Performance-Based Seismic Design Guidelines for Dikes: A Framework Misinterpreted

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ABSTRACT

This paper explains the key aspects of the Performance-Based (PB) design framework adopted when developing Seismic Design Guidelines for High Consequence Dikes in British Columbia, Canada. Some of the key benefits of the framework are highlighted and misinterpretations amongst designers and regulators are clarified. The key advantages of adopting the PB framework for seismic design of dikes and the optimizations of dike design that can be accomplished are illustrated via one of the recent dike designs completed for a site underlain by liquefiable soils. When the waterside and landside of a dike move differently towards water during seismic shaking and it is the landside post-earthquake crest elevation and the available freeboard that control the flood hazard. Similarly, a dike could experience large post-seismic settlements, as long as the dike core integrity, freeboard and filter functionality are not compromised. These behavioral observations can be utilized to optimize dike performance with back up on core and filter integrity. In this paper these two scenarios of lateral movement of crest and settlement are discussed with the typical dike design examples.

Keywords: Performance-Based Design, Dikes, Earthquake, Liquefaction, Earthquake Consequences

INTRODUCTION

Many dikes in British Columbia, Canada, have originally been constructed without major engineering design input, focused primarily on flood prevention. The age of the dikes constructed varies from recent upgrading of about 50 years ago to in excess of 100 years, where very little additional work has been done over that period. In highly populated regions with critical infrastructure, where lesser standards have been historically applied, it is evident that better safety standards are required, and more formalized approaches are necessary to reduce risks associated with dike breach and the resulting damage to the society and environment. The Netherlands, USA, Japan, and western Canada (Southwest British Columbia) have started in the recent years to formalize their approach to design and upgrading of dikes.

Historically, dikes have been designed using traditional design criteria, by prescribing factors of safety against failure, considering higher than average loading conditions and lower than average resistances. These traditional design criteria have evolved over time to achieve acceptable risks. When designing for seismic loading conditions, the traditional criteria consider the seismic shaking-induced inertial loads via a horizontal seismic coefficient with appropriate reductions in strength of dike materials. Deformations of the dike are seldom considered or addressed. The focus, in most instances, has been to address the hydraulics design (i.e., seepage gradients and control, free board for overtopping, etc.) of the dike as opposed to the overall resiliency that includes the strength and deformation considerations in addition to hydraulic design aspects.

PERFORMANCE-BASED SEISMIC DESIGN PHILOSOPHY AND APPLICABILITY FOR DIKES

In recent years, seismic design of dikes has evolved to include performance-based (PB) design criteria. The PB design framework involves defining more than one level of ground shaking return periods for seismic analysis, and explicitly specifying the acceptable performance criteria for each return period (or level of ground shaking). The performance criteria often consist of readily measurable parameters such as dike crest movement and settlement during and/or following ground shaking. The design should meet the criteria specified for all levels of ground shaking. Acceptable dike displacements are established for the expected functionality of the dike; i.e., minimum free board immediately after the earthquake, integrity of the core of the dike (i.e., differential horizontal and vertical displacements along the dike axis) and the minimum thickness of filters, etc.

The PB design framework provides a high degree of flexibility for both designers and regulators. Some of the key flexibilities are summarized below:

- A range of ground motion return periods can be considered for design, varying from about 30-yrs to 2,475-yrs depending on the importance category of the dike assessed and societal impact that can be tolerated/accommodated.

Generally, two to three return periods are selected for design. The return periods can be selected based on structure life, importance category, performance required for frequent (30-yrs to 200-yrs range) versus rare (475 to 2,475-yrs range) seismic ground motions.

- The required performance for ground motions with a given return period can be explicitly enforced rather than inferred.

  As an example, if a specific performance is required for the design flood events, often established via probabilistic methods of analyses; i.e. 200-yr flood, this can be enforced rather than being interpolated or inferred based on performance established for ground motions with other return periods.

- Several different seismic performance variables (i.e. dike crest movements) can be specified for dikes with different importance classifications with low consequence dikes designed for relaxed performance criteria and high consequence dikes designed for stricter criteria.

