Assessment of Aging Dams for Seismic Potential Failure Modes: A Delta Approach

National Dam Safety Program Technical Seminar | 2023

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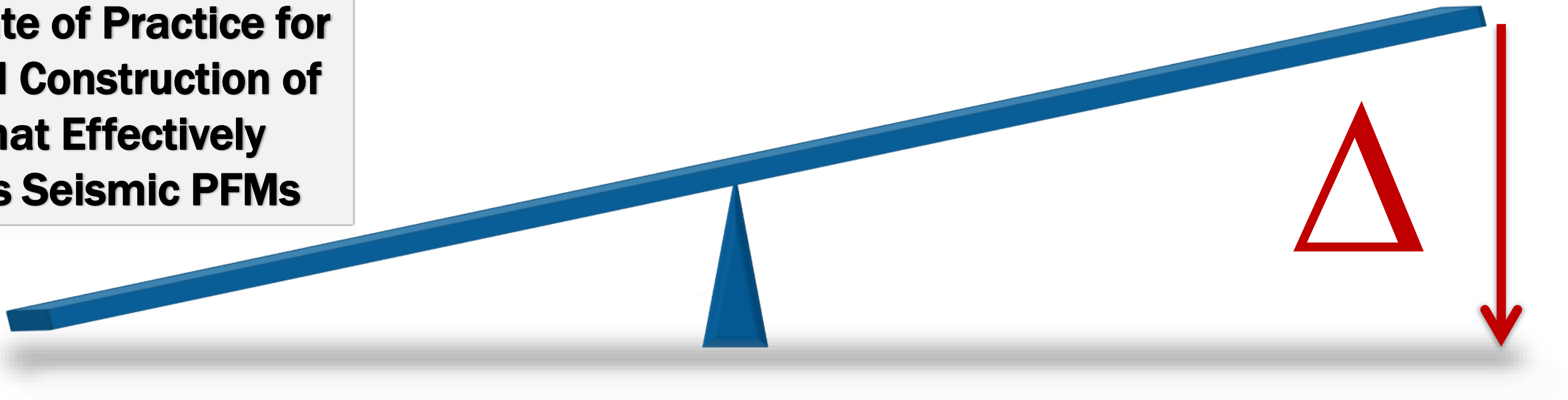
Assessment of Aging Dams for Seismic Potential Failure Modes: A Delta (Δ) Approach

Existing Dam with Poor Design and Construction [Affecting Static and Seismic PFMs]

Current State of Practice for Design and Construction of Dams that Effectively Addresses Seismic PFMs



Presentation Outline

- Challenges of seismic evaluation of dams.

  [Embankment dams]

- A “**Delta (Δ) Approach**”

  To transparently evaluate and communicate potential safety issues of an aging dam (example: an embankment dam).

- Framework of a “**Delta (Δ) Approach**” with examples.

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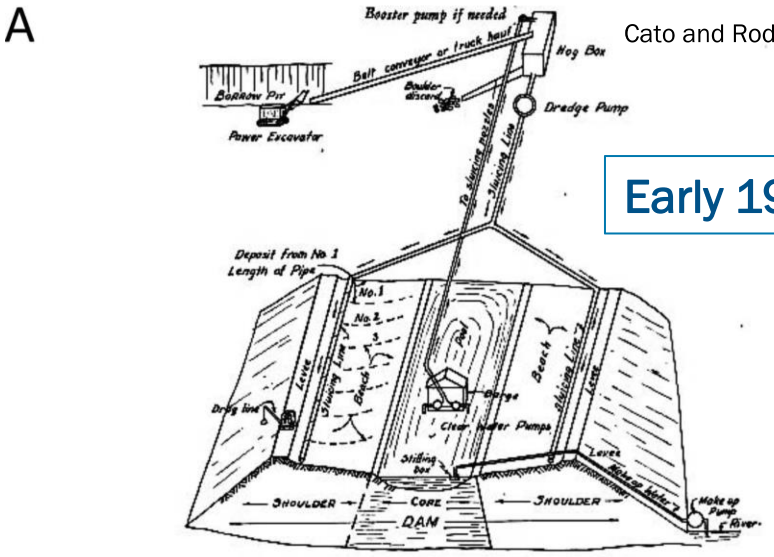
Challenges of Evaluating an Existing Dam for Seismic PFMs

- The state of practice in design and construction of embankment dams has been evolving for over a hundred years; with improvements of construction equipment and techniques, static and seismic design, and knowledge and understanding of resulting expected dam performance.
- However, many major US embankment dams that provide critical flood risk management, water supply, hydroelectric supply, and other services were constructed without modern dam design criteria and with poor construction methods. As a result, many older dams have non-seismic issues. Most of these dams also did not consider any modern seismic design standards.
- Seismic PFMs are important from a potential life loss standpoint, as well as from loss of functionality for extended periods and downstream damages.

