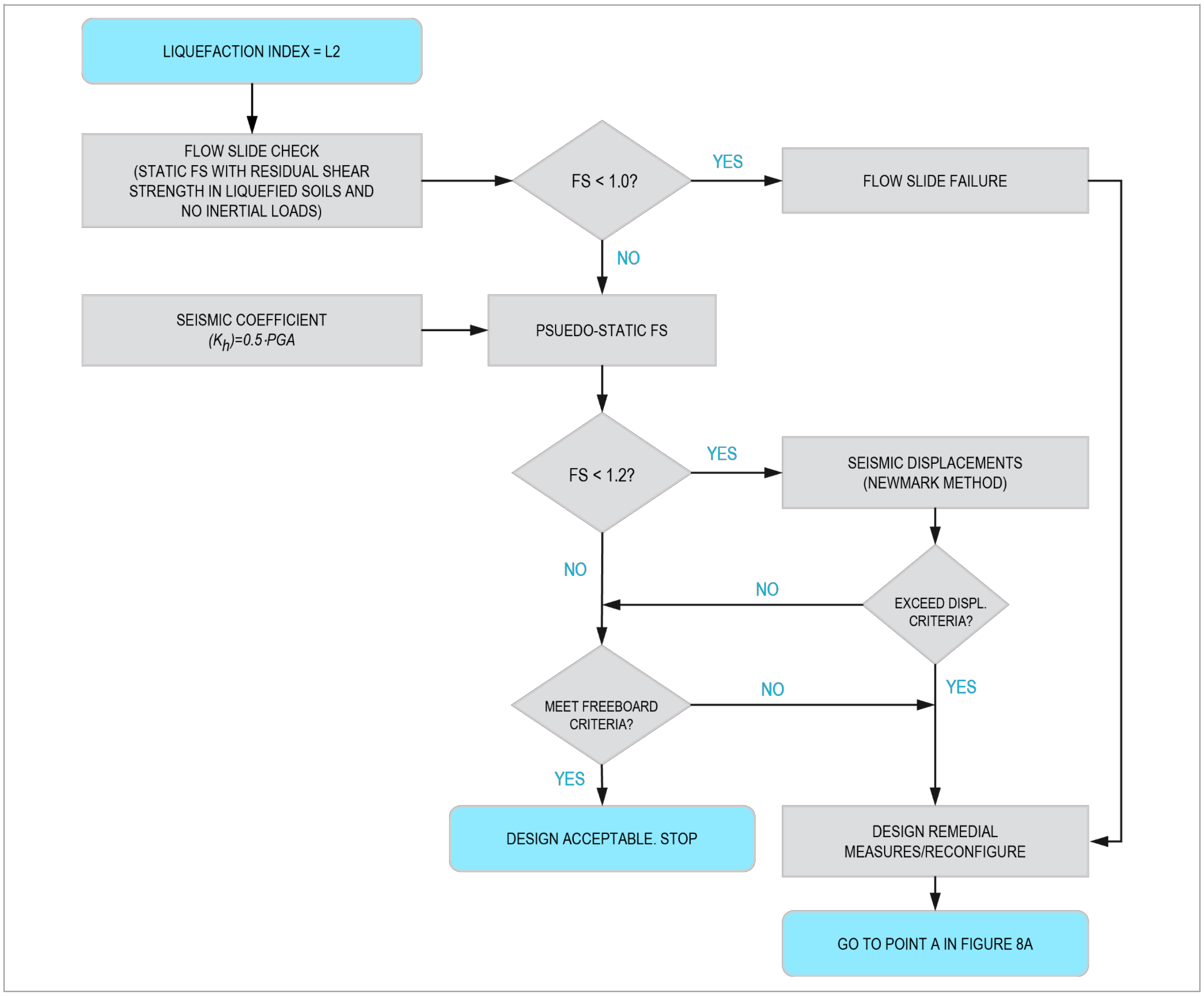

Figure 1: Typical Analysis Flowchart for Dike Sites With Zones of Soil Liquefaction of Limited Thickness

NOTES:

Abbreviation: FS = factor of safety

Figure adapted from the Ministry Guidelines (BC MFLNRORD 2014). A flow slide failure is defined as a significant translational type displacement of a land mass when static shear stresses exceed the undrained residual shear strength of liquefied soil (i.e., a factor of safety against slope failure equal to or less than 1.0 when using liquefied soil strengths and no inertial loads).

If the anticipated seismic Dike displacements are larger than the acceptable range, it should first be determined whether remedial measures will bring the Dike into alignment with the Ministry Guidelines. However, recognizing that it may not be possible to design some Dikes to meet the seismic design criteria, the Ministry Guidelines outline a number of design alternatives for consideration. These alternatives include:

- re-aligning the Dike to avoid the high cost of ground improvement;
- overbuilding the Dike to satisfy post-earthquake vertical displacement requirements while maintaining Dike integrity relative to flood protection;
- incorporating the Dike into massive fills required for adjacent land development referred to often as the "superdike" concept; and
- revising the applicable consequence classification for the Dike.

Based on Dike designs that have been implemented to date, and taking into consideration feedback received from stakeholders, these design alternatives were expanded to include the two-tiered design approach discussed in these guidelines.

See Section 3.6 Performance-Based Design and Section 3.7 Probabilistic-Based Design for further discussion of these approaches. Seismic flood hazard assessment is discussed in Section 3.7.2 Seismic Flood Hazard Assessment.

3.2.1.3 Seismic Hazard Assessment

The objective of a seismic hazard assessment is to establish ground motion parameters that apply to the seismic design. The design ground motions should represent the plate tectonic setting of the region, and should consider both the regional faults identified in geologic and seismic hazard maps, and evidence of potential fault movements within a radius of about 500 km from the site. Seismic hazard assessment in Canada continues to be developed and updated approximately every five years in support of the *National Building Code of Canada* (*NBC*). Improvements to the seismic hazard assessment process incorporate ongoing refinements of the professions' understanding of seismic source zones, ground motion prediction equations, and modelling uncertainties.

Seismic hazard maps and a seismic hazard calculator are available online via the "Seismic design tools for engineers" page on the Natural Resources Canada website, to compute ground motion parameters for a given site based on its latitude and longitude (Natural Resources Canada 2021). The seismic hazard calculator provides ground motion parameters for firm ground, or a reference ground condition, for four different return periods of 100-years, 475-years, 1,000-years, and 2,475-years, corresponding to probabilities of exceedance of 40%, 10%, 5%, and 2%, respectively, in an exposure period of 50 years. The ground motion parameters are provided in the form of uniform hazard response spectra (UHRS) for horizontal shaking. The de-aggregation of seismic hazard such as contribution of the magnitude–distance pairs to the seismic hazard at a site for varying structural periods can also be obtained from Natural Resources Canada upon request.

BC's unique plate tectonic environment results in three different earthquake types, each with its own characteristics; for example, intensity of ground shaking, magnitude, distance to fault rupture length, and duration of shaking:

- Shallow crustal earthquakes.
- Deep inslab earthquakes.
- Interface subduction earthquakes.

Seismicity in northwestern BC results from the strike-slip reverse faulting boundary between the Pacific and North American plates. The Queen Charlotte fault marks the major transpressive boundary (strike-slip and reverse faulting) between the Pacific and North American plates from northern Vancouver Island to northern BC. The Queen Charlotte fault extends more than 500 km from a southern triple junction with the Explorer, North American, and Pacific plates, to the southern extent of the Denali and Fairweather faults of Alaska. In eastern BC, away from the offshore plate tectonic boundaries, the historical seismicity is low.

In eastern and northwestern BC, shallow crustal earthquakes control site seismicity.

For a given site, the intensity and duration of shaking depend on the earthquake magnitude (a measure of how large the fault rupture is), the distance from the rupture zone to the site, and the fault rupture mechanism. The duration of strong shaking, which indirectly represents the number of cycles of loading, is correlated to the magnitude of the earthquake. The Moment Magnitude scale (denoted by M_w), which measures the total energy released by an earthquake, is commonly used for engineering applications. Incorporating the effects of both the intensity and duration of shaking is important when carrying out geotechnical analysis of foundations soils for performance-based design. Earthquakes of magnitude less than or equal to 5, regardless of the distance to the rupture zone, are not expected to cause damage in manufactured structures, such as well-constructed and well-maintained Dikes.

The Ministry Guidelines were developed when the location-specific seismic hazard and the corresponding ground motion parameters were being established using the fourth-generation seismic hazard models developed as input to the seismic design provisions in the 2010 *NBC*. The fourth-generation models did not include the contribution of seismic hazard from subduction interface earthquake sources in the probabilistic calculations. Instead, the practice that existed at that time was to consider the effects of a subduction interface earthquake on a deterministic basis. Both the peak ground shaking and earthquake magnitude assigned to a subduction interface earthquake often resulted in seismic loading-induced cyclic shear stresses that were comparable to ground motions with a 475-year return period. For this reason, subduction interface earthquake ground motions were not explicitly referenced in the Ministry Guidelines.

The return period of seismic ground motions and the seismic performance expected from Dikes for that return period are inseparable in performance-based design, and must not be viewed independently. The combination of seismic demand (or return period of ground motions) and seismic performance vary, depending on the type and importance of the structure and costs to achieve the stipulated performance. For example, for ground motions with a 2,475-year return period, the seismic performance expected from either a dam, a marine terminal, a bridge, or a building are considerably different. For a building of normal importance, the expected performance is life safety (or non-collapse to permit egress of occupants), whereas for a structure of high importance, such as a lifeline bridge, the expected performance is functionality of the bridge with repairable damage.

Following review of published guidelines on performance-based design, the following three combinations of probabilistic seismic ground motion return periods and performance expectations were established for seismic design of Dikes:

- **100-year return period and expected performance**: At this short return period, low levels of ground shaking are expected, and soil Liquefaction effects are less likely for most locations in the Lower Mainland. Consequently, only small Dike crest displacements are expected to occur. This level of ground shaking is not expected to compromise the post-earthquake flood protection capability of the Dike Segment.
- **475-year return period and expected performance**: At this intermediate return period, moderate levels of ground shaking are expected, and soil Liquefaction effects are likely for most locations in the Lower Mainland. Consequently, low-to-moderate Dike crest displacements are expected to occur, resulting in some damage to the Dike body that will require repairs. This level of ground shaking is not expected to compromise the post-earthquake flood protection capability of the Dike Segment.
- **2,475-year return period and expected performance**: At this long return period, moderate-to-high levels of ground shaking are expected, and soil Liquefaction effects would be prevalent for most locations in the Lower Mainland. Consequently, moderate-to-large Dike crest displacements are

expected to occur, resulting in significant damage to the Dike body that will potentially require complex subsurface repairs. This level of ground shaking may compromise the short-term flood protection capability of the Dike Segment. In other regions of BC, such as in the Interior, the anticipated ground shaking levels can be significantly lower and the anticipated impact on Dike displacements can also be lower.

3.2.1.4 Water Levels

Water levels are important in the geotechnical analysis of seismic stability of Dikes. In the Ministry Guidelines, it was considered that combining the peak water levels that occur annually over a short period with rare earthquake ground shaking for use in a Dike stability/displacement analysis would generally result in overly conservative designs.

In order to avoid unrealistically low joint probabilities, it is recommended in the Ministry Guidelines that mean annual river water level and mean annual sea water level be used when carrying out stability and displacement analyses as part of the seismic design of Dikes; no definition is provided for these water levels. Provision is made for assessing the sensitivity of the stability and displacements to varying water levels for special instances (e.g., for sea Dikes exposed daily to both high and low tides). Engineering Professionals are also required to demonstrate that the displaced configuration of the Dike System would provide at least 0.3 m of post-earthquake freeboard above 10-year return period water level, in addition to meeting the required seismic performance criteria.

For more information, refer to the BC Ministry of Environment document titled *Climate Change Adaptation Guidelines for Sea Dikes and Coastal Flood Hazard Land Use – Sea Dike Guidelines* (BC MOE 2011a).

3.2.1.5 Dike Performance Categories

Following review of the limited documented and available data on Dike performance during past devastating earthquakes, such as after the 2011 earthquake in Christchurch, New Zealand, the following three broad and subjective performance categories were established for seismic performance of Dikes with insignificant, moderate, and significant consequences:

- **Performance Category A**: No significant damage to the Dike body; post-seismic flood protection ability is not compromised
- **Performance Category B**: Some repairable (moderate) damage to the Dike body; post-seismic flood protection ability is not compromised
- **Performance Category C**: Significant damage to the Dike body; post-seismic flood protection ability is possibly compromised

Recognizing that the end result of seismic ground shaking would be to induce permanent displacements in the Dike, which are expected to be largest at or in the vicinity of the Dike crest, the approximate and subjective (judgment-based) Dike crest displacements were established for the seismic design of a given Dike Segment (Table 1: Seismic Performance Category and Dike Crest Displacements for Dike Integrity).

Typical Dike displacement criteria published by the United States Army Corps of Engineers (USACE) for post-event flood protection capability of Dikes in urban and urbanizing areas, simplified to suit the objectives of the studies carried out for BC, were used as a guide when establishing subjective Dike crest displacements in the Ministry Guidelines. The USACE criteria are summarized in Table 2: USACE Criteria on Post-Seismic Performance, Dike Deformations, Remaining Freeboard, and Damage to Internal Structures.

The seismic ground motion return periods that would cause the Dike crest displacements identified for each performance category (i.e., A, B, and C) were then correlated with the return period of ground motions (and associated peak ground shaking levels), based on local professional experience and consensus of the authors of the Ministry Guidelines. The correlations are summarized in Table 3: Correlation Between Seismic Performance Category and Return Period of Ground Motions.

Table 1: Seismic Performance Category and Dike Crest Displacements for Dike Integrity

PERFORMANCE CATEGORY	MAXIMUM ALLOWABLE VERTICAL CREST DISPLACEMENT	MAXIMUM ALLOWABLE HORIZONTAL CREST DISPLACEMENT
A	Small (<0.03 m)	Small (<0.03 m)
B	0.15 m	0.3 m
C	0.5 m	0.9 m

NOTE:
Abbreviation: m = metre(s)

Table 2: USACE Criteria on Post-Seismic Performance, Dike Deformations, Remaining Freeboard, and Damage to Internal Structures

POST-SEISMIC PROTECTION ABILITY	AMOUNT OF DEFORMATION	REMAINING FREEBOARD FOR POST-SEISMIC EVALUATION	SIGNIFICANT DAMAGE TO INTERNAL STRUCTURES
Probably uncompromised	<0.3 m	>0.3 m	No
Possibly uncompromised	0.3 to 0.9 m	>0.3 m	Possibly
Likely compromised	0.9 to 3 m	None	Likely if existing
Compromised	Unlimited	None	Yes

NOTE:
Abbreviations: m = metre(s); USACE = United States Army Corps of Engineers

Table 3: Correlation Between Seismic Performance Category and Return Period of Ground Motions

PERFORMANCE CATEGORY	RETURN PERIOD OF GROUND MOTIONS/EARTHQUAKE SHAKING LEVEL
A	100-year/EQL-1
B	475-year/EQL-2
C	2,475-year/EQL-3

NOTE:
Abbreviation: EQL = earthquake shaking level

3.2.1.6 Geotechnical Investigation

The objective of the geotechnical investigation outlined in the Ministry Guidelines is to collect subsurface data to develop geotechnical models applicable for the analysis of the cross sections of the Dike Segment being assessed. Identifying zones of potentially liquefiable soils, and the likely lateral and vertical displacements that could occur both during and after earthquake shaking for each specified return period, are critical to assessing the damage to the Dike core when following the performance-based design framework adopted in the Ministry Guidelines.