  This is often forgotten by both the designers and regulators, which is one of the most important aspects of the PB design framework.

- The framework can be easily combined with the traditional dike design criteria to achieve the desired resiliency of the dikes to seismic loading.

  The PB framework is an extension of the current practice and has been established for other critical infrastructure such as port facilities and bridges, is relatively easy to understand, and can focus on site-specific conditions as opposed to generalized ground conditions.

An alternative to the PB framework is to establish a risk-based design framework for the dikes. Although a risk-based approach is considered a better method to assess the requirements of flood control dikes and to prioritize available upgrading and maintenance funds consistent with the potential of damage and loss of life, the framework requires extensive upfront planning, design/analysis and training efforts for designers and regulators of dike infrastructure that often involves 300 km to 400 km of dikes constructed on varying ground conditions with varying dike cross sections (i.e. materials, geometry, degree of compaction, etc.). A risk-based framework also requires the establishment of risks associated with the likelihood of floods, the likelihood that the dikes will not perform as designed or intended, and the consequences as a result of failure on people, property and environment. These aspects can be formulated to derive fragility curves for typical dike sections comprising the infrastructure that can readily be implemented with limited engineering efforts to establish the desired level of flood protection.

Typical criteria on seismic loading-induced displacements and remaining free-board along with the post-event flood protection capability of the dike (or performance), proposed by the U.S Corps of Engineers [1] for urban and urbanizing areas, are summarized in Table 1.

Table 1. Post-Earthquake Flood Protection Capability – After U.S Army Corps of Engineers

Dike Deformation	**Significant Damage to Internal Structures (i.e. core, filters, etc.)**	**Remaining Freeboard For Post-Seismic Evaluation**	**Post-Seismic Protection Ability**
< 0.3 m	No	> 0.3 m	Probably Uncompromised
0.3 to 0.9 m	Possibly	> 0.3 m	Possibly Uncompromised
0.9 to 3 m	Likely if existing	None	Likely Compromised
Unlimited	Yes	None	Compromised

The criteria shown in the table are independent of the return period of ground motions and address the "ultimate" performance expectations. The range of dike deformations provided in the table for post-seismic protection ability can be used to address the variability of dike cross sections, foundation soil conditions, dike construction details, and the associated dike performance expectations under seismic loading conditions. For example, if the post-earthquake flood protection ability of a given dike segment is expected to be "probably uncompromised" for the 475-yr return period ground motions, the dike needs to be designed to achieve less than 0.3 m of deformations and to have more than 0.3 m of free-board post-shaking. However, if the flood protection ability is assessed as "likely compromised" for the same return period ground motions, then the dike deformations can be larger varying from 0.9 m to 3 m. Such criteria may be more suitable for ground shaking associated with long return periods and for dikes with low consequences of failure.

RELEVANCE OF GROUND MOTION RETURN PERIOD IN SEISMIC ASSESSMENT OF DIKES

Historically, both regulators and designers have adopted the ground motion return period stipulated in the National Building Code of Canada (NBCC) without fully understanding the implications on the engineering aspects. In the seismic design of buildings, the primary performance expectation is that the structure should not collapse when subjected to the design ground motions and provide egress for the occupants. Unless the structure under considerations is classified as a post-disaster facility, there are no other requirements of functionality. Applying the same criteria for an earthen dike or a dam is not justifiable. The return period of ground motions alone (whether we consider 100-yr, 475-yr, 2,475-yr or even 4,975-yr) provides estimates of seismic demand anticipated at a given site location. For satisfactory design of a given structure (and from financial considerations), it is important to specify the performance expected for each of the return periods. This is an aspect that is not understood by both designers and regulators. The design can be optimized by assigning reasonable dike deformation and free-board expectations. These criteria are often established based on engineering judgement and need to be confirmed or verified via bench marking studies and cost-benefit analyses prior to adopting for design. The PB framework establishes structure-specific performance expectations and hence provides practical design criteria that can take into consideration the critical aspects that need to be incorporated for the specific structure under consideration. As an example, the seismic deformations established for marine structures for ground motions with a return period of 100-yrs will not be suitable for an earthen dike or a bridge.