Challenges of Evaluating Existing Dams for Seismic PFMs

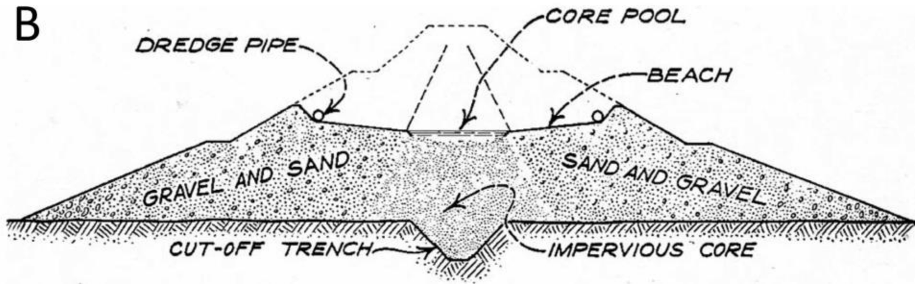
- Seismic analysis protocols and seismic-related potential failure modes (PFMs) are sometimes poorly understood by decisionmakers and practitioners.
- Significant efforts have sometimes been spent to show satisfactory expected performance for an embankment that was not designed and constructed to perform satisfactorily for the appropriate and current evaluation-level earthquakes.
- Seismic analysis and evaluation processes could be considered complex, and they require reliable data and appropriate levels of technical capability and judgment. Due to lack of clarity regarding data requirements, situation-specific seismic analysis requirements, and the lack of historic documents to help to guide site investigation and dam characterization, analyses, and development of PFMs, it is common to sometimes miss PFMs and/or to make incomplete and/or optimistic projections of expected seismic performance.
- Seismic potential failure modes are not tested often (compared to flood-related PFMs), but consequences of failures can be large. This is a dichotomy affecting policy and practice.
- Earthquakes could be damaging for poorly constructed and/or aging dams, and many older dams face potentially significant levels of seismic loading. Given the potential consequences, and the potential costs of mitigation, overall risk exposure should be carefully assessed.

Historical Poor Construction Techniques for Embankment Dams – From Hydraulic Fill (Early 1900's) to Spread Compaction by Dozers (Up to 1960's/1970's)