The Ministry Guidelines state that the geotechnical investigation should be of sufficient lateral extent and depth to collect data both with respect to the Dike and its foundation. In order to minimize extrapolation of geotechnical data/site conditions and develop some level of confidence on the seismic displacements estimated for the Dike, as a minimum, the investigation should collect information on:

- soil stratigraphy on either side and within the Dike;
- depth to mean groundwater levels on either side of and within the Dike;
- characteristics of soil strata susceptible to Liquefaction in the form of penetration resistance, strength, and shear wave velocity; and
- index properties of soils comprising the Dike and underlying foundation soils, such as particle size distributions, and Atterberg limits.

The investigation needs to be carried out using techniques currently accepted by the profession as appropriate for seismic assessment of soil-structure systems, including reliable characterization of the cyclic resistance of soils comprising the Dike body and foundation.

The Ministry Guidelines stipulate that a minimum of three borings per Dike section be analyzed, with one boring through the centre of the Dike, one on the land side, and one on the water side, to develop a soil stratigraphy section appropriate for quantifying seismic displacements using both simplified and detailed analysis methods. Sections are to be analyzed at distances not exceeding 300 m along the Dike alignment.

3.2.1.7 Analysis and Design

A key objective of the Ministry Guidelines is to describe in detail the analysis methods that are acceptable to the MFLNRORD, so practitioners follow consistent methodology in the design and analysis of Dikes. The expectation is that practitioners will produce Dike designs that are consistent throughout the different regions of BC, so that the MFLNRORD and municipalities can assess the relative impact of Dike upgrades and associated costs. It also relieves the MFLNRORD of the burden of reviewing various different methodologies followed by different practitioners in Dike design.

Pseudo-static slope stability analysis methods with prescribed seismic coefficients and soil shear strengths are recommended in the Ministry Guidelines when carrying out stability analysis of Dike sections. The results of slope stability analyses can be used to estimate seismic displacements induced in Dikes using simplified methods.

The well-known Newmark displacement analysis method is recommended as the acceptable method; however, under certain circumstances when the Newmark method yields results that are borderline (relative to the acceptable crest displacements), or when the displacements exceed the limits and it is required to optimize ground improvement requirements and/or Dike configurations at a given site to bring the crest displacements to be within the specified values, provision is made to permit the use of detailed finite element or finite difference models as acceptable methods of analyses.

3.2.2 DEVELOPMENTS SINCE 2014

Since the Ministry Guidelines were published in 2014, several new developments in key areas emerged that affect the practice of seismic design of Dikes. These areas of development are briefly described below.

3.2.2.1 Dike Classification System

The MFLNRORD engaged a consultant to examine the exposure consequence level from a major Dike failure, for each Dike in BC regulated under the *Dike Maintenance Act*. The study culminated with the publication in 2019 of the province-wide *BC Dike Consequence Classification Study, Final Report* (BC MFLNRORD 2019).

The study examined a total of 212 Dikes distributed throughout BC, classified into the following five consequence categories:

- High consequence (35 Dikes)
- Major consequence (36 Dikes)
- Moderate consequence (90 Dikes)
- Minor consequence (43 Dikes)
- Insignificant consequence (8 Dikes)

It is reported that the 35 Dikes classified as High Consequence Dikes cover 75% of the total area protected by all Dikes analyzed: 95% of the total protected population and 94% of the total protected building value. The study fills an important long-term data gap and illustrates the impact that High Consequence Dikes have on flood protection.

Refer to the *BC Dike Consequence Classification Study, Final Report* (BC MFLNRORD 2019) for more information.

3.2.2.2 Seismic Hazard Parameters

Since the Ministry Guidelines were issued, two other generations of seismic hazard models have been developed: the fifth-generation hazard model for consideration in the *NBC 2015*, and the sixth-generation hazard model for consideration in the upcoming *NBC 2021*.

The *NBC 2021* is expected to consider the sixth-generation hazard models (Kolaj et al. 2020) and maps developed by Natural Resources Canada, and will mark significant improvements in this area of earthquake engineering relative to ground motion models, percentile hazard parameters, frequency content of ground motions, site amplification factors, and de-aggregation results.

3.2.2.3 Seismic Source-Based Uniform Hazard Spectrum

For the southern half of BC, the hazard contributions come from three main sources of shaking: crustal, in-slab, and interface earthquakes. For BC, the uniform hazard spectrum (UHS) available for design is developed by first computing the hazard at various spectral periods, using response spectral attenuation relations considering the different contributions from the three main sources.

Through a probabilistic seismic hazard assessment, an individual UHS can be calculated for each of these three main contributing sources. This type of analysis is presented in Halchuck et al. (2016) using the Natural Resources Canada fifth-generation seismic hazard model. An example of an individual UHS for each of the three main sources of shaking, based on Halchuck et al. (2016) for a site in Vancouver, BC, along with the total UHS, is presented in Figure 2.

Seismic engineering designs can be produced by analyzing the seismic response of a Dike section to multiple spectra. The reason for using a UHS rather than using three spectra for the individual scenarios is to reduce the number of engineering analyses required. However, depending on the contribution from each source to the total UHS, using three spectra in the design may lead to less-conservative results.

The use of seismic source-based UHS is not included as a design method in the Ministry Guidelines; however, the Professional of Record may consider using this method, if it is deemed appropriate for a particular Dike project.

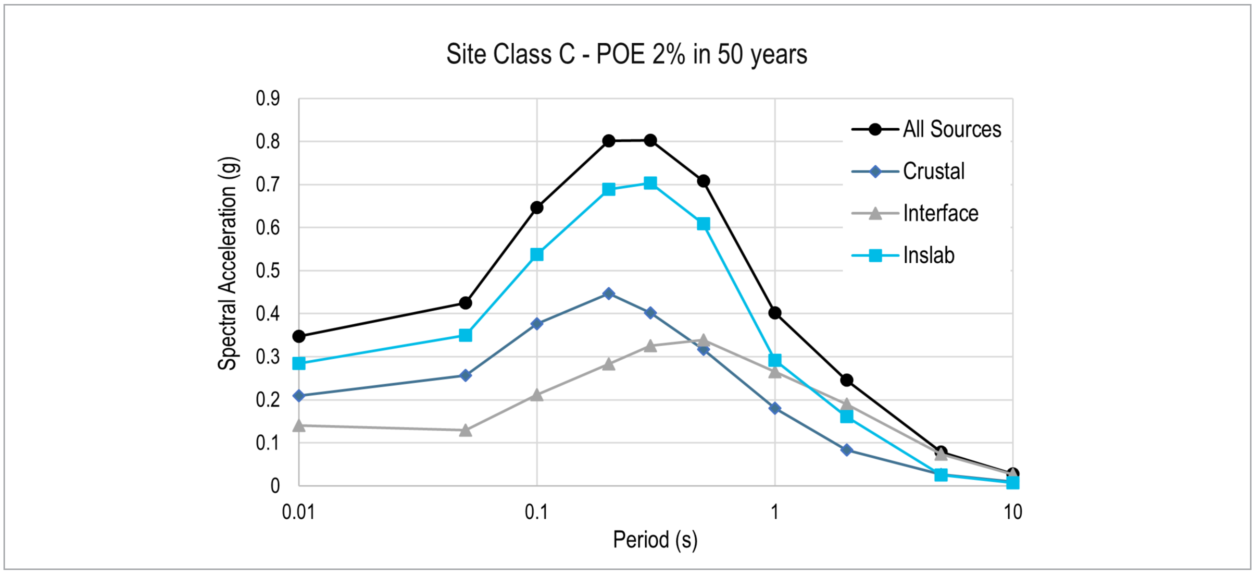

Figure 2: Comparison of Site Class C UHS from the Fifth-Generation Models for a Select Site in Vancouver, British Columbia; Total UHS and Individual UHS for Three Seismic Sources; POE 2% in 50 Years

NOTES:

Adapted from Halchuck et al. (2016)

Abbreviations: g = the acceleration due to Earth's gravity; POE = probability of exceedance; s = seconds; UHS = uniform hazard spectrum

3.2.2.4 Filling Geotechnical Data Gaps

The Fraser Basin Council, recognizing that information gaps about the seismic vulnerability of Dikes posed challenges to design professionals and stakeholders alike, initiated a data collection project in 2018, primarily for High Consequence Dike Segments in the Lower Mainland (Fraser Basin Council 2021).

This ongoing work includes collecting available data from all municipalities, identifying geotechnical data gaps, completing borings to fill the data gaps to the extent practicable, and developing detailed analytical models to quantify seismic displacements at select Dike sections. The goal of this research is to better understand the seismic vulnerability of selected Dike Segments along the High Consequence Dike System. The database developed will be available to practitioners and developers, and may provide additional information on subsurface conditions for select Dike Segments in the Lower Mainland.

The Metro Vancouver Seismic Microzonation Project also has work underway to develop maps on regional Liquefaction Susceptibility, slope instability, and soil amplification (Metro Vancouver 2021). This work is funded by the Institute for Catastrophic Loss Reduction (ICLR) and Emergency Management BC.

3.2.2.5 Addressing Climate Change

The Ministry Guidelines do not specifically discuss incorporating considerations for future sea level rise or river level rise into Dike design. However, in practice, many diking authorities have established interim and future Dike crest elevations, taking into consideration future water level rise due to climate change. Similarly, mean annual river water levels and mean annual sea water levels are routinely established by hydrotechnical consultants with and without considerations of future sea level rise due to climate change.

This specific aspect of Dike design was revisited while preparing these guidelines, and additional commentary and guidance on sea level rise are provided in Section 3.5 Climate Change and Future Considerations.

3.2.2.6 Optimizing Performance-Based Design Displacement Criteria

A longer-term strategy in the Ministry Guidelines, although it was not explicitly noted, was to formulate an analytical framework that would be easy to implement and modify in situations where the prescribed Dike crest displacements could be varied, depending on the importance classification of the Dike.

The intent was to first establish a Dike classification system, and then address the applicable prescriptive displacement criteria for lower consequence categories of Dikes; e.g. permit larger displacements (and hence a higher potential for damage and a breach) for intermediate to low consequence Dikes than for High Consequence Dikes for a given return period of ground shaking.

Designers should consult the local diking authority for acceptable displacement criteria for different Dike consequence categories.

3.2.2.7 Probabilistic-Based Seismic Vulnerability Assessments

The MFLNRORD and the Fraser Basin Council have engaged a consultant to develop probabilistic-based seismic vulnerability assessments to use for screening and prioritizing Dikes that are seismically vulnerable to damage.

These criteria will consider a range of ground-shaking intensities, flood levels, and Dike geometries, and will ultimately be focused on the development of vulnerability under different levels of seismic shaking. These methodologies will also address rapid reconstruction and response times for Dikes. Additional commentary and guidance on probabilistic-based Dike design are provided in Section 3.7 Probabilistic-Based Design.

3.2.3 IMPLEMENTATION CONSIDERATIONS OF THE MINISTRY GUIDELINES

After the Ministry Guidelines were published in 2014, practitioners, municipalities, and other stakeholders raised concerns about the costs of meeting the geotechnical field investigation requirements and seismic displacement limits specified for High Consequence Dikes. These concerns were subsequently collected through workshops and feedback surveys completed since 2014 and are presented in this section.

Considerations for implementation were reviewed during preparation of these guidelines to the extent practicable, and guidance is provided here on possible solutions.

3.2.3.1 Seismic Hazard Parameters

Practitioners shall use the ground motion parameters that correspond to the latest building code in effect at the time of application for *Dike Maintenance Act* approval.

3.2.3.2 Maximum Dike Crest Displacements for Dikes

There is consensus that the cost of Dike seismic design completed to date using the performance-based design guidance outlined in the Ministry Guidelines for High Consequence Dikes far exceeds the cost of Dike raising without seismic strengthening.

Dikes designed using the probabilistic-based design methodology outlined in Section 3.7 Probabilistic-Based Design is an acceptable alternative in some circumstances, and additional commentary and limits of use is provided on this methodology in this section.

As noted previously in Section 3.2.1.1 General Principles, the Ministry Guidelines were developed at a time when a province-wide classification system for consequence levels for Dikes did not exist.

3.2.3.3 Number of Borings and Analysis Section Spacing

The requirement in the Ministry Guidelines to carry out three test holes per Dike section (water side, land side, and crest) at distances not exceeding 300 m along the Dike alignment (see Section 3.2.1.6 Geotechnical Investigation), was commented upon by various stakeholders, including developers, municipalities, and practitioners, who expressed concerns about access, environmental impact, and cost considerations, particularly for the boreholes located on the water side.

The Professional of Record in the geotechnical discipline must develop an investigation plan that considers the balance between having closely-spaced analysis sections developed from individual test holes (resulting in less detail in the subsurface model at each analysis section, but providing more frequent analysis sections), and having widely-spaced analysis sections developed from groupings of test holes (resulting in more detail in the subsurface model at each analysis section, but providing fewer analysis sections).

The investigation plan must be sufficiently detailed, to assess the overall seismic performance of the Dike and meet the input data requirements outlined in Section 3.4 Required Input Data. In some instances, closely spaced analysis sections may provide a better overall assessment of Dike performance than widely-spaced analysis sections. At critical locations, such as those with steep waterside slopes or pump stations, more detailed subsurface models are appropriate.

Selection of the appropriate level of investigation should consider factors such as the adequacy of available information and the consequence classification of the Dike.

At a minimum, the number of test holes should be based on an overall average spacing equal to at least one per 100 m of linear length of the Dike, and should include collecting cross sectional data to develop suitable subsurface models at critical analysis sections, such as pump station locations and steep slopes. At the Professional of Record's discretion, more test holes may be required at critical sections to provide a sufficient level of detail to develop representative analysis sections at these locations. The Professional of Record must provide a technical rationale regarding the selection of test hole locations and spacings, and must document this in the Seismic Dike Report. The test holes should be located to develop representative analysis sections, which in no case should be spaced at, on an overall average, more than 300 m along the Dike.

3.2.3.4 Seismic Flood Hazard Assessment and Documentation to Support Exposure Consequence Reclassification

Section 5 of the Ministry Guidelines discusses alternatives in situations where the displacement criteria cannot be met, including steps for justifying removal of a High Consequence Dike classification by:

> "documenting expected damage, putting together a remediation plan, restricting land use and regulating floodplain development in the protected area (e.g., flood proofing bylaws and other regulatory tools)…".

Practitioners seeking this alternative route should refer to Section 3.7 Probabilistic-Based Design of these guidelines. Note that completing a probabilistic-based design does not alter the MFLNRORD-produced consequence classification of the Dike.

3.2.3.5 Geometry of a Superdike

The concept of a very wide superdike was introduced in the Ministry Guidelines for situations where displacement criteria cannot be met, and ground improvement is not feasible. Criteria defining the geometry of a superdike was not specified, resulting in different interpretations adopted by different practitioners.

Commentary on the concept and geometry to be considered for superdikes is available in Section 3.6.4 Superdikes and Setback Dikes.

3.2.3.6 Commonly used Platforms for Dynamic Site Response Analyses

The Ministry Guidelines prescribe a methodology to assess seismic-induced displacements of Dikes. Such displacements, however, may also be assessed using more comprehensive finite difference or finite element platforms, which are capable of incorporating the combined effects of non-linear soil behaviour and groundwater flow.

The finite difference software program FLAC® and the finite element software program PLAXIS© are commonly used by geotechnical earthquake engineering practitioners in the Lower Mainland when conducting dynamic site response analysis. Computer programs such as FLAC and PLAXIS form powerful platforms for seismic loading-induced deformation analysis of Dikes, and the results are suitable for the purposes of assessment of Dike performance, provided appropriate constitutive models and boundary conditions are implemented. It is expected that, when performed properly, both programs should provide a similar assessment of seismic deformations (both horizontal displacements and settlement) of a Dike under seismic loading conditions.