The current PB seismic design guidelines released by MLFNRO [2] for seismic design of High Consequence Dikes in British Columbia, Canada, consider seismic ground motions with return periods of 100-yr, 475-yr, and 2,475-yr and associated performance indicators. Including ground motions with a longer return period of 2,475-yrs does not imply that the dikes are designed for a stringent seismic demand. What matters is the targeted performance indicator for the 2,475-yr ground motions. By allowing larger dike movements and smaller free-board criteria for the 2,475-yr ground motions, and by tightening the maximum dike movements for the 100-yr or 475-yr ground motions, the performance design can be made to be controlled by the lower return period ground motions. This flexibility in design offered by the PB framework, is often misinterpreted amongst the designers and regulators, and often results in the question *"Why are we designing dikes for ground motions with a long return period or for the NBCC ground motions?"*

CURRENT PB DESIGN FRAMEWORK ADOPTED IN MFLNRO

The PB design framework in MFLNRO [2] is defined for appropriate levels of design earthquake shaking corresponding acceptable levels of damages and further discussed in Atukorala et al. [3, 4]. The design earthquake motions include those from frequent events that are likely to occur within the life of the dike as well as infrequent or rare events that typically involve very strong ground shaking.

The acceptable levels of damage are specified in terms of displacements to be experienced by the dike system. Damage is categorized in terms of "Performance Categories", which are related to the effort required to restore the full functionality of the dike system.

The performance of the dike system should be checked for all three Design Earthquake Ground Motion Levels defined below:

Design Earthquake Ground Motions

Ground motions that correspond to three different return periods are considered in seismic design:

- Earthquake Shaking Level 1 (EQL-1) equivalent to ground motions with a 100-yr return period
- Earthquake Shaking Level 2 (EQL-2) equivalent to ground motions with a 475-yr return period
- Earthquake Shaking Level 3 (EQL-3) equivalent to ground motions with a 2,475-yr return period

Performance Categories and Permissible Displacements

- Performance Category A – No significant damage to the dike body, post-seismic flood protection ability is not compromised.
- Performance Category B – Some repairable 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.

The maximum allowable dike displacements to achieve the desired performance are provided in Table 2.

Table 2. Summary of PB Maximum Dike Crest Displacements Corresponding to Performance Categories

Performance Category	EQ Shaking Level	Maximum Vertical Crest Displacement	Maximum Horizontal Crest Displacement
A	EQL-1	< 0.03 m	< 0.03 m
B	EQL-2	0.15 m	0.3 m
C	EQL-3	0.5 m	0.9 m

The maximum allowable displacements given in Table 2 have been established with the intent of preserving the structural integrity of the dike body. They represent total displacements. It is implied that for earthen dikes, satisfying the maximum allowable dike crest displacements at sections that are located at a maximum horizontal distance of 300 m along the dike would reduce the hazards associated with a dike breach as a result of differential or relative displacements.

The designer has to independently confirm that the displaced configuration of the diking system would provide at least 0.3 m of post-earthquake freeboard above 1:10-yr return period water level to meet performance expectations. Individual communities that are assessed as having high economic loss and damage to environment as a result of flooding may impose more stringent minimum post-earthquake freeboard than specified herein.

DIKE EXAMPLE

A dike design example is presented here to illustrate how the PB design framework could have been used to optimize the design. Latitude to change/modify the criteria outlined in the MLFNRO Guidelines document [2] are not permitted by the regulators, but the focus of this paper is to illustrate how the PB design framework could have been used to achieve economic benefits without compromising the desired level of flood protection.