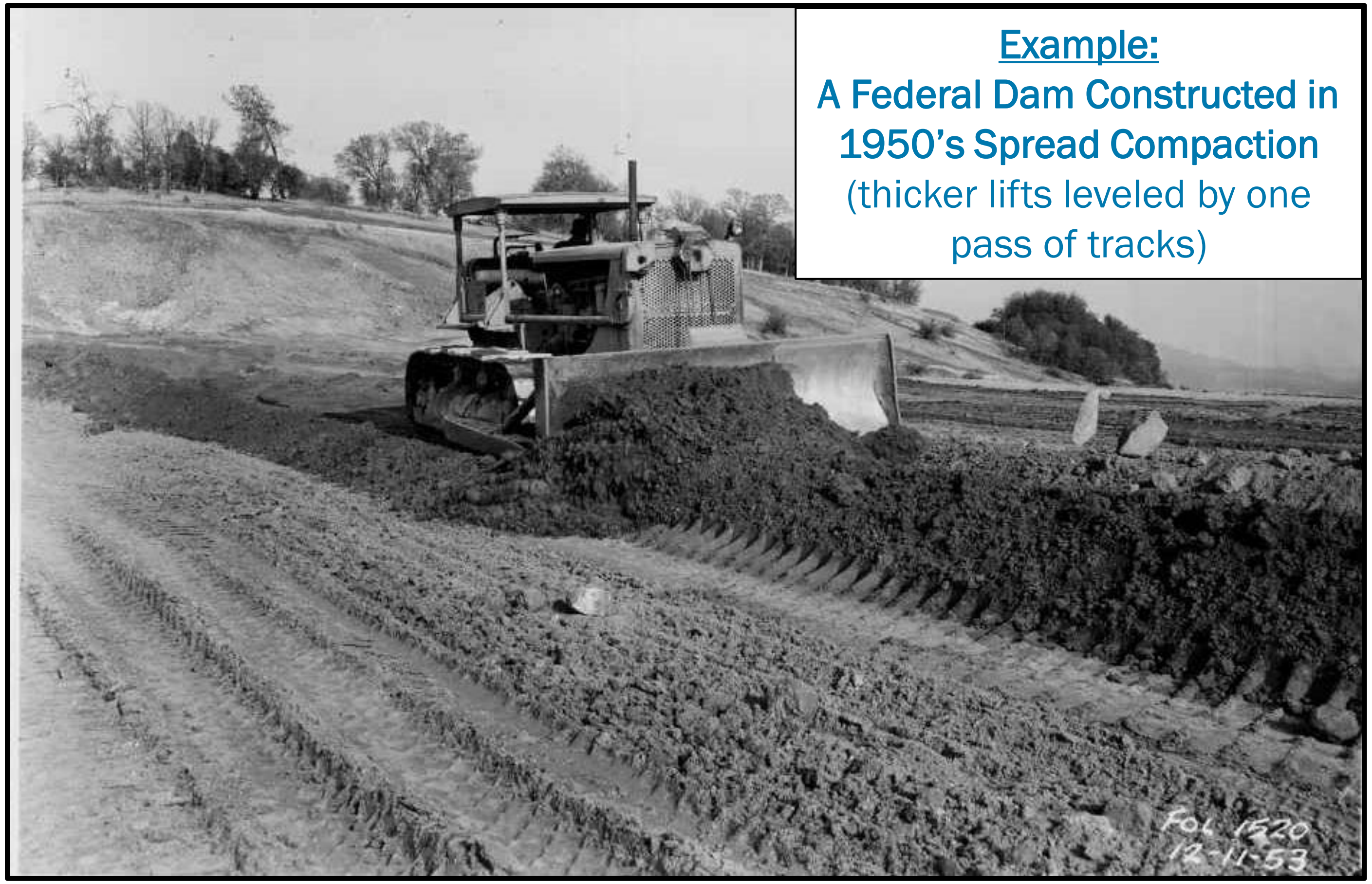


Cato and Rodgers, 2018

Early 1900's



Hydraulic Fill



Example:
A Federal Dam Constructed in 1950's Spread Compaction
(thicker lifts leveled by one pass of tracks)

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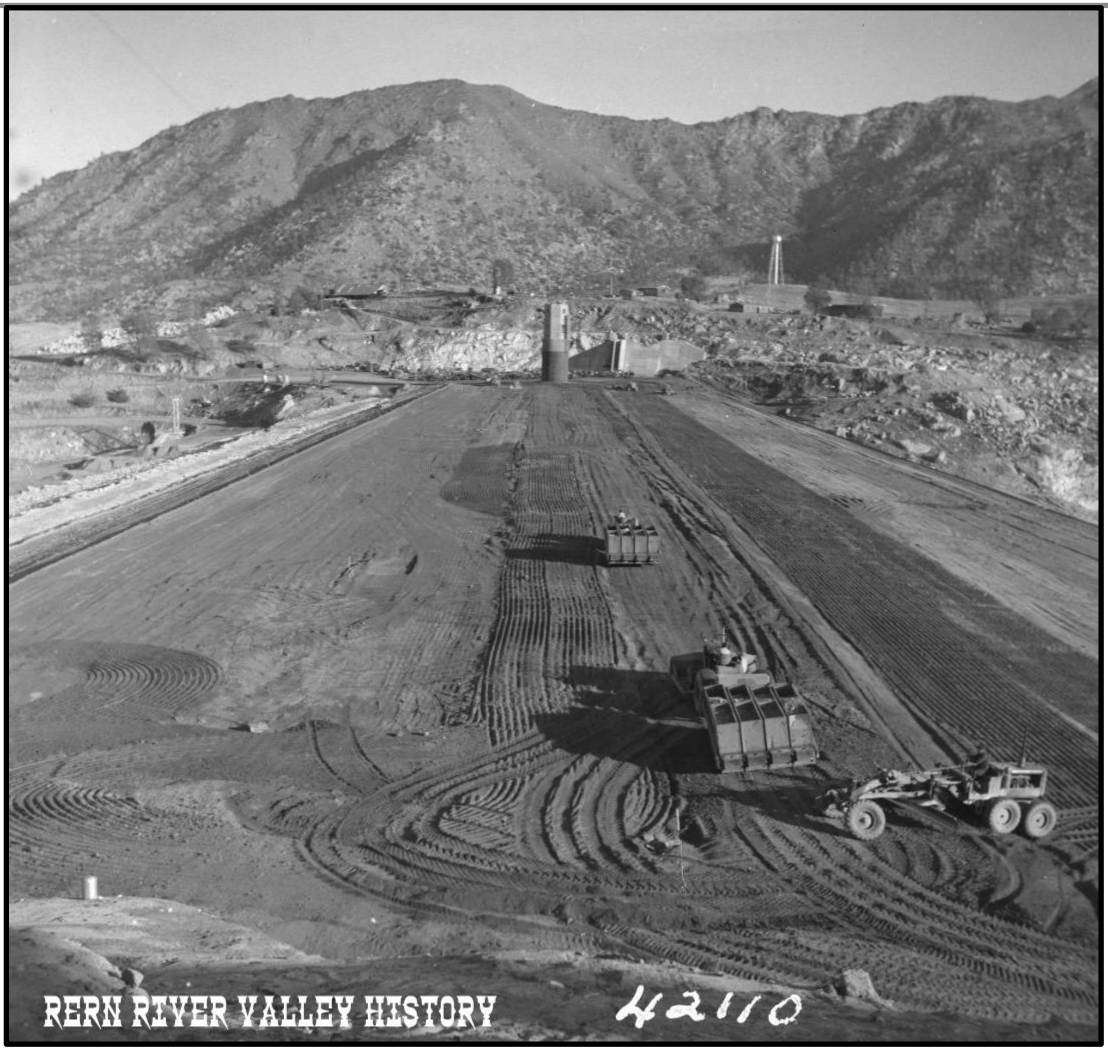
Historical Poor Construction Techniques for Embankment Dams – Pneumatic Roller [Cart Full of Soil Pulled by Dozers] (Early 1900's - 1970's?)