Engineering Professionals should demonstrate that an appropriate level of constitutive model calibration has been carried out, and that appropriate boundary conditions have been selected, when using finite element or finite difference programs in site response analyses.

Current practice for dynamic analyses covers a wide range of approaches, which can make it difficult for regulatory agencies and local authorities to assess the appropriateness of any particular analysis, boundary conditions, and/or constitutive model used. Therefore, thorough documentation practices including a clearly documented rationale for the approach chosen are necessary to ensure similar quality assurance requirements are used among practitioners.

For information related to documentation requirements, see Section 3.8 Reporting Requirements.

3.3 DESIGN CRITERIA FOR DIKES OTHER THAN HIGH CONSEQUENCE DIKES

The Ministry Guidelines only apply to High Consequence Dikes in high-seismic areas, as discussed in Section 3.2 Overview of Seismic Design Guidelines for Dikes.

However, if the Inspector specifies that the Ministry Guidelines are to be followed for any other consequence category of Dike, the local diking authority must determine the acceptable seismic design criteria. The local diking authority must then seek approval from the Inspector for the seismic design criteria it is using, and communicate the approved criteria to the Design Team.

3.4 REQUIRED INPUT DATA

3.4.1 SITE-SPECIFIC INFORMATION

When undertaking a seismic design of a Dike, site-specific input data must be collected with consideration given to the guidance described in Section 3.2.1.6 Geotechnical Investigation, Section 3.2.2.4 Filling Geotechnical Data Gaps, and Section 3.2.3.3 Number of Borings and Analysis Section Spacing.

In addition, the input data in the following subsections is required.

3.4.2 ADDITIONAL INPUT DATA

In addition to the information noted above, the following input data is required:

- **Available record drawings for the Dike**: These include details on the as-built condition of the Dike including cross sections; materials used for construction; construction details, such as level of compaction for the Dike Segments of concern and adjoining segments; and drawings and design details for appurtenant structures, such as flood boxes and pump stations.

- **Historical performance of the Dike**: This includes inspection reports summarizing past performance of the Dike Segment such as settlement, scouring, seepage concerns, vegetation, evidence of animal burrows, and land use changes.
- **Available geotechnical borings**: Inquire with the Fraser Basin Council regarding their Database for Dikes in the Lower Mainland, and refer to reports and record drawings prepared and completed by engineers and contractors during initial Dike construction and subsequent modifications/alterations (if applicable) in other jurisdictions. Existing borings are often useful for defining stratigraphy, but they may have unreliable standard penetration test (SPT) resistance values, due to unknown energy levels associated with the hammer type and lift/drop mechanism.
- **Data on water levels for analysis**: It is required that mean river-water levels, mean ocean-water levels, and groundwater conditions be established, including the phreatic surface within the Dike when necessary, by seepage analysis (refer to the Ministry Guidelines, Appendix E, Section E: Analysis Methodology). Water levels should consider climate change effects.
- **Ground shaking levels for return periods of 100-years, 475-years, and 2,475-years**: These must be obtained by establishing the UTM coordinates for the site, and then inputting the coordinates into the interactive Natural Resources Canada hazard calculator to obtain the results (Natural Resources Canada 2021).
- **Surface topography/bathymetry on both sides of the Dike**: This must include the riverbed or seabed level and its lateral variation away from the Dike, at least for a distance within which a potential failure mechanism could develop.
- **Other available information**: These include surficial geology maps, aerial photographs, and maps showing the Liquefaction Susceptibility of soils and flood hazards developed for the area (when available).

When conducting Liquefaction assessments, new test-hole investigations should consider, as a minimum, one test hole to a depth of 30 m or practical refusal. The use of the SPT should consider energy measurements and various correction factors suggested in Idriss and Boulanger (2008). Satisfactory use of the SPT for Liquefaction analyses requires that the apparatus and procedures conform with the ASTM D1586 standard. Gravelly sites should be investigated with the instrumented Becker penetration test (iBPT), which allows a direct measurement of the energy delivered to the tip (DeJong et al. 2014; DeJong et al. 2016). Direct soil sampling should always be the primary means for determining fines contents for the purpose of determining equivalent “clean sand” values (Idriss and Boulanger 2008).

When conducting site-response analyses, or using code-based ground motion amplification factors, shear wave velocity (V_s) should be measured using appropriate techniques (see Hunter and Crow 2015), which may include the seismic cone penetration test (SCPT), surface wave methods, or downhole testing. Refraction microtremor (ReMi)-based techniques should be avoided due to potential for bias, particularly at depth (Stewart et al. 2014). Although numerous empirical correlations exist for estimating V_s from penetration resistance, these should not be used for ground response analyses applications when the results are sensitive to small variations in V_s.

Any required input data necessary for the project that is not otherwise available must be provided by the owner.

3.4.3 UTILITIES AND OTHER STRUCTURES

Flood boxes and pump houses are often constructed within or in proximity to Dikes. The differential seismic performance of these structural units will result in an interface with the Dike that is vulnerable to piping failure following earthquake shaking, and may form the weakest link in the Dike Segment being analyzed.

Dike Segments that are directly connected to these structures may be required to be designed to more stringent displacements. Consideration may be given to the provision of wing walls designed to reduce the hydraulic gradients to acceptable levels to reduce the risk of piping failure. The use of approved Dike fills abutting the wing walls compacted to the standards defined in Dike construction guidelines must be followed. Geotechnical Engineering Professionals must coordinate all required analyses with the structural Engineering Professional and implement suitable designs.

It should be noted that the approval process under the *Dike Maintenance Act* only relates to the performance of the Dike and not to the design of any utilities or other structures. In addition to meeting the requirements under the *Dike Maintenance Act*, requirements of other design standards may apply.

3.5 CLIMATE CHANGE AND FUTURE CONSIDERATIONS

As global warming continues, the effects of climate change on local riverine floods and coastal water levels will become further understood. Guidance from various BC Government Ministries states that permanent flood protection structures, such as Dikes, are likely to require upgrading periodically to account for the increasing knowledge (BC MFLNRORD 2014; BC MWLAP 2003; BC MOE 2011a; BC MOE, 2011b).

When providing upgrades to a Dike, such as to address seismic conditions, the hydrotechnical design event should be reviewed and, if necessary, updated. For example, a previously applied 1-in-200-year (0.5% annual exceedance probability) flood may have a higher magnitude based on updated understanding of current and future conditions.

Government guidance suggests Dikes should be designed with consideration of projected conditions for at least 90 to 100 years into the future (BC MOE 2011a); however, consideration of intermediate time periods may be required where design water levels during the intermediate periods may be higher than for future periods. (For example, for many rain-on-snow dominated watersheds in BC, climate change is expected to result in increasing rainfall intensity as well as decreasing snowpack. The relative rate and timing of these counteracting trends may result in a period of greatest probability of extreme floods different than the end of the study period.) Alternative time horizons may be applied based on design life or adoption of adaptive plans for future upgrades; however, they should only be applied following consultation with the Dike owner and the Inspector.

When assessing the design event, guidance from the BC Government should be adhered to. The projection of future conditions should account for the following:

- For coastal Dikes, the following should be considered:
  - Sea level rise
  - Subsidence
  - Local settlement
  - Projected changes in waves, wind, storms (intensity, frequency, duration, direction, timing)
  - Changes in shoreline that may affect wave effects and runup
  - Uncertainty
- For river Dikes, the following should be considered:
  - Changes in design flow (magnitude, timing, duration, defining process)
  - Changes in hydrotechnical design conditions and channel conditions (ice, debris, sediment, bed, banks, channel form, channel process)

- – Local settlement
  – Uncertainty
- For Dikes along lakes and reservoirs, the following should be considered:
  – Changes in magnitude, timing, and duration of design inflow
  – Changes in outflow or hydrologic loss from the lake
  – Changes in wind, setup, and waves
  – Changes in ice cover
  – Changes in sediment supply and bed changes (particularly at outlets along Dikes)
  – Local settlement
  – Uncertainty
- For Dikes along estuary and tidally influenced rivers, the following should be considered:
  – Applicable coastal Dike and river Dike conditions listed above
  – Changes in timing and probability of simultaneous occurrence of high flows and high coastal water levels

Freeboard is typically applied as a mechanism to account for local variations in water level and uncertainty in the data and analysis used to calculate the design conditions. Freeboard of 0.6 m is commonly used in BC; however, freeboard as low as 0.3 m and as much as 1.0 m or more have been used, depending on the source of the hazard, quality of data used, and calculation method to determine the design event.

Refer to the *Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC* (Engineers and Geoscientists BC 2018) and the *Guidelines of for Sea Dikes and Coastal Flood Hazard Land Use – Sea Dike Guidelines* (BC Ministry of Environment 2011).

3.6 PERFORMANCE-BASED DESIGN

The magnitude of seismic deformations within a Dike largely depends on whether Liquefaction of the foundation soils occurs. If Liquefaction is predicted to occur, the performance requirements of the Ministry Guidelines often will not be met. If Liquefaction is not predicted to occur, deformations tend to be small (i.e., less than 1 m), but if Liquefaction does occur, deformations can be much larger (i.e., greater than 1 m), depending on site-specific factors.

Usually, a gradual increase in displacement does not tend to occur with increasing seismic hazard (i.e., with stronger ground shaking), but a large increase may occur when earthquake ground motions exceed a threshold level that initiates Liquefaction. Accordingly, Liquefaction is the most significant contributor to the seismic vulnerability of most Dikes.

Liquefaction results in the loss of strength and stiffness of granular soil. Seismic deformation of Dikes depends on many factors, such as earthquake ground motion intensity, earthquake magnitude, extent of Liquefaction, Dike configuration, and site topography and bathymetry.

In general, larger deformations can be expected where:

- Dikes are close to slopes (such as riverbanks);
- there are steeper slopes (including those of the Dikes and of the riverbanks);
- the slopes and/or Dikes are higher;
- thicker liquefiable soil is present;
- thinner non-liquefiable crust is present; and
- the design seismic hazard has a higher return period than the seismic hazard that initiates Liquefaction.

The first three points above all relate to the static shear stress bias (i.e., a destabilizing force, such as a slope or surcharge). Higher stress biases are caused by higher and steeper slopes. Areas without a static shear stress bias (i.e., flat ground) would not be expected to experience large deformation caused by Liquefaction. Setback Dikes, short Dikes, and Dikes on non-liquefiable subgrades, such as clay-like soils, unsaturated soil, and sufficiently dense granular soils, can be expected to have smaller seismic deformations under a given seismic hazard.

Dikes constructed over soils where Liquefaction (and, accordingly, potentially large seismic deformations) is anticipated to occur may require ground improvement (see Section 3.6.1 Ground Improvement). If displacement criteria cannot be met, and if ground improvement is not feasible, the Ministry Guidelines offer possible design alternatives, as discussed in Section 3.2.1.2 Seismic Design Process. As noted there, alternatives that could be considered include:

- realigning Dikes to less seismically vulnerable areas;
- overbuilding Dikes to accommodate seismic displacements;
- building very wide "superdikes"; and
- removing the High Consequence Dike classification.

As outlined in Section 3.2.3.4 Seismic Flood Hazard Assessment and Documentation to Support Exposure Consequence Reclassification, practitioners seeking removal of the High Consequence Dike classification are now directed to Section 3.7 Probabilistic-Based Design of these guidelines, which outlines a probabilistic-based approach that can be followed by developing comprehensive flood risk and flood protection strategies, including post-earthquake Dike repair plans. Note that completing a probabilistic-based design does not alter the MFLNRORD-produced consequence classification of the Dike.

The following subsections discuss design alternatives that the Design Team can use to align the Dike design with the Ministry Guidelines using performance-based design options. The performance-based alternatives include ground improvements as well as the first three items in the list above. Analytical and documentation efforts must justify using the probabilistic-based approach, where the Dike design will not meet the performance-based criteria of the Ministry Guidelines. See Section 3.7 Probabilistic-Based Design for details.

3.6.1 GROUND IMPROVEMENT

3.6.1.1 Current Ground Improvement Methods

Mitigation of seismic deformations can often be accomplished using ground improvement. Ground improvement using stone columns is currently one of the most suitable and cost-effective ground-improvement methods for non-plastic and cohesionless soils.

Compaction piles, soil mixing, and jet grouting are other alternatives to increase the strength of sand to limit Liquefaction. However, these alternatives may cost more than stone columns, and could be more difficult to adapt to changing or unexpected subsurface conditions.

Compaction piles can consist of timber, precast concrete, or steel pipe piles. These compaction piles can be slightly more, to considerably more, expensive than the cost of stone columns per treated soil volume. Compaction piles may be the most practical alternative where ground improvement is required underwater.

Soil mixing methods include deep-soil mixing and cutter-soil mixing. These methods are consistently more expensive than the cost of stone columns per treated soil volume. Jet grouting is another method that also costs more than stone columns.

Partial ground improvement may also be considered, often in conjunction with one of the options discussed above, such as building superdikes in areas of lower seismic deformations.

As an alternative to ground improvement, some specific circumstances may use ground reinforcement.

3.6.1.2 Innovative Ground Improvement Methods

Innovative ground improvement techniques are being developed across the globe. These techniques have the potential to provide unconventional solutions for achieving desired ground improvement levels for projects involving the seismic design of Dikes.

Engineering Professionals may consider using innovative ground improvement methods where appropriate, but using such methods should be discussed with the owner and the Inspector, as the techniques may not always be appropriate. If innovative methods will be used, Engineering Professionals should consider:

- whether specialists should be used to assist in design and implementation;
- requirements for testing, reviewing, and monitoring (including long-term monitoring) of the efficacy of the technique;
- the potential impact of the technique on the environment;
- other potential impacts; and
- the need for a contingency plan if the expected results are not achieved.

Caution should be used when implementing innovative ground improvement methods, and the work should only be undertaken by Engineering Professionals who are appropriately qualified and experienced in this area of practice. Engineering Professional should always thoroughly investigate and evaluate the validity of innovative methods before making the recommendation to move forward with one. Two bio-mediated techniques for Liquefaction mitigation are discussed in this section and include microbial denitrification and microbially induced calcite precipitation (MICP).

Microbial denitrification (i.e., nitrate reduction) is a biological process in which nitrate is reduced stepwise to nitrogen gas. By generating gas, the potential for pore pressures to increase as soil particles are compressed during seismic shaking is significantly reduced. Nitrogen produced by the denitrification process is the most suitable biogas for sand desaturation, because it is chemically inert and its solubility in water is very low (Phu Pham et al. 2018). One of the disadvantages of this technique is that gas bubbles can induce settlements, so this aspect should be considered when evaluating this technique as a Liquefaction-mitigation solution.

MICP consists of cementing the interparticle contacts by precipitating calcium carbonate ($CaCO_3$) through biogeochemical processes using bacteria that can be native to the ground. $CaCO_3$ precipitation reduces permeability and improves the strength, stiffness, and dilatancy of the soil by pore filling, particle roughening, and interparticle binding. While MICP has not been commercialized, promising results have been obtained in the laboratory and in limited field trials in the Netherlands (van Paassen et al. 2010) and Canada (Zeng et al. 2021). Field trials will likely be required to test the applicability of biogrouting at large scales, and in particular to improve Dike Reaches.

3.6.2 DIKE REALIGNMENT

A new alignment for the Dike may be a more cost-effective option to consider than the other design alternatives, and may improve access and constructability.

When undertaking a Dike realignment, items to consider include, but are not limited to, geotechnical conditions along the proposed realignment, land acquisition requirements, environmental and archaeological impacts, construction access, noise impacts, site utilities, and adjacent infrastructure.

One type of Dike realignment is a setback Dike, as discussed in Section 3.6.4 Superdikes and Setback Dikes.

3.6.3 OVERBUILDING

Overbuilding Dikes may be feasible where deformations are relatively small, but the deformations do not meet the performance-based criteria of the Ministry Guidelines relative to the available freeboard.