The example project involved upgrading two 200 m long sections of dikes along Fraser River located in Delta, BC, Canada, referred to herein as Dike Segment-1 and Dike Segment-2. The Dike Segment-1 protects an existing LNG Plant whereas the Dike Segment-2 protects a future LNG facility development in the adjoining property. The original dikes were constructed in the late 1970s when seismic design standards were not in use. The dikes consist of a silty core with sand fill slopes constructed at slopes varying from 3H:1V to 2.5H:1V on both sides. A typical cross section of the dike inferred from the historical data is presented in Figure 1.

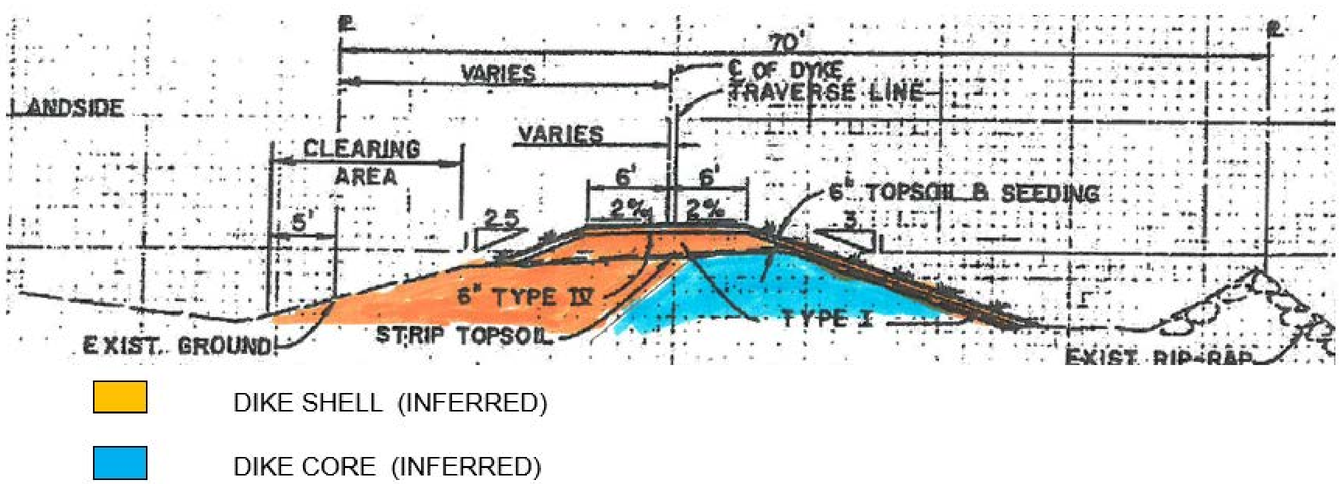
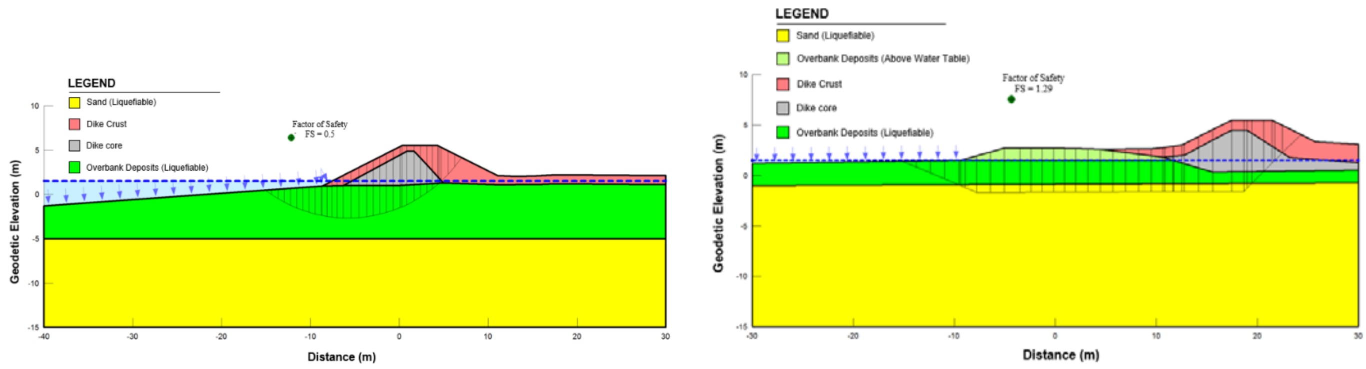