Example: Lake Isabella Dam Original Construction

Modern Dam Construction to Address Static/Hydrologic and Seismic PFMs (Example: Lake Isabella Dam Safety Modification)

Vibratory Compactor for Coarse-Grained Granular Materials in Embankment Zones Such as Dam Shells, Filter, and Drainage Zones [Thinner Lifts]

Sheepsfoot Roller for Fine-Grained (Plastic) Materials in Embankment Zones Such as the Dam Core [Thinner Lifts]

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Typical Topics to Communicate Delta (Δ) Approach
Example: An Aging Embankment Dam

- ✓ Topic 1: General Information
- ✓ Topic 2: Design and Construction Standards/Criteria
- ✓ Topic 3: Foundation Conditions [Geologic and Site Preparation]
- ✓ Topic 4: Embankment Core [Construction and Performance
- ✓ Topic 5: Filter and Drainage Zones
- ✓ Topic 6: Embankment Shell Zones
- ✓ Topic 7: Embankment-Abutment Contact Area and Soil-Structure Interactions
- ✓ Topic 8: Existing Distress Conditions (Static and Hydraulic)
- ✓ Topic 9: Seismic Freeboard
- ✓ Topic 10: Appurtenant Structures and Systems with Significance in Post-Earthquake Response and Performance
- ✓ Topic 11: Site-Specific [This is not a comprehensive list]

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Topic 1: General Information

General Information		
Dam Type		
Design Period		
Construction Period		
Purpose of the Dam		
Number of Dams in the System and Downstream Levees		
Reservoir Capacity		
Crest Elevation and Maximum Dam Height (ft)		
Reservoir Pool Height and Available Freeboard (90 Percentile and 50 Percentile)		
Downstream population: (1) during the design, and (2) the current population		
Critical Appurtenant Works [e.g. Spillway (Elevation and height above D/S toe), Low Level Outlet Works, and other Critical and Lifeline Features]		

Topic 1: General Information [Example]

General Information		
Dam Type	Zoned Embankment Dam	
Design Period	1953-1955	
Construction Period	1957-1959	
Purpose of the Dam	Flood control, water supply for drinking and irrigation, hydroelectric, recreation	
Number of Dams in the System and Downstream Levees	Subject dam is the main embankment dam. System includes concrete spillway structure, and 10 saddle embankment dams with heights ranging from 30 to 150 feet.	
Reservoir Capacity	1.1 Million acre-ft	
Crest Elevation and Maximum Dam Height (ft)	Crest Elevation: 750 feet ; Height of the Dam = 300 feet (measured from D/S toe to Crest)	
Reservoir Pool Height and Available Freeboard (90 Percentile and 50 Percentile)	90 Percentile: Reservoir Pool Elevation = 740 feet and Freeboard: 10 feet 50 Percentile: Reservoir Pool Elevation = 690 feet and Freeboard: 60 feet	
Downstream population: (1) during the design, and (2) the current population	During Design: Less than 10 thousand	Current: About 1.7 million (2020 census)
Critical Appurtenant Works [e.g. Spillway (Elevation and height above D/S toe), Low Level Outlet Works, and other Critical and Lifeline Features]	During Design: (1) Concrete Spillway: EL. 710 (2) **Unlined emergency spillway.** (3) **No low level outlet**, except hydroelectric tunnel with 5,000 cfs capacity (6 months to lower pool from spillway elevation to low level elevation). (4) Critical and lifeline features downstream: 1 major highway.	Current: (1) Spillway: EL. 710 (2) **Unlined emergency spillway (never used).** (3) **No low level outlet**, except hydroelectric tunnel with 5,000 cfs capacity (6 months to lower pool from spillway elevation to low level elevation). (4) Critical and Lifeline Features Downstream: **2 major highways (part of evacuation routes), 3 major hospitals, one major power plant, multiple data centers for major telecommunication and high-tech industry.**