Because of the uncertainty in accurately predicting seismic deformations, and the potential for damage to the Dike core, this approach may not be suitable where large seismic deformations are anticipated. The feasibility of overbuilding a Dike should be assessed by the Professional of Record based on the specific project details.

3.6.4 SUPERDIKES AND SETBACK DIKES

Dikes can be designed by using either a superdike or a setback Dike. Conceptually, a superdike would extend beyond the zone of lateral spread, and a setback Dike would be behind the zone. These two types of Dikes are discussed here together, because both provide flood protection by maintaining a Dike Segment with a setback beyond the zone of large seismic deformations and lateral spread.

Typically for seismic considerations, a superdike width is at least 20 times the combined height of the Dike and riverbank slope (i.e., to the bottom of the river channel). Similarly, the setback Dike is typically located a distance at least 20 times the height of the riverbank.

It is well-documented that seismic-induced lateral spreading near an open channel or face can extend large distances from the open face attenuating toward land. The general concept for seismic design of a superdike is to build a Dike that is wide enough to accommodate retaining an acceptable Dike section behind the area with large seismic deformations that will ensure the overall water retention capacity is not compromised.

Similarly, setback Dikes should be constructed far enough from the zone of large deformations, so the performance criteria of the Ministry Guidelines is met. The assessment of the setback (or crest width of superdikes) should be assessed using numerical analytical methods, as limit equilibrium methods do not accurately predict the magnitude and pattern of large deformations.

3.7 PROBABILISTIC-BASED DESIGN

If performance-based options such as adding ground improvements, realigning the Dike, designing an overbuilt Dike, or constructing a superdike or setback Dike are not feasible, the only remaining option is to develop a design that does not meet the performance-based criteria of the Ministry Guidelines. This option is known as a probabilistic-based design.

Undertaking a probabilistic-based design requires an additional level of training and experience; therefore, an Engineering Professional undertaking this type of work should refer to Section 5.2 Education, Training, and Experience for more information on the specific educational and experience indicators.

Considerations for this option include developing a comprehensive flood risk and flood protection strategy, including post-earthquake Dike repair plans, the goal of which is to justify using a probabilistic-based design.

Before undertaking a probabilistic-based design, a documented process must be followed to assess the feasibility of the performance-based design alternatives, and an explanation must be provided as to why no other options are considered viable (see Section 3.7.1 Feasibility Assessment of Performance-Based Design Alternatives). Then, an assessment of the level of flood protection after the occurrence of each of the earthquake levels required by the Ministry Guidelines (100-year, 475-year, and 2,475-year return periods) must be completed (see Section 3.7.2 Seismic Flood Hazard Assessment). As this would result in a reduced level of flood protection after an earthquake, the probabilistic-based option would have to demonstrate that the flood risk would be acceptable before the Dike could be rebuilt.

It should be noted that providing this documentation to the Inspector does not guarantee that a probabilistic-based design will be accepted; rather, this documentation is required if a probabilistic-based design is to even be considered. Final approval will be subject to Inspector review. Therefore, it would be prudent for Engineering Professionals to initiate discussions with the Inspector at a preliminary stage about the intent to develop a probabilistic-based design, to facilitate the process.

3.7.1 FEASIBILITY ASSESSMENT OF PERFORMANCE-BASED DESIGN ALTERNATIVES

During a feasibility assessment, a documented process must be followed to assess the performance-based design alternatives, and an explanation must be provided as to why no other options are considered viable.

Based on a review of the findings of the following assessments, the feasibility of the ground improvements and the design alternatives must be assessed and discussed in the Seismic Dike Report.

Note that it is not sufficient to just state that ground improvements and design alternatives are not feasible; the various aspects need to be considered and estimated. In particular, high-level cost estimates must be provided, such as a Class C or Class D cost estimate. When the cost estimate is shown to be prohibitive to moving forward with a performance-based design alternative, a probabilistic-based design alternative may be considered.

During the feasibility assessment, the following types of performance-based design alternatives discussed in Section 3.6 Performance-Based Design need to be identified and considered:

- Ground improvement
  - From a technical perspective, the types of ground improvement that could be implemented to meet the Ministry Guidelines
- Extent
  - For each technically feasible type of ground improvement, the extents, such as horizontal extents and depth
- Design alternatives
  - Other design alternatives, such as Dike realignment, overbuilding, and superdiking, that could be considered

In addition, for each technically feasible performance-based design alternative, the following need to be considered:

- Cost
  - The estimated cost of the viable ground improvements and design alternatives
    - Specific, not general, cost estimates for the performance-based design must be provided
    - A Class C or Class D cost estimate needs to be developed
- Property encroachment and/or acquisitions
  - If the horizontal extent of the ground improvements/design alternatives extend beyond the footprint of the Dike, whether the ground improvements can fit within the property boundary constraints
  - If not, the amount of required property acquisition
- Access for construction
  - Whether ground improvements/design alternatives can be implemented using only the same access required for the Dike construction, or additional access would be required to implement the ground improvements/design alternatives
    - For example, if ground improvements are required beyond the footprint of a Dike, out into the edge of a river channel, whether a barge would be required to implement these ground improvements
- Environmental impacts
  - If the horizontal extent of the ground improvements/design alternatives may extend beyond the footprint of the Dike, whether they would impact any adjacent environmentally sensitive areas
  - In particular, since the majority of Dikes are located in areas adjacent to water bodies, whether ground improvements may require disturbance within these water bodies

- Whether the potential environmental impacts are considered permanent or temporary
- The kind of environmental compensation that might be required to offset these impacts

- **Archaeological impacts**
  - Whether ground improvements/design alternatives pose a risk to any known archaeological sites
  - Whether an archaeological assessment has been conducted
  - The potential for archaeological impact of the proposed development
- **Noise impacts**
  - Any noise concerns related to the proposed ground improvement/design alternatives
  - Whether there are homes and/or businesses nearby
- **Impacts on adjacent utilities, buildings, or critical infrastructure**
  - Whether there is a risk of impacting nearby utilities or critical infrastructure
- **Traffic impacts**
  - Effects on the movement of people and vehicles through the project area, i.e., traffic, pedestrians, or park users
  - How long the ground improvements will take

3.7.2 SEISMIC FLOOD HAZARD ASSESSMENT

3.7.2.1 Defining a Unique Seismic Flood Hazard

Historically, the provincial flood protection standard was set based on historical floods, without consideration of seismic hazards. However, there is growing awareness that Dikes can also be damaged by earthquakes, which introduces an additional flood hazard. It should be noted that regional and tectonic subsidence of the earth's crust has not been considered in these guidelines.

Dike crest elevations could be lowered following an earthquake, due to deformations and cracking. For a seismically damaged Dike, the elevation at which the Dike is considered competent is the effective Dike crest elevation (referred to in these guidelines as the "failure level"). As a result, an earthquake-damaged Dike would be vulnerable to flooding at water surface elevations lower than those for which the Dike was originally designed. This increased vulnerability would persist until the Dike has been rebuilt and the Dike crest restored to the required design elevation. The time required to rebuild the earthquake-damaged Dike is therefore an important consideration in assessing this vulnerability. It is also important that freeboard is handled in a consistent way when addressing seismic and non-seismic flood hazards.

Under this approach, the unique seismic flood hazard is defined as:

> flooding that occurs as a result of water levels exceeding the failure level of a Dike that has been deformed by an earthquake, but not exceeding the original failure level of the Dike before it was deformed.

In other words, the seismic flood hazard accounts for flooding that would have been prevented if the Dike had not been damaged by an earthquake.

The seismic flood hazard for a given Dike or Dike System can be compared to the corresponding non-seismic flood hazard using an annual exceedance probability or a return period. This comparison helps Dike owners understand the importance of each hazard relative to the performance of their Dike System and to their community's flood risk.

Seismic flood hazard can also be combined with non-seismic flood hazard, to estimate a total flood hazard. This total flood hazard can then be compared to an acceptable level of hazard defined by regulatory requirements and/or government policy. An implied minimum acceptable total flood hazard for Dikes in BC can be calculated by combining provincial standard design criteria (e.g., a Dike crest 0.6 m above the Dike design flood level) with the acceptable seismic deformations specified in the Ministry Guidelines.

By considering the combination of seismic flood hazards and historical (non-seismic) flood hazards, Engineering Professionals, Dike owners, and regulators can identify the most practical, economical, and effective strategies to reduce the overall flood hazard for a community.

3.7.2.2 Considerations for the Seismic Flood Hazard Assessment

When the displacement-based performance criteria from the Ministry Guidelines cannot practicably be met, the Engineering Professional must undertake a formal seismic flood hazard assessment as described in this section, or as otherwise accepted by the Inspector.

Determining the seismic flood hazard requires comprehensive geotechnical, probabilistic, and recovery-time analyses, and a commitment from the owner to implement an emergency recovery plan for repairing the Dike after it has been damaged by strong seismic shaking. Like most other areas of engineering, a seismic flood hazard assessment can provide input at the conceptual (e.g., regional planning and prioritization), preliminary (e.g., mitigation options evaluation), and detailed (e.g., mitigation design) levels. As the assessment progresses from conceptual to detailed, some inputs to the process, such as the rebuild time, may evolve iteratively. Note that the seismic flood hazard assessment described in these guidelines does not consider consequence, and therefore does not comment on seismic flood risk.

The development of a seismic flood hazard assessment requires establishing the vulnerability of a Dike to a seismic hazard (i.e., failure level) and the associated rebuild time. The likelihood of damage and the corresponding rebuild time are expected to be a function of the earthquake return period, with longer return-period earthquakes causing more damage and possibly requiring longer rebuild times. It is recognized that evaluating the feasibility of repair and reconstruction within a set rebuild time is complex and may require significant effort to demonstrate, as discussed in the following excerpt from Ministry Guidelines:

> "While rapid re-construction may be feasible for discrete, short sections of dikes, re-construction to address widespread damage throughout the diking system may be difficult when dike work would be competing for resources for re-construction of other critical infrastructures such as water, sewer, roads and bridges. If the dikes cannot be repaired promptly, large sections of communities in low lying areas would be vulnerable to flooding, even from low return period events" (MFLNRORD 2014).

The seismic flood hazard can be reduced either by improving the post-seismic level of protection provided by the Dike, by reducing the rebuild time, or by using a combination of both methods.

A seismic flood hazard assessment must be conducted and documented by an appropriately qualified Engineering Professional. The seismic flood hazard assessment must:

- include a scope of work and a level of detail commensurate with the complexity of the Dike Segment being analyzed, where the scope includes, as a minimum, the engineering analyses and methodology summarized in Figure 3;
- describe the process and approach that were used in undertaking the seismic flood hazard assessment;
- apply the emergency recovery plan process established by the authority having jurisdiction over the area protected by the Dike;
- quantify the seismic flood hazard; and
- recommend appropriate flood management or mitigation measures such that the seismic flood hazard is within the acceptable level as determined by the local diking authority and as approved by the Inspector.

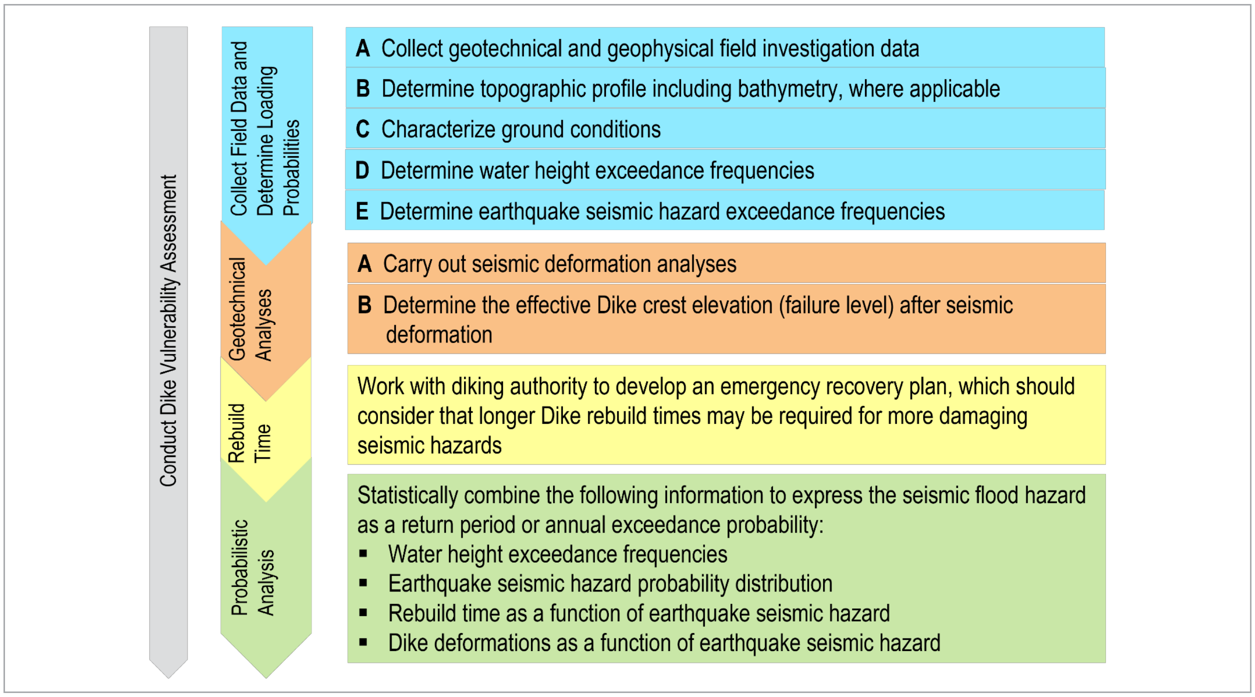

Figure 3: Minimum Recommended Engineering Analysis and Methodology to be Included in a Seismic Flood Hazard Assessment

If, in the opinion of the Inspector, the seismic flood hazard assessment submitted by the Dike owner was developed in accordance with these guidelines, a Dike owner must implement measures outlined in the seismic flood hazard assessment as authorized in writing by the Inspector.

Examples of specific technical considerations to be addressed by the Engineering Professional include the following:

- **Purpose of Analysis**: The level of complexity for any analysis should reflect the intended use of the results. For example, a regional assessment aimed at prioritizing issues across a portfolio of Dikes will typically allow for a simpler assessment than the design of site-specific mitigation works.
- **Decision Context**: The Engineering Professional should understand how results will be used by the client, and should structure the analysis so that results are compatible with the intended use. Seismic flood hazard determined using a complex model of Dike behaviour should not be compared to non-seismic flood hazard determined using a simplified model. In addition, decisions that are more sensitive to uncertainty—such as mitigating seismic flood hazard by overbuilding the Dike—will typically require more detailed analysis.
- **Spatial Extent**: The analysis should establish whether results will reflect at-a-section conditions, or whether section results will be extrapolated to represent the behaviour of a Dike Reach. The basis for identifying reaches and establishing representative sections should be carefully considered, as should the methodology for combining results from multiple reaches, to provide an overall level of seismic flood hazard for a Dike System.
- **Data Availability**: The Engineering Professional should consider what level of analysis the available data and/or data acquisition budget can support, and whether that level of analysis will be appropriate for the client's intended use.