Figure 1. Typical Dike Cross Section

The two segments of the dike are underlain by several meters of overbank sediments comprising a mixture of clayey silt, low to non-plastic silts and silty sands (green layer in Figure 2) followed by a 25 to 30 m thick deposit of Fraser River sand (yellow layer in Figure 2), in turn, underlain by marine silts and clays extending to depths in excess of 150 m. The project involved raising the dike crest by about 0.6 m to meet the current flood protection criteria developed by the municipality having jurisdiction of the site. The dike raising required compliance with the current MLFNRO seismic design criteria summarized above, with an option to raise the dike in the future by another 1.4 m to accommodate water level rise due to global warming. Initial engineering analyses indicated that the seismic performance of the Dike Segment-2 is better than Dike Segment-1. During the design of dike remediation options, the following key aspects of dike behaviour were noted:

- The seismic performance of the Dike Segment-2 was assessed to be better than Dike Segment-1, resulting primarily from the 2 m high bench of overbank sediments forming a bar on the waterside acting as a buttress dike. Both the overbank sediments and the sands underlying the dike were assessed as having a high potential for liquefaction for EQL-2 and EQL-3 shaking. The liquefaction extends over the full depth of the Fraser River sand deposit, and results in a flow slide failure in Dike Segment-1. For dike Segment-2, a flow slide failure was not predicted, and the computed lateral displacements were less than the maximum prescribed in the Guidelines. In summary, for seismic stability of the dike segments, remedial measures were only required for Dike Segment-1, although both Segments 1 and 2 form flood protection for the same industrial facility. The comparison of post-liquefaction stability of the dike segments is presented in Figure 2.



(a) (b)

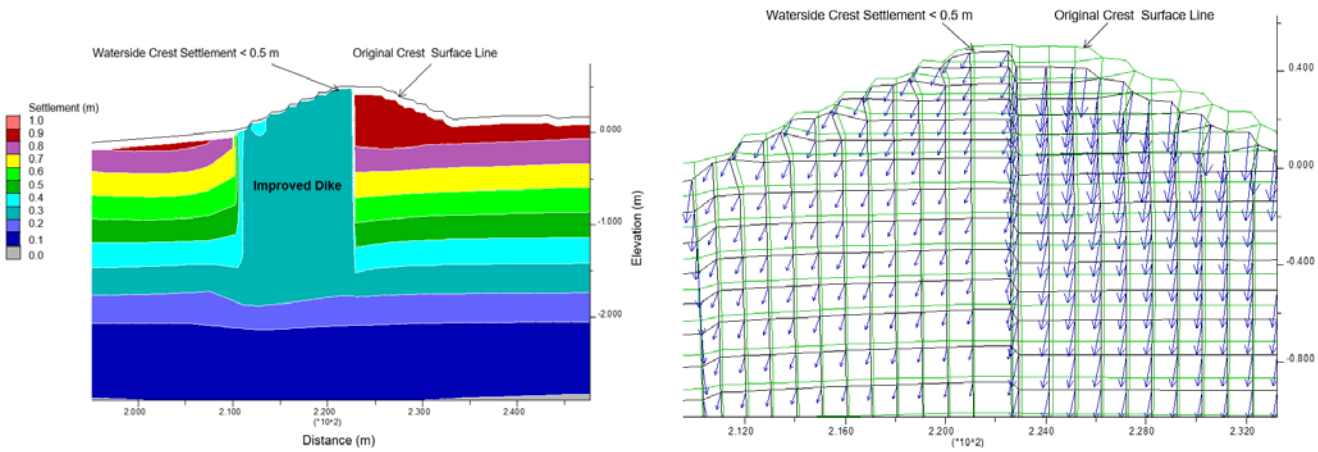
Figure 2. Post-Liquefaction Stability of Dike Segments: (a) Segment-1 (Sloping Ground Towards Waterside – $FOS_{flowslide}$ < 1.0), (b) Segment-2 (Buttressed Towards Waterside – $FOS_{flowslide}$ > 1.0).

- Although Dike Segment-2 was assessed as stable and meeting the lateral displacement criteria, the estimated post-liquefaction settlements were close to 1 m, about twice the maximum settlement permitted in the MFLNRO Seismic Design Guidelines for Dikes. Even with 1 m of settlement, the post-earthquake configuration of the dike meets the free-board criterion specified in the guideline (i.e., 0.3 m above 1:10-yr flood elevation). The settlements were calculated using the Tokimatsu-Seed [5] empirical method by assigning a volumetric strain to each liquefied layer and summing the settlement of each layer. Out of the 1 m settlement, about 0.7 m is estimated to occur as deep-seated settlements throughout the site and in the neighboring properties.

A recent study by Cetin et al. [6] indicates that based on past earthquake case-histories, the surface manifestation of vertical settlements resulting from soil liquefaction at depth and the associated volumetric strains is limited to the upper 18 m of the soil deposits, which is in line with the findings of other researchers (i.e. Ishihara et al. [7]) who have suggested similar depths (e.g. 15 m) for settlement computations. Using this approach, the estimated reconsolidation settlement is within the tolerance criteria in the Guidelines. However, the authority having jurisdiction for the subject dike segment has been reluctant to approve the results of these latter studies, for purposes of consistency with dike improvements being carried out throughout the province. Further compilation of available case history data is required to support this type of dike behavior. The authors were unable to locate case histories that are specifically applicable for dikes to support this assessment. It is the authors' assessment that widespread and deep-seated settlements should have a low risk of compromising the integrity of the dike core.

The maximum allowable crest settlements summarized in Table 2 represent the total settlement of the dike crest. These values, for different earthquake return periods, were established with the intention of maintaining the integrity of the dike core. The PB design framework expect designers and regulators to maintain not just only the maximum vertical settlement below the specified allowable values but, to maintain the minimum required freeboard for flood protection. This aspect of the PB design guideline was not very well understood by designers and regulators. It is the authors' assessment that wide spread deep-seated settlement should have a low risk of impacting the integrity of the dike core, as explained above, and the dike crest does not need to maintain the required freeboard across the entire width of the dike crest. A portion of the dike crest needs to maintain the required freeboard following an earthquake event to provide flood protection required. The damaged part of the dike can be rebuilt within a reasonable time frame, once the minimum required infrastructure is restored. Designers and regulators may economically optimize their dike design to achieve the minimum flood protection requirements.

The concept of maintaining the required freeboard for the flood level is illustrated in Figure 3, where improvement for the Dike Segment-1 was considered only along on the river side of dike crest. A FLAC 2D model was developed to optimize the dimensions of improvement zone for the dike. The post-liquefaction distorted mesh showing the resultant dike crest movements are presented in Figure 3. The contours showing the settlement are presented in Figure 3a and the distorted mesh after the post-liquefaction settlement is presented in Figure 3b. The ground improvement design was carried out to optimize the dike crest settlement and to maintain the free board for 1:10-yr return flood. In this example, the waterside crest settlement was estimated to be of the order of 400 mm and the landside crest settlement was estimated to be of the order of 900 mm, which exceeded the settlement specification provided in the Dike Guidelines. It is the authors' assessment that waterside crest with ground improvement would maintain the required freeboard for flood protection.



(a) (b)

Figure 3. Computed Post-Earthquake Dike Settlement Pattern with Ground Improvement: (a) Displacement Contours after Settlement, (b) Distorted Mesh around the Crest after Settlement.