- **Dike Seismic Response**: A numerical analysis that estimates Dike deformation for a range of seismic events provides the most complete description of expected Dike behaviour. However, there may be some situations where a simplified behaviour model can be considered. For example, if the Dike deformation is expected to be very sensitive to the Liquefaction threshold, it may be acceptable for a screening-level analysis to model deformation as a rigid-perfectly plastic response (i.e., zero deformation up to a threshold event that induces a fixed deformation, then no further increase in deformation for more intense loading).
- **Uncertainty in Deformation Estimates**: Like all engineering analyses, even the most detailed assessments of Dike deformation have significant uncertainty. A simple analysis will typically adopt the expected value for each deformation estimate. More sophisticated analyses can consider variability through approaches that range from approximations based on engineering judgment to detailed Monte Carlo simulation.
- **Representation of Dike Failure Probability**: There are a number of mechanisms of possible Dike failure, including (but not limited to) overtopping, surface erosion, and internal erosion ("piping"). A "fragility curve" provides the most accurate representation of Dike failure by relating the probability of failure to available freeboard. However, the development of a site-specific fragility curve is resource-intensive, and generic fragility curves have yet to be adopted in BC. Simplifying assumptions (e.g., representing the fragility curve as a step-function) must be carefully selected such that outcomes will be conservative but realistic. See Figure 4: Example of a Fragility Curve for Strategic Level Assessment for an example of a fragility curve for a narrow river Dike in England (DEFRA 2007):

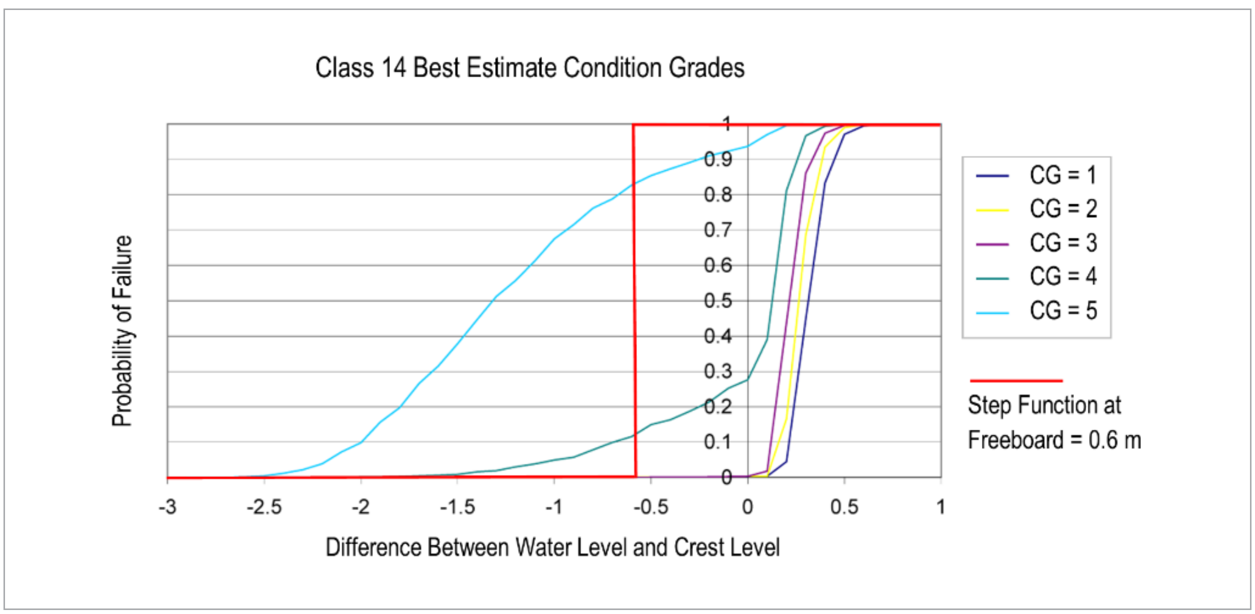

Figure 4: Example of a Fragility Curve for Strategic Level Assessment

NOTES:

Figure adapted from: Performance and Reliability of Flood and Coastal Defences (DEFRA 2007). The abbreviation CG stands for "condition grade" with 1 being excellent and 5 being poor. The CG is an assessment of the physical characteristics such as the quality of the Dike and the erosion resistance at the crest and the inside slope of the Dike.

- **Differences in Dike Failure Behaviour Before and After Seismic Event**: Seismic deformation will reduce the effective Dike crest elevation, but it may also change the failure behaviour of the Dike. Where important, such changes should be addressed by updating the shape of the post-seismic fragility curve. Simplified step-functions could account for this change in reliability by increasing the freeboard remaining at failure.
- **Rebuild Time**: As previously discussed, the concept of rebuild time is key to any seismic flood analysis. Initial analyses may treat rebuild time as a variable to inform development of an emergency recovery plan by the owner. More detailed analyses will require that the Dike owner commit to implementing a specific emergency recovery plan for repairing the Dike after it has been damaged by an earthquake. Particularly critical analyses may need to consider the gradual recovery of Dike capacity throughout the rebuild time (e.g., by prioritizing repair of the highest-hazard locations). Rebuild times of less than one year should be considered carefully with regard to potential seasonality of the flood hazard.

As noted, consideration of the above factors does not imply that a complex analysis is required; rather, the Engineering Professional should provide clear justification where one or more of the above factors is omitted or subjected to simplifying assumptions.

3.7.2.3 Probabilistic Analysis

This section describes the calculation of probability for the seismic flood hazard, as described in Section 3.7.2.1 Defining a Unique Seismic Flood Hazard. The approach is intended to apply across a range of applications that reflect the considerations discussed in Section 3.7.2.2 Considerations for the Seismic Flood Hazard Assessment.

The probability of flooding due to an earthquake-damaged Dike (the seismic flood hazard) is equal to the probability that a flood higher than the failure level of the earthquake-damaged Dike will occur, multiplied by the probability that the Dike has been damaged, since earthquakes and floods are independent events. The equation is as follows:

$$P[F, EQ] = P[F_{EQ}] \cdot P[EQ_D],$$

where $P[F, EQ]$ is the probability of flooding due to failure of an earthquake-damaged Dike;
$P[F_{EQ}]$ is the probability of a flood higher than the failure level of the earthquake-damaged Dike; and
$P[EQ_D]$ is the probability that the Dike has been damaged by an earthquake.

The probabilities of earthquake and flood events are usually expressed as return periods or annual exceedance probabilities. The return period is the average time interval between events, and the average exceedance probability is the inverse of the return period. These are often evaluated using the Poisson distribution or the binomial distribution. The limitation of the binomial distribution is that it is not valid if there is the possibility of more than one event occurring in a binomial time interval, although most of the time (i.e., for infrequent events) it provides a reasonable approximation. For coastal Dikes, the binomial distribution does not work because of the need to consider multiple events per binomial time interval (e.g., per year). Approaches using both the Poisson distribution and the binomial distribution are presented below.

The general equation for the Poisson distribution probability mass function is as follows:

$$P_t(n) = \frac{(t/T)^n}{n!} e^{-t/T},$$

where $P_t(n)$ is the probability of n events in a time interval t;
n is the number of events;
t is the time interval; and
T is the event return period.

The general equation for the binomial distribution is as follows:

$$P_t(n) = \left(\frac{t!}{(t-n)!n!}\right)\left(\frac{1}{T}\right)^n \left(1-\frac{1}{T}\right)^{t-n},$$

where $P_t(n)$ is the probability of n events in a time interval t;
n is the number of events;
t is the time interval; and
T is the event return period.

Following these equations, the probability that one or more events has occurred in a time interval is 1 minus the probability that no events have occurred, resulting in:

$$P[n > 0] = 1 - e^{-\frac{t}{T}} \qquad (Poisson), \text{ and}$$

$$P[n > 0] = 1 - \left(1-\frac{1}{T}\right)^t \qquad (binomial).$$

Looking at the probability of the Dike being damaged by an earthquake at any time, this becomes:

$$P[EQ_D] = 1 - e^{-\frac{tr}{T_{EQd}}} \qquad (Poisson), \text{ and}$$

$$P[EQ_D] = 1 - \left(1-\frac{1}{T_{EQd}}\right)^{tr} \qquad (binomial),$$

where tr is a time interval equal to the rebuild time; and
T_{EQd} is the earthquake return period that damages the Dike.

If, for example, the Dike has a five-year rebuild time, the probability of the Dike being damaged at any point in time is equal to the probability that a damaging earthquake has occurred within the five years prior to that point in time. If a damaging earthquake occurred prior to that (e.g., six years previously), the Dike will have been repaired already.

Recognizing that the relevant hazard is floods that occur because the Dike has been damaged by an earthquake, only floods between the earthquake-damaged Dike failure level and the pre-damaged Dike failure level should be included (since water levels above the pre-damaged Dike failure level have resulted in flooding anyways).

The probability of a flood is then:

$$P\left[F_{EQ}\right] = P[F_1] - P[F_2],$$

where $P[F_1]$ is the probability of a flood higher than the failure level of the damaged Dike; and
$P[F_2]$ is the probability that the flood is higher than the failure level of the undamaged Dike.

Using the equation for the Poisson distribution, this becomes:

$$P\left[F_{EQ}\right] = e^{-t/T_2} - e^{-t/T_1},$$

where T_1 is the flood return period of the damaged Dike;
T_2 is the design flood return period; and
t is a time interval.

To assess the probability of flooding this becomes:

$$P\left[F_{EQ}\right] = 1 - e^{-1/T_{1-2}},$$

where $T_{1-2} = \frac{T_1 \cdot T_2}{T_2 - T_1}$, and

where T_{1-2} represents the return period of flooding between the T_1 and T_2 return periods.

Alternatively, the probability of a flood can be calculated as:

$$P\left[F_{EQ}\right] = \frac{1}{T_1} - \frac{1}{T_2}.$$

The probability of flooding can be easily changed back to a return period using the formula for the Poisson distribution or as the inverse of the probability. The resulting differences between the Poisson distribution and binomial distribution are typically very small.

Total flood hazard can be calculated by summing the seismic and non-seismic probabilities as follows:

$$P[F_{tot}] = P\left[F_{EQ}\right] + P\left[F_{non\,EQ}\right].$$

It may appear that total flood hazard can also be calculated by simply omitting the $P[F_2]$ term when calculating $P[F_{EQ}]$; however, calculations done in this way will underestimate the total flood hazard, unless the analysis includes the full range of seismic event probabilities (from 0 to 1).

3.7.3 INPUT REQUIRED FROM THE LOCAL DIKING AUTHORITY

3.7.3.1 Acceptable Level for Seismic Flood Hazard

Under the probabilistic-based approach, an acceptable level for the seismic flood hazard has not yet been defined by the Ministry Guidelines.

In the absence of a provincial standard, local diking authorities will need to establish the acceptable level for the seismic flood hazard within their jurisdiction. Local diking authorities should set these standards as part of an overall management strategy, as opposed to establishing the standard on a case-by-case or project-by-project basis. Further, any strategy developed by the local diking authority will be subject to review and acceptance by the Inspector.

3.7.3.2 Rebuild Time

In addition to establishing the acceptable level for the seismic flood hazard, the local diking authority also needs to establish the rebuild time that can be used as input into the probabilistic-based design.

Rebuild time is a component of an emergency recovery plan that must be presented to the Design Team in order for them to undertake a probabilistic-based design.

3.7.4 WORKED EXAMPLE

A worked example of the probabilistic-based design approach demonstrating Dike failure probability as a simplified step function, is provided in Appendix B: Worked Example.

Results compare seismic flood hazard to non-seismic flood hazard, and compare total flood hazard to the implied "acceptable hazard" determined from a combination of the Dike design event and the performance-based seismic deformations specified in the Ministry Guidelines.

3.8 REPORTING REQUIREMENTS

3.8.1 GENERAL DOCUMENTATION REQUIREMENTS

Engineering Professionals are required to establish and maintain documented quality management processes that include retaining complete project documentation for a minimum of ten years after the completion of a project or ten years after engineering documentation is no longer in use.

As part of project documentation for projects involving the seismic design of Dikes, Engineering Professionals should document design assumptions, selection of design soil properties, calibration procedures, and results of analyses, so that both documented checks and independent reviews can be appropriately carried out.

For more information, refer to the *Quality Management Guides – Guide to the Standard for Retention of Project Documentation* (Engineers and Geoscientists BC 2021d) and Section 4.1.4 Retention of Project Documentation of these guidelines.

3.8.2 SEISMIC DIKE REPORT DOCUMENTATION REQUIREMENTS

Documenting the design process in the Seismic Dike Report is recommended, and there are several advantages, because the information:

- will be easily accessible if questions by reviewers or regulatory agencies arise, which could add value over the long term;
- could be independently reproduced if necessary;
- can facilitate the necessary independent review process; and
- can improve insights and benefits for Engineering Professionals involved in the original design process.

Engineering Professionals should include the following information in a Seismic Dike Report:

- Project location and background information.
- Design or assessment approach in relation to the Ministry Guidelines and these guidelines.
- Methodology used for calculating the design surface peak ground acceleration.
- Background information, including historical data such as air photos; data on buried/abandoned streams/channels in the general area, surficial geology, and available Liquefaction Susceptibility; landslide and flood hazard maps; previous geotechnical reports and geotechnical investigations; and record drawings.
- Underground and surface utilities and infrastructure that could impact the mechanical and hydraulic behaviour of the Dike.
- Documentation of any cracks or other signs of disturbance including animal burrows.
- Dike design surface geometry and presence of surface armouring material, if it is different from the body of Dike material. The presence of a water collection system or ditch on the landside should also be documented.
- Documentation of the design water levels for the site, and the methodology employed to obtain these values.
- Drillhole type and location.
- Description of material zones, strength, and stiffness characteristics of the Dike and foundation materials including:
  - fines contents, adjusted SPT N60 or Qt design values;
  - angle of internal friction, cohesion, total and submerged unit weights;
  - small-strain shear moduli and damping ratio profiles;
  - peak undrained shear strength and post-Liquefaction residual shear strength of soils;
  - hydraulic conductivity values; and
  - estimated over-consolidation stress.
- Documentation of the methodology employed to conduct the Liquefaction Potential assessment.
- Summary of the selection of appropriate shaking levels and representative earthquake magnitudes for Liquefaction analysis for each of the three return periods for simplified analysis.
- Documentation of the selection of the static and post-seismic design soil shear strengths.
- Results of limit equilibrium analyses or continuum-based numerical models.
- A summary of displacement levels for different seismic return periods including post-Liquefaction settlements.

If a probabilistic-based assessment or design is undertaken, as per Section 3.7 of these guidelines, additional documentation should be prepared for that work including, but not limited to, the following:

- Design water elevations from hydrotechnical studies
- Seismic hazard up to the return period of interest
- A discussion on the failure modes considered
- Uncertainties in in the probabilistic estimates of Dike damage, including identification of what additional data and analyses would be required to reduce these uncertainties

The Seismic Dike Report should include a section that documents the independent reviewer's comments and how those comments were addressed and incorporated (see Section 4.1.8 Documented Independent Review of High-Risk Professional Activities or Work). This section should also include the name of the reviewing Engineering Professional, and may include a copy of the reviewer's letter or report; alternatively, the reviewer's letter or report may be retained on file with the project documentation and the findings summarized in the Seismic Dike Report.

4.0 QUALITY MANAGEMENT IN PROFESSIONAL PRACTICE

4.1 ENGINEERS AND GEOSCIENTISTS BC QUALITY MANAGEMENT REQUIREMENTS

Engineering Professionals must adhere to applicable quality management requirements during all phases of the work, in accordance with the Engineers and Geoscientists BC Bylaws and quality management standards.

To meet the intent of the quality management requirements, Engineering Professionals must establish, maintain, and follow documented quality management policies and procedures for the following activities:

- Use of relevant professional practice guidelines
- Authentication of professional Documents by application of the professional seal
- Direct supervision of delegated professional engineering activities
- Retention of complete project documentation
- Regular, documented checks using a written quality control process
- Documented field reviews of engineering designs and/or recommendations during implementation or construction
- Where applicable, documented independent review of structural designs prior to construction
- Where applicable, documented independent review of high-risk professional activities or work prior to implementation or construction

Engineering Professionals employed by a Registrant firm are required to follow the quality management policies and procedures implemented by the Registrant firm as per the Engineers and Geoscientists BC's permit to practice program.