Similarly, the maximum allowable displacements given in Table 2 represent the total crest displacements. These displacements specified for earthen dikes, are the maximum allowable dike crest displacements for sections that are at maximum horizontal distances of 300 m along the dike, would reduce the hazards associated with a dike breach as a result of differential or relative displacements. Since the potential lateral movement of the dike is towards the river, the waterside crest displacement is expected to be higher than the landside crest displacement. As part of the PB design framework, the designers are to protect the land from a 1:10-yr return period flood by specifying adequate freeboard after allowing for the shaking-induced deformations of the dike. Therefore, the designers may optimize the dike design by allowing dike crest to move more than the allowable lateral displacement, provided that the dike can maintain its flood protection ability with the remaining landside dike crest. The damaged part of the dike can be rebuilt, once the minimum required infrastructure is restored.

Flood retaining capacity of the landside dike, following a possible earthquake induced lateral displacement, is schematically illustrated in Figure 4, where the waterside dike is displaced towards water source however the landside dike core still is intact. If the top elevation of the intact dike section is greater than the design flood elevation and minimum required freeboard, the intact dike section could be considered to provide required immediate flood protection following an earthquake induced damage. The damaged landside section of the dike can be rebuilt, within an acceptable time frame, once the minimum required infrastructure is restored.

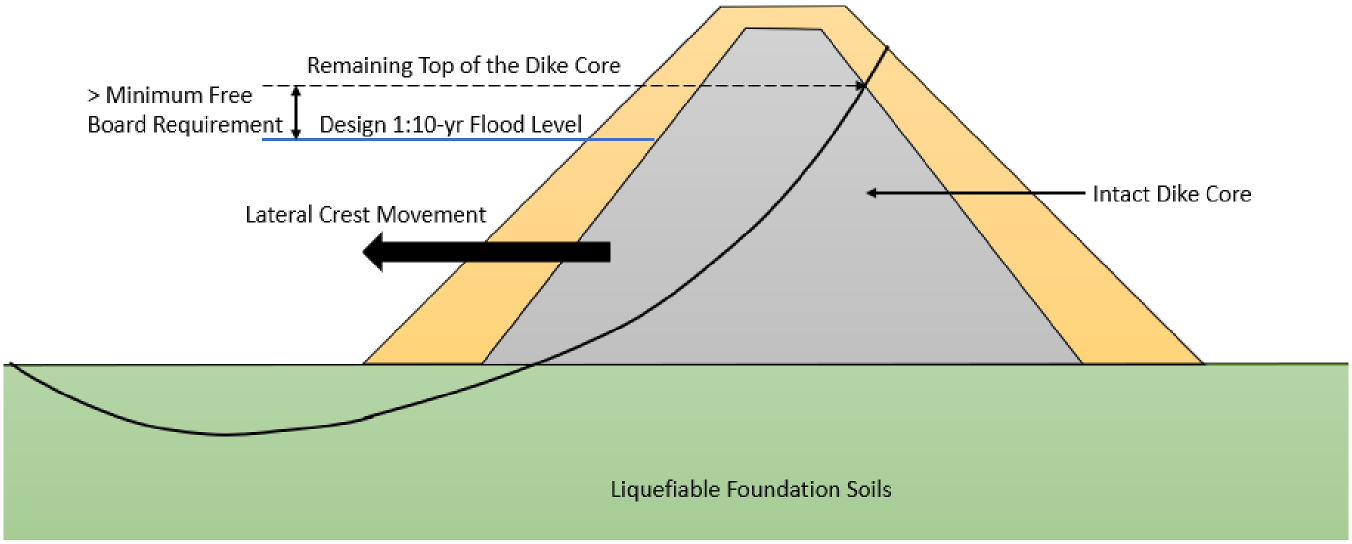
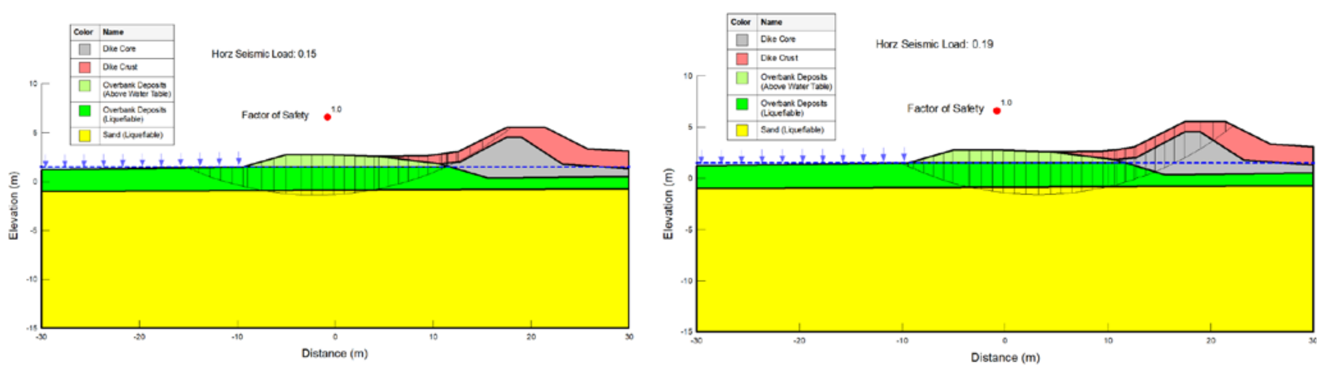


Figure 4. A Schematic Diagram Illustrates theWater Retaining Capacity of the LandSide Dike Core is Functional after Waterside Dike Core is Comprimised

The difference between the waterside and landside lateral displacements is illustrated in Figure 5 with the help of Dike Segment-2. Figure 5a shows the predicted post-liquefaction yield acceleration at the waterside crest of the dike and Figure 5b shows the predicted post-liquefaction yield acceleration at the landside crest of the dike. Based on the yield accelerations presented in Figures 5a and 5b, the estimated lateral displacements using simplified Newmark's [8] approach at waterside and landside of the dike crests are in the order of 275 mm and 100 mm, respectively for the 2,475-yr return period earthquake. Although, both predicted lateral displacements are within the specifications provided in Table 2 for the Dike Segment 2, they can differ by a factor of 3. This example shows the comparison of the lateral displacements at the waterside and landside crests of the dike.



(a) (b)

Figure 5. Computed Yield Acceleration for Dikes: (a) for the Movement of Waterside Slope (Dike Core Undisturbed), (b) For the Movement of Landside Slope (Diek Core Disturbed, However the Flood Protection not Compromised).

CONCLUSIONS

The key advantages of adopting the PB design framework for seismic design of dikes and the design optimizations that can be accomplished, are summarized and illustrated via typical dike designs completed for a dike with two segments underlain by liquefiable soils.

The common misinterpretations in the PB design framework adopted in the development of seismic design guideline for the high consequences dikes in British Columbia are highlighted and clarified with examples. The PB design frame work for dikes does not imply that the long return period earthquake ground motions, such as the 2475-yr return period motions, would control the dike design.

The economic benefits and consequences of a dike breach need to be considered carefully when optimizing the dike design. An example dike design of controlling the vertical settlement and maintaining the flood protection freeboard on waterside crest of the improved dike is discussed for design optimization, where the estimated landside vertical displacement of the dike exceeded the specifications provided in the seismic dike design guidelines, when designing the dikes for longer period earthquake motions.

Economies can be also achieved by considering landside crest movement and to maintain the flood protection freeboard rather than comparing the waterside crest movement to the Guideline specifications. This has been illustrated through a typical dike design example.

Post-earthquake settlements calculated using simplified methods for deep soil deposits comprising liquefiable soils may be conservative for use in design. Although over building the dikes is an option, confirming the dike core integrity using analytical methods alone is difficult without case-history evidence. Non-dike specific case-histories analyzed indicate that soil liquefaction below about 18 m may not contribute to post-earthquake settlements that will lead to surface manifestations in the form of subsidence and fissures. While these findings have a positive impact on estimating realistic post-earthquake settlements in dikes, these alone may not be sufficient to convince the authorities having jurisdiction over the dike segments without dike-specific case history data supporting overall dike response.

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