4.1.1 USE OF PROFESSIONAL PRACTICE GUIDELINES

Engineering Professionals are required to comply with the intent of any applicable professional practice guidelines related to the engineering work they undertake. As such, Engineering Professionals must implement and follow documented procedures to ensure they stay informed of, knowledgeable about, and meet the intent of professional practice guidelines that are relevant to their professional activities or services. These procedures should include periodic checks of the Engineers and Geoscientists BC website to ensure that the latest versions of available guidance is being used.

For more information, refer to the *Quality Management Guides – Guide to the Standard for the Use of Professional Practice Guidelines* (Engineers and Geoscientists BC 2021a), which also contains guidance for how an Engineering Professional can appropriately depart from the guidance provided in professional practice guidelines.

4.1.2 AUTHENTICATING DOCUMENTS

Engineering Professionals are required to authenticate (seal with signature and date) all Documents, including electronic files, that they prepare or deliver in their professional capacity to others who will rely on the information contained in them. This applies to Documents that Engineering Professionals have personally prepared and those that others have prepared under their direct supervision. In addition, any Document that is authenticated by an individual Engineering Professional must also have a permit to practice number visibly applied to the Document. A permit to practice number is a unique number that a Registrant firm receives when they obtain a permit to practice engineering or geoscience in BC.

Failure to appropriately authenticate and apply the permit to practice number to Documents is a breach of the Bylaws.

For more information, refer to the *Quality Management Guides – Guide to the Standard for the Authentication of Documents* (Engineers and Geoscientists BC 2021b).

4.1.3 DIRECT SUPERVISION

Engineering Professionals are required to directly supervise any engineering work they delegate. When working under the direct supervision of an Engineering Professional, an individual may assist in performing engineering work, but they may not assume responsibility for it. Engineering Professionals who are professional licensees engineering may only directly supervise work within the scope of their licence.

When determining which aspects of the work may be delegated using the principle of direct supervision, the Engineering Professional having ultimate responsibility for that work should consider:

- the complexity of the project and the nature of the risks associated with the work;
- the training and experience of individuals to whom the work is delegated; and
- the amount of instruction, supervision, and review required.

Careful consideration must be given to delegating field reviews. Due to the complex nature of field reviews, Engineering Professionals with overall responsibility should exercise judgment when relying on delegated field observations and should conduct a sufficient level of review to have confidence in the quality and accuracy of the field observations. When delegating field review activities, Engineering Professionals must document the field review instructions given to a subordinate. (See Section 4.1.6 Documented Field Reviews During Implementation or Construction.)

For more information, refer to the *Quality Management Guides – Guide to the Standard for Direct Supervision* (Engineers and Geoscientists BC 2021c).

4.1.4 RETENTION OF PROJECT DOCUMENTATION

Engineering Professionals are required to establish and maintain documented quality management processes to retain complete project documentation for a minimum of ten (10) years after the completion of a project or ten (10) years after an engineering Document is no longer in use.

These obligations apply to Engineering Professionals in all sectors. Project documentation in this context includes documentation related to any ongoing engineering work, which may not have a discrete start and end, and may occur in any sector.

Many Engineering Professionals are employed by firms, which ultimately own the project documentation. Engineering Professionals are considered compliant with this quality management requirement when reasonable steps are taken to confirm that (1) a complete set of project documentation is retained by the organizations that employ them, using means and methods consistent with the Engineers and Geoscientists BC Bylaws and quality management standards; and (2) they consistently adhere to the documented policies and procedures of their organizations while employed there.

For more information, refer to the *Quality Management Guides – Guide to the Standard for Retention of Project Documentation* (Engineers and Geoscientists BC 2021d).

4.1.5 DOCUMENTED CHECKS OF ENGINEERING AND GEOSCIENCE WORK

Engineering Professionals are required to perform a documented quality checking process of engineering work, appropriate to the risk associated with that work. All Engineering Professionals must meet this quality management requirement.

The checking process should be comprehensive and address all stages of the execution of the engineering work. This process would normally involve an internal check by another Engineering Professional within the same organization. Where an appropriate internal checker is not available, an external checker (i.e., one outside the organization) must be engaged. In some instances, self-checking may be appropriate. Where internal, external, or self-checking has been carried out, the details of the check must be documented. The documented quality checking process must include checks of all professional deliverables before being finalized and delivered.

Engineering Professionals are responsible for ensuring that the checks being performed are appropriate to the level of risk associated with the item being checked. Considerations for the level of checking should include:

- the type of item being checked;
- the complexity of the subject matter and underlying conditions related to the item;
- the quality and reliability of associated background information, field data, and elements at risk; and
- the Engineering Professional's training and experience.

As determined by the Engineering Professional, the individual doing the checking must have current expertise in the discipline of the type of work being checked, be sufficiently experienced and have the required knowledge to identify the elements to be checked, be objective and diligent in recording observations, and understand the checking process and input requirements.

For more information, refer to the *Quality Management Guides – Guide to the Standard for Documented Checks of Engineering and Geoscience Work* (Engineers and Geoscientists BC 2021e).

4.1.6 DOCUMENTED FIELD REVIEWS DURING IMPLEMENTATION OR CONSTRUCTION

Field reviews are reviews conducted at the site of the construction or implementation of the engineering work. They are carried out by an Engineering Professional or a subordinate acting under the Engineering Professional's direct supervision (see Section 4.1.3 Direct Supervision).

Field reviews enable the Engineering Professional to ascertain whether the construction or implementation of the work substantially complies in all material respects with the engineering concepts or intent reflected in the engineering Documents prepared for the work.

For more information, refer to the *Quality Management Guides – Guide to the Standard for Documented Field Reviews During Implementation or Construction* (Engineers and Geoscientists BC 2021f).

4.1.7 DOCUMENTED INDEPENDENT REVIEW OF STRUCTURAL DESIGNS

Engineering Professionals developing structural designs are required to engage an independent review of their structural designs. An independent review is a documented evaluation of the structural design concept, details, and documentation based on a qualitative examination of the substantially complete structural design Documents, which occurs before those Documents are issued for construction or implementation. It is carried out by an experienced Engineering Professional qualified to practice structural engineering, who has not been involved in preparing the design.

The Professional of Record must conduct a risk assessment after conceptual design and before detailed design to (1) determine the appropriate frequency of the independent review(s); and (2) determine if it is appropriate for the independent reviewer to be employed by the same firm as the Professional of Record, or if the independent reviewer should be employed by a different firm.

The risk assessment may determine that staged reviews are appropriate; however, the final independent review must be completed after checking has been completed and before the Documents are issued for construction or implementation. Construction must not proceed on any portion of the structure until an independent review of that portion has been completed.

For more information, refer to the *Quality Management Guides – Guide to the Standard for Documented Independent Review of Structural Designs* (Engineers and Geoscientists BC 2021g).

4.1.8 DOCUMENTED INDEPENDENT REVIEW OF HIGH-RISK PROFESSIONAL ACTIVITIES OR WORK

Engineering Professionals must perform a documented risk assessment prior to initiation of a professional activity or work to determine if that activity or work is high risk and therefore requires a documented independent review.

If the activities or work are deemed high risk, and an independent review is required, the results of the risk assessment must be used to (1) determine the appropriate frequency of the independent review(s); and (2) determine if it is appropriate for the independent reviewer to be employed by the same firm as the Professional of Record, or if the independent reviewer should be employed by a different firm.

The documented independent review of high-risk professional activities or work must be carried out by an Engineering Professional with appropriate experience in the type and scale of the activity or work being reviewed, who has not been involved in preparing the design.

The documented independent review must occur prior to implementation or construction; that is, before the professional activity or work is submitted to those who will be relying on it.

For seismic assessment and seismic design of Dikes in BC, as described in these guidelines, both the performance-based analysis and the probabilistic-based analysis require independent review as per the standard, and both must be a Type 2 independent review, where the independent reviewer must be from outside of the firm undertaking the design.

For more information, refer to the *Quality Management Guides – Guide to the Standard for Documented Independent Review of High-Risk Activities or Work* (Engineers and Geoscientists BC 2021h).

4.2 OTHER QUALITY MANAGEMENT REQUIREMENTS

Engineering Professionals must also be aware of any additional quality management requirements from other sources that are relevant to their work, which may include but are not limited to:

- legislation and regulations at the local, regional, provincial, and federal levels;
- policies of authorities having jurisdiction at the local, regional, provincial, and federal levels;
- agreements and service contracts between clients and Engineering Professionals or their firms; and/or
- standards for engineering firms, particularly those that apply to quality management system certification, such as the ISO 9000 family.

Engineering Professionals should assess any areas of overlap between the Engineers and Geoscientists BC quality management requirements and the requirements of other applicable sources. If the requirements of different sources overlap, Engineering

Professionals should attempt to meet the complete intent of all requirements.

Where there are conflicts between requirements, Engineering Professionals should negotiate changes or waivers to any contractual or organizational requirements which may conflict with requirements of legislation, regulation, or the Engineers and Geoscientists BC Code of Ethics. Generally, no contractual obligation or organizational policy that may apply to an Engineering Professional will provide justification or excuse for breach of any of the Engineering Professional's obligations under any legislation, regulation, or the Engineers and Geoscientists BC Code of Ethics. Where such conflicts arise and cannot be resolved, Engineering Professionals should consider seeking legal advice from their own legal advisers on their legal rights and obligations in the circumstances of the conflict, and they may also seek practice advice from Engineering and Geoscientists BC on any related ethical dilemma that they may face in the circumstances.

4.3 PRACTICE ADVICE

Engineers and Geoscientists BC provides their Registrants and others with assistance addressing inquiries related to professional practice and ethics.

Practice advisors at Engineers and Geoscientists BC can answer questions regarding the intent or application of the professional practice or quality management aspects of these practice guidelines.

To contact a practice advisor, email Engineers and Geoscientists BC at practiceadvisor@egbc.ca.

5.0 PROFESSIONAL REGISTRATION & EDUCATION, TRAINING, AND EXPERIENCE

5.1 PROFESSIONAL REGISTRATION

Engineering Professionals have met minimum education, experience, and character requirements for admission to their profession. However, the educational and experience requirements for professional registration do not necessarily constitute an adequate combination of education and experience for performing seismic assessment and seismic design of Dikes in British Columbia (BC). Professional registration alone does not automatically qualify an Engineering Professional to take professional responsibility for all types and levels of professional services in this area of practice.

It is the responsibility of Engineering Professionals to determine whether they are qualified by training and/or experience to undertake and accept responsibility for carrying out seismic assessment and seismic design of Dikes (Code of Ethics Principle 2).

5.2 EDUCATION, TRAINING, AND EXPERIENCE

Seismic assessment and seismic design of Dikes requires minimum levels of education, training, and experience in many overlapping areas of engineering.

Engineering Professionals who take responsibility for seismic assessment and seismic design of Dikes must adhere to the second principle of the Engineers and Geoscientists BC Code of Ethics, which is to "practice only in those fields where training and ability make the registrant professionally competent" and, therefore, must evaluate their own qualifications and must possess the appropriate education, training, and experience to provide the services.

The level of education, training, and experience required of Engineering Professionals should be adequate for the complexity of the project. This section describes indicators that Engineering Professionals can use to determine whether they have an appropriate combination of education and experience.

Note that these indicators are not an exhaustive list of education and experience types that are relevant to seismic assessment and seismic design of Dikes in BC. Satisfying one or more of these indicators does not automatically indicate adequate competence in seismic assessment and seismic design of Dikes in BC.

5.2.1 EDUCATIONAL INDICATORS

Certain indicators show that Engineering Professionals have received education that might qualify them to participate professionally in seismic assessment and seismic design of Dikes in BC. Educational indicators are subdivided into formal education (such as university or engineering school) and informal education (such as continuing professional development).

Formal educational indicators include having obtained or completed one or more of the following:

- An undergraduate-level degree in civil engineering or a related engineering field from an accredited engineering program
- A graduate-level degree specializing in geotechnical engineering, seismic engineering, coastal engineering, or hydrotechnical engineering from an accredited engineering program

Informal educational indicators include having participated in or undertaken one or more of the following:

- Training courses and/or mentorship facilitated by the Engineering Professional's employer that focus on seismic assessment and seismic design of Dikes
- Continuing education courses or sessions offered by professional organizations (such as Engineers and Geoscientists BC) that focus on geotechnical engineering, seismic engineering, coastal engineering, and hydrotechnical engineering
- Conferences or industry events that focus on topics related to seismic aspects of Dike design
- A rigorous and documented self-study program involving a structured approach that contains materials from textbooks and technical papers on seismic assessment and seismic design of Dikes

5.2.2 EXPERIENCE INDICATORS

Certain indicators show that Engineering Professionals have an appropriate combination of experience that might qualify them to participate professionally in seismic assessment and seismic design of Dikes in BC.

Experience indicators include having completed one or more of the following:

- For an extended duration (greater than one year) and/or as an Engineering-in-Training (EIT), participated in seismic assessment and seismic design of Dikes under the direct supervision of an Engineering Professional with an appropriate combination of education and experience
- Participated in past projects working alongside Engineering Professionals with an appropriate combination of education and experience, and developed a sufficient knowledge of the various aspects of seismic assessment and seismic design of Dikes
- Demonstrated experience working on seismic Dike projects
- Participated in academic or industry working groups that focus on topics related to seismic assessment and seismic design of Dikes

Specific areas of knowledge applicable to seismic Dike design include the following:

- Principles of seismic design
- 1-D and 2-D ground response analyses and groundwater flow modelling
- Fluvial geomorphology, watershed hydrology, and groundwater geology
- Basics of soil mechanics
- Probability concepts in engineering
- Understanding of the effects of climate change on watersheds
- Environmental requirements for design
- Risk analysis
- Cost-benefit analyses

If a Professional of Record intends to complete a probabilistic-based design of Dikes, as outlined in Section 3.7 Probabilistic-Based Design of these guidelines, in addition to the above, experience indicators for this type of work include the following:

- Five years of related experience in design, construction, and/or performance evaluation of Dikes
- Previous involvement in at least three projects utilizing probabilistic-based seismic design for Dikes, either as a Professional of Record or working under the direct supervision of another Professional of Record
- Previous experience undertaking hazard and risk assessments for floods, geohazards, and seismic hazards

6.0 REFERENCES AND RELATED DOCUMENTS

Documents cited in the main guidelines appear in Section 6.1 Legislation, Section 6.2 References, and Section 6.3 Codes and Standards.

Related documents that may be of interest to users of these guidelines but are not formally cited elsewhere in this document appear in Section 6.4 Related Documents.

6.1 LEGISLATION

The following legislation is referenced in these guidelines:

Dike Maintenance Act [RSBC 1996], Chapter 95.

Drainage, Ditch and Dike Act [RSBC 1996], Chapter 102.

Professional Governance Act [SBC 2018], Chapter 47.

6.2 REFERENCES

The following documents are referenced in these guidelines:

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6.3 CODES AND STANDARDS

The following codes and standards are referenced in these guidelines.

ASTM D1586, Standard Test Method for Penetration Test and Split-Barrel Sampling of Soils.

National Building Code of Canada (NBC).

6.4 RELATED DOCUMENTS

The following references are provided for information:

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7.0 APPENDICES

APPENDIX A: AUTHORS AND REVIEWERS

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APPENDIX B: WORKED EXAMPLE

B1 SEISMIC FLOOD HAZARD: SIMPLE CASE STUDY AND WORKED EXAMPLE

The following case study and worked example present the results of a "strategic-level" seismic flood hazard assessment completed for a coastal Dike protecting a community in British Columbia (BC). This analysis follows the methodology presented in Section 3.7.2 Seismic Flood Hazard Assessment of these guidelines.

The work presented here focuses on developing a framework for analysis rather than applying that framework to specific hazard mitigation decisions.

B1.1 PROBLEM STATEMENT

A coastal Dike owned by a local government was recently raised to a crest elevation of 4.7 m geodetic in anticipation of sea-level rise. Hydraulic design criteria were governed by future coastal flood levels, but no analysis of wave effects or overtopping was available. (Consideration of ground subsidence has been omitted from this example for simplicity.)

The Engineering Professional previously completed a performance-based assessment of the Dike, as required by Section 3.6 Performance-Based Design of these guidelines. The performance-based assessment confirmed that the Dike did not meet the allowable seismic deformation criteria specified in the *Seismic Design Guidelines for Dikes, 2nd Edition*, published by the Ministry of Forests, Lands, Natural Resource Operations and Rural Development (MFLNRORD), referred to here as the "Ministry Guidelines" (MFLNRORD 2014).

The Engineering Professional also previously prepared a Class D construction cost estimate for the ground improvement that would be needed for the Dike to meet the Ministry Guidelines. The cost estimate confirmed the Dike owner's expectation that implementing ground improvement would severely limit and delay their plans to further raise the Dike in response to climate change.

The Dike owner, who is the client, does not clearly understand seismic flood hazard and wants to consider the costs and benefits of alternatives to ground improvement. Therefore, the Dike owner has asked the Engineering Professional to help develop a strategic approach for assessing and mitigating seismic flood hazards. The Dike owner has confirmed that a post-seismic recovery and reconstruction plan has not been developed (i.e., a rebuild time has not yet been identified).

B1.2 BASIS OF ASSESSMENT

As a starting point, the Engineering Professional confirms the client's need for a high-level analysis that can:

- provide baseline information to help the client understand its seismic flood hazard;
- support the client's consideration of alternative mitigation concepts that could efficiently reduce the community's overall flood hazard (for example, by demonstrating how different concepts could achieve a comparable level of protection); and
- inform the development of a recovery and reconstruction plan (particularly rebuild times for a damaged Dike).

The analysis is intended to support strategic discussions and would eventually need to be applied at multiple locations for comparison and prioritization. The Engineering Professional concludes that a simplified approach is appropriate for this project.

B1.3 DIKE DEFORMATION ANALYSIS

Sufficient geotechnical data were available to inform a numerical analysis of Dike deformation under seismic loading at various return periods. This work was previously completed as part of the performance-based assessment required by Section 3.6 Performance-Based Design of these guidelines.

The predicted vertical seismic displacements for the Dike are shown in Figure B - 1. The return period axis is shown at a logarithmic scale because displacements between the analyzed points are interpolated assuming a log-linear relationship with the earthquake return period.

The Engineering Professional recognizes that there is considerable uncertainty in these deformation estimates, but is satisfied that using expected values to characterize deformation is sufficient to meet the client's strategic objectives for this project.

B1.4 FLOOD LEVELS

Still-water elevations for various coastal flood return periods at the Dike location are presented in Figure B - 2. The relationship between flood elevation and return period is also interpolated as log-linear. Values in the table are geodetic elevations that account for storm surge and 1 m of sea-level rise, but do not include wind setup or wave effects. Extrapolated flood levels are limited to the 500-year return period to respect uncertainty arising from the limited period of record.

B1.5 DIKE FAILURE MODEL

As is typically the case in BC, the Engineering Professional does not have enough information to apply a fragility curve to represent the probability of Dike failure; instead, appropriate simplifying assumption(s) must be adopted.

Representing the probability of Dike failure as a step-function is considered reasonable for this analysis. The step-function assumes that:

- the Dike will survive any event where still-water flood levels are less than a designated "failure elevation" (i.e., 0% probability of failure); and
- the Dike will fail in any event where still-water flood levels meet or exceed the designated failure elevation (i.e., 100% probability of failure).

The Engineering Professional recognizes that most coastal Dikes will fail before the still-water level reaches the Dike crest. For this strategic analysis, the Engineering Professional assumes a failure level equal to the 500-year return period still-water flood elevation of 3.77 m for the undamaged Dike. Freeboard at failure (i.e., the difference between the 4.7 m Dike crest and the 3.77 m still-water level assumed to initiate failure) is therefore 0.93 m.

After an earthquake, the deformed Dike may have a cracked and disturbed cross-section that is less reliable than the undamaged Dike. The Engineering Professional considers the need for a more conservative failure assumption in the post-seismic analysis, but decides that using the pre-seismic assumption of 0.93 m freeboard at failure will be sufficient for this strategic analysis.

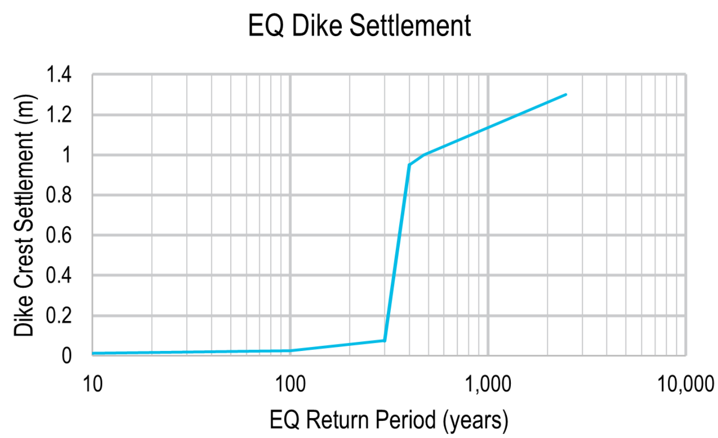
As a result, the failure level of the deformed Dike can be calculated by subtracting the amount of deformation from the failure level of the undamaged Dike, with no additional allowance for changes in reliability. For example, a 475-year return period earthquake (causing a 1.00 m vertical deformation) would reduce the failure level of the damaged Dike by 1 m, from its original value of 3.77 m to a new value of 2.77 m.

Figure B - 1: Predicted Vertical Seismic Displacements

(A)

EQ DAMAGE/DEFORMATION	
RETURN PERIOD (years)	SETTLEMENT (m)
1	0
100	0.025
300	0.075
400	0.95
475	1.00
2,475	1.30

(B)



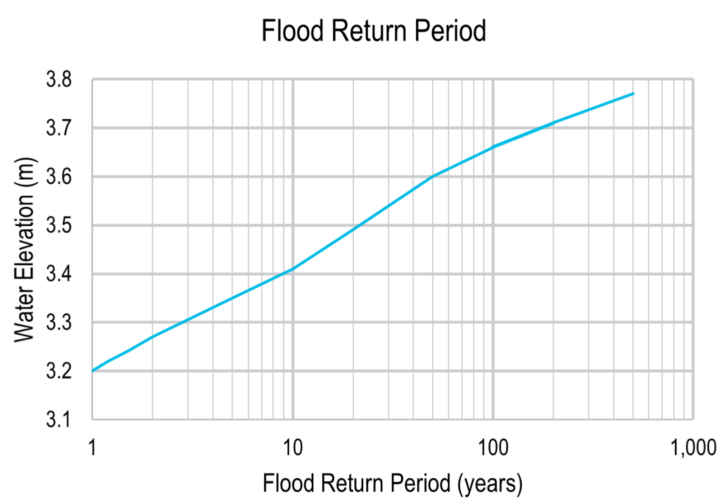
NOTE: Abbreviations: EQ = earthquake; m = metre(s)

Figure B - 2: Still-Water Elevations for Coastal Flood Return Periods

(A)

FLOOD ELEVATIONS	
RETURN PERIOD (years)	ELEVATIONS (m)
1	3.20
1.2	3.22
1.5	3.24
2	3.27
5	3.35
10	3.41
20	3.49
50	3.60
100	3.66
200	3.71
500	3.77

(B)



NOTE: Abbreviation: m = metre(s)

B1.6 SEISMIC FLOOD HAZARD PROBABILITY CALCULATIONS

As discussed in these guidelines, the probability of flooding due to an earthquake-damaged Dike (the seismic flood hazard) is equal to the probability that a flood higher than the failure level of the earthquake-damaged Dike will occur, multiplied by the probability that the Dike has been damaged, since earthquakes and floods are independent events. The equation is written as:

$$P[F, EQ] = P[F_{EQ}] \cdot P[EQ_D] \qquad [1]$$

where $P[F, EQ]$ is the probability of flooding due to failure of an earthquake-damaged Dike;
$P[F_{EQ}]$ is the probability of a flood higher than the failure level of the earthquake-damaged Dike; and
$P[EQ_D]$ is the probability that the Dike has been damaged by an earthquake.

For this worked example, the probability that the Dike has been damaged by an earthquake ($P[EQ_D]$) has been calculated in increments of earthquake return period. This allows the shapes of the relationships between earthquake return period and Dike crest settlement, and between flood return period and flood elevation, to be accurately captured.

The Engineering Professional selects the Poisson distribution to represent the seismic Dike deformation hazard. Recognizing that a complete set of frequent coastal flood probabilities is not available (e.g., Figure B - 2 (A)) does not include events with return period <1 year), the Engineering Professional selects the binomial distribution to approximate the flood hazard.

The probability of the Dike being damaged by an earthquake is calculated as follows:

$$P[EQ_D] = 1 - e^{-\frac{tr}{T_{EQd}}} \qquad [2]$$

where tr is a time interval equal to the rebuild time; and
T_{EQd} is the earthquake return period that damages the Dike.

The relevant hazard is floods that occur only because the Dike has been damaged by an earthquake (and would have been prevented if the Dike were not damaged). Accordingly, the probability of a seismic flood is then:

$$P[F_{EQ}] = P[F_n] - P[F_{design}] \qquad [3]$$

where $P[F_n]$ is the probability of a flood higher than the failure level of the damaged Dike (i.e., in an EQ damaging return period interval); and
$P[F_{design}]$ is the probability that the flood is higher than the failure level of the undamaged Dike.

The probability of a flood for the return period interval that causes Dike settlement using the return period is calculated as:

$$P[F_{EQ}] = \frac{1}{T_n} - \frac{1}{T_{design}} \qquad [4]$$

Rebuild time will usually vary with the extent of damage to a Dike System, and is therefore typically a function of EQ intensity. However, another key goal of this analysis is to help the client understand the effect of rebuild time on seismic flood hazard. Therefore, the Engineering Professional decides to treat rebuild time as constant for all EQ intensities, but provide separate calculations of $P[F, EQ]$ for rebuild times from 1 year to 10 years.

Table B - 1 summarizes the seismic hazard calculation for a rebuild time of 2 years.

Columns A, B, and C are the calculation of the failure elevation for the deformed Dike. Columns A and B are from Figure B - 1(A). Column C is the water level at failure (the "failure level") for the deformed Dike based on the assumptions described above.

Columns D, E, and F calculate the incremental probability that the Dike has been damaged in each of these earthquake return period intervals using equation 2. As noted, rebuild time usually depends on the amount of deformation, but it is assumed here at 2 years for all damage levels to inform the client's understanding of the relationship between rebuild time and seismic flood hazard.

Columns G and H calculate the probability of a flood exceeding the failure level of the damaged Dike, but not exceeding the failure level of the undamaged Dike (i.e., using equation 4). The flood return periods in column G are log-linear interpolations from Figure B - 2(A) Still-Water Elevations for Coastal Flood Return Periods that correspond to the Dike failure elevations in column C.

Column I calculates the probability of flooding due to an earthquake damaging a Dike (i.e., $P[F, EQ]$) for each earthquake return period interval using equation 1. The seismic flood hazard (in this case, for a constant 2-year rebuild time) is the sum of these probabilities. For the example, calculation for the seismic flood hazard is 0.5% annual exceedance probability (AEP), which corresponds to a return period of 200 years.

This example uses 7 analysis intervals for the purpose of clearer presentation. A more detailed analysis using 200 intervals yielded a seismic flood hazard return period of 1 in 170 years (i.e., an AEP of 0.6%).

Table B - 1: Seismic Hazard Calculation for a Rebuild Time of 2 Years

A	B	C	D	E	F	G	H	I
EQ DIKE DAMAGE			[P] OF EQ DAMAGED DIKE			[P] FLOOD-DAMAGED DIKE		
RETURN PERIOD (years)	SETTLEMENT (m)	WL AT FAILURE (m)	REBUILD TIME (years)	P[EQd] (total)	P[EQd] (increment)	RETURN PERIOD (years)	P[Feq]	P[F, EQ]
0	0.000	3.77	2	1.000	0.135	500.0	0.000	0.00%
1	0.000	3.77	2	0.865	0.845	500.0	0.000	0.00%
100	0.025	3.75	2	0.020	0.013	341.3	0.001	0.00%
300	0.075	3.70	2	0.007	0.002	162.5	0.004	0.00%
400	0.950	2.82	2	0.005	0.001	1.0	0.998	0.08%
475	1.000	2.77	2	0.004	0.003	1.0	0.998	0.34%
2,475	1.300	2.47	2	0.001	0.001	1.0	0.998	0.08%

NOTE:
Abbreviations: m = metre(s); WL = water level

B1.7 CONSIDERATION OF ALTERNATIVE REBUILD TIMES

Because the client has not yet defined a rebuild time, the Engineering Professional repeats the above calculations for constant rebuild times from 1 year to 10 years. The process follows the approach outlined in Table B - 1, with the substitution of rebuild time in Column D. The results obtained are shown in Table B - 2. All calculations use seven analysis intervals for consistency.

Table B - 2: Rebuild Times from 1 Year to 10 Years

REBUILD TIME	SEISMIC FLOOD HAZARD	
(years)	AEP	RP (years)
1	0.25%	400
2	0.50%	200
3	0.75%	134
4	1.00%	100
5	1.24%	80
6	1.49%	67
7	1.74%	58
8	1.98%	50
9	2.23%	45
10	2.47%	40

NOTE:
Abbreviations: AEP = annual exceedance probability;
RP = return period

B1.8 COMPARISON OF SEISMIC AND TRADITIONAL (NON-SEISMIC) FLOOD HAZARDS

The calculations of seismic flood hazard probability presented above specifically exclude the possibility of Dike failure in the absence of a seismic event. However, this "non-seismic" hazard has historically been the exclusive focus of most Dike owners. Because this traditional (non-seismic) hazard assumes an undamaged Dike, it does not change based on an assumed rebuild time.

To illustrate the relative importance of seismic flood hazard, as well as the dependence of seismic flood hazard on rebuild time, the Engineering Professional plots seismic flood hazard (from Table B - 2) and traditional (non-seismic) flood hazard against rebuild time as shown in Figure B - 3: Seismic Flood Hazard and Dike Rebuild Time. The traditional (non-seismic) flood hazard is shown as a blue line in the graph and reflects the assumed failure level (500-year return period still-water level, or 0.2% AEP) for the undamaged Dike.

Showing these results with AEP on the vertical axis makes it clear that the seismic flood hazard is greater (higher) than the non-seismic flood hazard for all potential rebuild times, potentially by up to an order of magnitude. Allowing for reduced reliability of the deformed Dike would further increase the seismic flood hazard.

These results confirm that seismic flood hazard should be a priority consideration for the Dike owner. They also clearly show the importance of an expedited recovery and reconstruction plan that prioritizes repair to a damaged Dike.

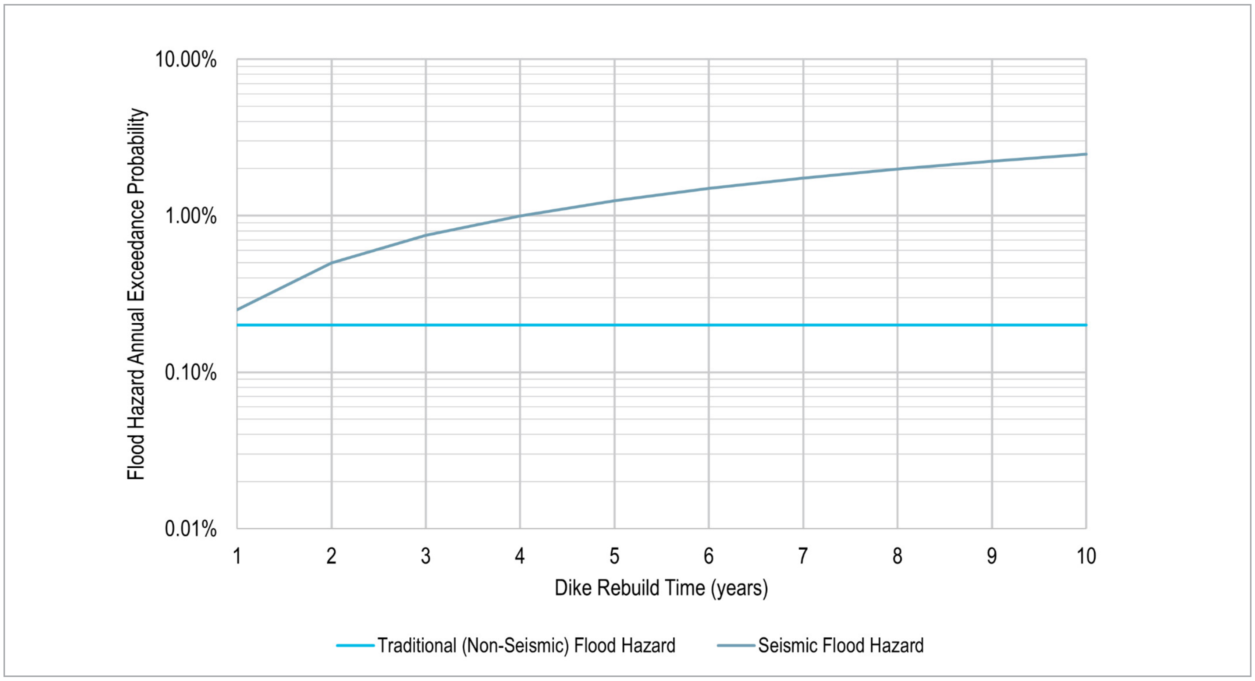


Figure B - 3: Seismic Flood Hazard and Dike Rebuild Time

Table B - 3: Total Flood Hazard

REBUILD TIME		SEISMIC FLOOD HAZARD		NON-SEISMIC FLOOD HAZARD		TOTAL FLOOD HAZARD
(years)	AEP	RP (years)	AEP	RP (years)	AEP	RP (years)
1	0.25%	400	0.20%	500	0.45%	222
2	0.50%	200	0.20%	500	0.70%	143
3	0.75%	134	0.20%	500	0.95%	105
4	1.00%	100	0.20%	500	1.20%	84
5	1.24%	80	0.20%	500	1.44%	69
6	1.49%	67	0.20%	500	1.69%	59
7	1.74%	58	0.20%	500	1.94%	52
8	1.98%	50	0.20%	500	2.18%	46
9	2.23%	45	0.20%	500	2.43%	41
10	2.47%	40	0.20%	500	2.67%	37

NOTE: Abbreviations: AEP = annual exceedance probability; RP = return period

B1.9 CALCULATING TOTAL FLOOD HAZARD

The Engineering Professional calculates the total flood hazard by adding the probabilities of the seismic and traditional (non-seismic) flood hazards at each rebuild time. The results are shown in Table B - 3.

These results demonstrate how quantifying seismic flood hazard can substantially change a Dike owner's perception of total flood hazard. Even for the shortest Dike rebuild time of 1 year, the actual level of protection provided by the Dike (estimated as 0.45% AEP, or 222-year return period) is much less than the previously understood 1-in-500-year return period (0.2% AEP). With a longer rebuild time, the community's total flood hazard would be almost entirely attributable to seismic flood hazard.

B1.10 DEFINING "ACCEPTABLE" TOTAL FLOOD HAZARD

To help the Dike owner apply resources efficiently, the Engineering Professional must be able to define the point at which the total flood hazard is reduced to a level that provides an adequate margin of safety based on the known site conditions and accepted best practices in Dike assessment and design. The community has not previously considered seismic flood hazard, has not adopted a policy defining an "acceptable" level of total flood hazard, and lacks the resources to undertake a detailed quantitative risk assessment.

In the absence of locally-defined hazard acceptance criteria, the Engineering Professional applies the procedure shown in Table B - 1: Seismic Hazard Calculation for a Rebuild Time of 2 Years to calculate an "implied" acceptable total flood hazard for a coastal Dike that is designed to:

- withstand the 500-year return period water level in the absence of a seismic event; and
- meet the performance-based seismic deformation criteria provided in the Ministry Guidelines (Figure B - 4(A)).

This calculation effectively converts the performance-based deformation criteria from the Ministry Guidelines into a seismic flood hazard, then combines that result with the community's previously-accepted non-seismic flood hazard.

In this hypothetical situation, if a Dike were designed to withstand the 500-year flood and meet the Ministry Guidelines, it would satisfy all applicable provincial and local guidelines. It is therefore "implied" that the resultant total flood hazard would be acceptable.

The Engineering Professional recognizes that the community may ultimately choose to adopt a more conservative level of acceptable hazard, and presents this concept to the Dike owner as an upper limit on acceptable flood hazard rather than a recommended value.

Table B - 4: Calculation of the Acceptable Total Flood Hazard shows the calculation of the acceptable total flood hazard obtained by combining the design event with seismic deformations from the Ministry Guidelines. Calculations are shown for a constant 2-year rebuild time.

Columns A, D, E, and F in Table B - 4 (shown in grey) are unchanged from Table B - 1: Seismic Hazard Calculation for a Rebuild Time of 2 Years, since they reflect the same *EQ* return periods and rebuild time. Column B (shown in bold) reflects Dike deformations interpolated from the Ministry Guidelines. Columns C, G, H, and I are updated based on the new values in Column B following the approach explained for Table B - 1. The seismic flood hazard (sum of column I) for a constant rebuild time of 2 years is approximately 0.05% AEP, which corresponds to a return period of about 1 in 2,000 years.

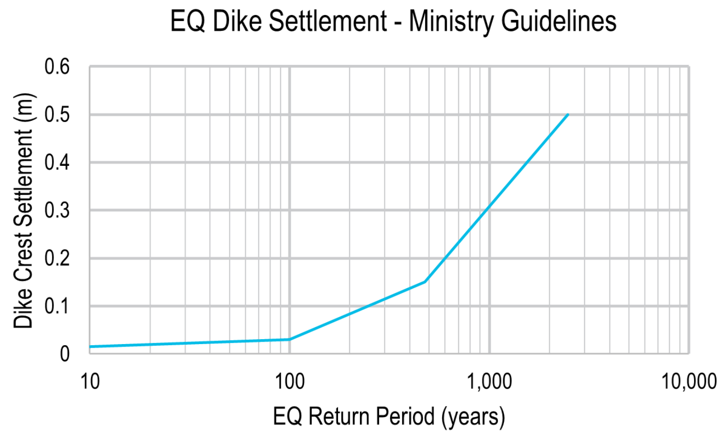
The "implied" acceptable total flood hazard for other rebuild times from 1 year to 10 years are obtained by repeating the calculation. Results are shown in Table B - 5: Acceptable Total Flood Hazard and Figure B - 5: Accepted and Implied Total Flood Hazard.

Figure B - 4: Performance-Based Seismic Deformation Criteria (A) and Earthquake Dike Settlement (B) According to the Ministry Guidelines

(A)

EQ DAMAGE/DEFORMATION (PER MINISTRY GUIDELINES [a])	
RETURN PERIOD	SETTLEMENT
(years)	(m)
1	0
100	0.03
475	0.15
2,475	0.50

(B)



NOTE: Abbreviations: EQ = earthquake; m = metre(s)

[a] See BC MFLNRORD 2014.

Table B - 4: Calculation of the Acceptable Total Flood Hazard

A	B	C	D	E	F	G	H	I
EQ DIKE DAMAGE [a]			[P] OF EQ DAMAGED DIKE [a]			[P] FLOOD-DAMAGED DIKE		
RETURN PERIOD	SETTLEMENT	WL AT FAILURE	REBUILD TIME	P[EQd]		RETURN PERIOD	P[Feq]	P[F, EQ]
(years)	(m)	(m)	(years)	(total)	(increment)	(years)		
0	**0.000**	3.77	2	1.000	0.135	500.0	0.000	0.000%
1	**0.000**	3.77	2	0.865	0.845	500.0	0.000	0.000%
100	**0.030**	3.74	2	0.020	0.013	316.2	0.001	0.002%
300	**0.115**	3.66	2	0.007	0.002	94.8	0.009	0.001%
400	**0.137**	3.63	2	0.005	0.001	73.4	0.012	0.001%
475	**0.150**	3.62	2	0.004	0.003	63.0	0.014	0.005%
2,475	**0.500**	3.27	2	0.001	0.001	2.0	0.498	0.040%

NOTES:

Abbreviations: EQ = earthquake; m = metre(s); WL = water level

[a] See Section B1.10 for discussion of these results. Data in columns A, D, E, F (in grey) are unchanged from Table B - 1. Data in column B (in bold) are interpolated from the Ministry Guidelines. Data in columns C, G, H, and I are updated based on the new values in Column B.

Table B - 5: Acceptable Total Flood Hazard

REBUILD TIME	SEISMIC FLOOD HAZARD		NON-SEISMIC FLOOD HAZARD		TOTAL FLOOD HAZARD	
(years)	AEP	RP (years)	AEP	RP (years)	AEP	RP (years)
1	0.02%	4,096	0.20%	500	0.22%	446
2	0.05%	2,049	0.20%	500	0.25%	402
3	0.07%	1,367	0.20%	500	0.27%	366
4	0.10%	1,026	0.20%	500	0.30%	336
5	0.12%	821	0.20%	500	0.32%	311
6	0.15%	685	0.20%	500	0.35%	289
7	0.17%	587	0.20%	500	0.37%	270
8	0.19%	514	0.20%	500	0.39%	254
9	0.22%	457	0.20%	500	0.42%	239
10	0.24%	412	0.20%	500	0.44%	226

NOTE:

Abbreviations: AEP = annual exceedance probability; RP = return period

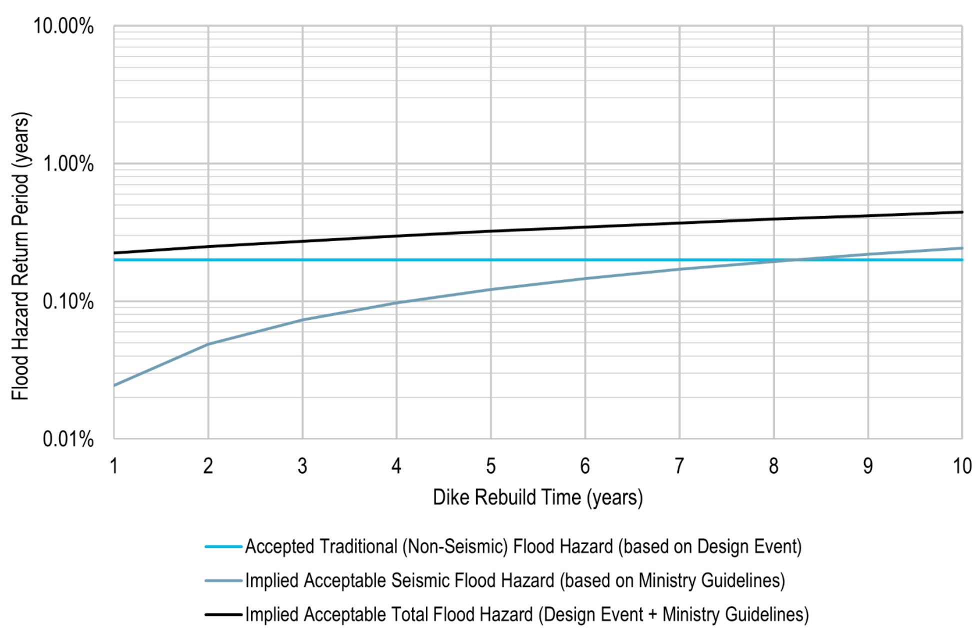


Figure B - 5: Accepted and Implied Total Flood Hazard

B1.11 COMPARING FLOOD HAZARDS TO ACCEPTABLE THRESHOLDS

The final figure compares the site-specific total flood hazard from Table B - 3: Total Flood Hazard against the implied acceptable flood hazard from Table B - 5: Acceptable Total Flood Hazard. The total flood hazard is shown to be well above the acceptable level.

Implementing ground improvement to limit deformation to the Ministry Guidelines criteria would be one way of reducing total flood hazard (shown as a red line) to the acceptable level (shown as a black line). However, the performance-based assessment already concluded that this would be cost-prohibitive.

The Engineering Professional presents this graph (and supporting calculations) as a conceptual tool that could help the Dike owner explore whether other approaches can achieve the same acceptable total flood hazard at a lower cost.

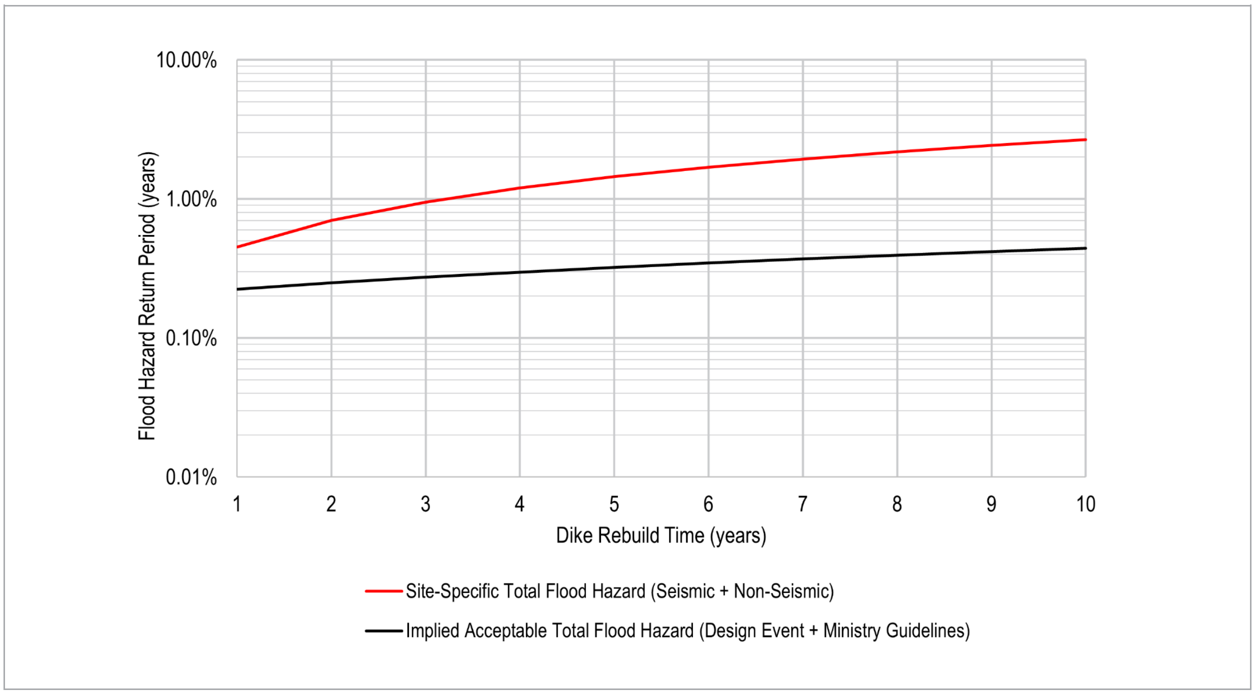


Figure B - 6: Total Flood Hazard

NOTES:

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