Topic 2: Design and Construction Standards/Criteria

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(B). Design and Construction Standards and Considerations			
B1. Design criteria for seismic loading			
B2. Design investigations and parameter development for seismic analysis			

Topic 2: Design and Construction Standards/Criteria [Example and Commentary]

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(B). Design and Construction Standards and Considerations			
B1. Design criteria for seismic loading	Operating Basis Earthquake (OBE) at 475 years return period with performance objective of little or no damage and without interruption of function, and Maximum Design Earthquake (MDE) with performance objective of no uncontrolled release. Site MDE return period 1250 years (Cascadia Subduction Zone).	No design standards for seismic loading was used in original design and construction in 1950s. No national or local standards were available.	(1) This embankment dam was designed and constructed without considering any seismic criteria. Potential impacts of a Cascadia subduction zone earthquake were discovered by scientists in late 1990s to early 2000s. (2) As the dam was designed and constructed without seismic criteria and considerations using poor construction techniques, potential for poor seismic performance should not be a surprise.
B2. Design investigations and parameter development for seismic analysis	Site characterization with focus on potential contributing factors for poor seismic performance. These include fault study, liquefaction., soft soils, key embankment design features and construction criteria, abutment conditions, foundation cutoff, freeboard requirement, etc.	Original site investigation information is inadequate for modern seismic site characterization and any seismic analyses. Subsequent investigations, unfortunately are inadequate also. .	Without site-specific reliable data, any seismic assessment is mostly engineering judgment based. Site-specific seismic focused site investigation-based site characterization is essential for fact-based seismic analyses and evaluations.

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Topic 3: Foundation Conditions [Geologic and Site Preparation]

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(C). Foundation Conditions [Geologic and Site Preparation]			
C1. Presence of mapped or potential faults in dam footprint or proximity			
C2. Presence of Historical or Recent Alluvium in foundation			
C3. Presence of stream deposits, irregular rock, or other source(s) of significant geologic contrasts within the dam footprint			
C4. Presence of active or old landslides adjacent to the dam			
C5. Foundation preparation and grouting			
C6. Abutment mapping, inspection and treatment. Monitoring of abutting fill placement. Etc.			
C7. Etc. [Site Specific]			

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Topic 3: Foundation Conditions [Geologic and Site Preparation] [Example and Commentary]

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(C). Foundation Conditions [Geologic and Site Preparation]			
C1. Presence of mapped or potential faults in dam footprint or proximity	A fault in dam footprint or proximity indicates potential for near source effects such as (1) permanent foundation offset displacement and (2) strong ground motions (fling and pulse). Features such as wider drainage features, berm, etc. to address permanent offset and strong ground motions are utilized in modern design.	A mapped splay fault is located under the main embankment and near the right abutment of the dam. It has potential to rupture or offset with the main fault rupture. No design features currently exists to address potential fault rupture hazard.	In the absence of design features to minimize impacts of a fault offset or near-source ground motions, risk of potential failure is increased. In addition to immediate seismic deformations, delayed impacts such as development of backward erosion piping (BEP) due to lack of adequate filter capability is also possible.
C2. Presence of Historical or Recent Alluvium in foundation	The State of Practice for the modern dam construction is removal of potentially liquefiable or cyclically weakening soils from the foundation and then emplacement of engineered fill to establish a competent foundation beneath the embankment. Ground improvement techniques (such as densification) can also be utilized.	Existing dam was constructed without removal of recent Alluvium from foundation. Upper foundation layers in both upstream and downstream consist of an about 10 to 25 feet thick potentially liquefiable sandy and gravelly soils.	Presence of potentially liquefiable and/or cyclic weakening soils is one of the most common flaws in embankment dams, and can contribute to upstream and/or downstream seismic deformations ranging from limited freeboard loss to flow slides with larger loss of freeboard (overtopping).

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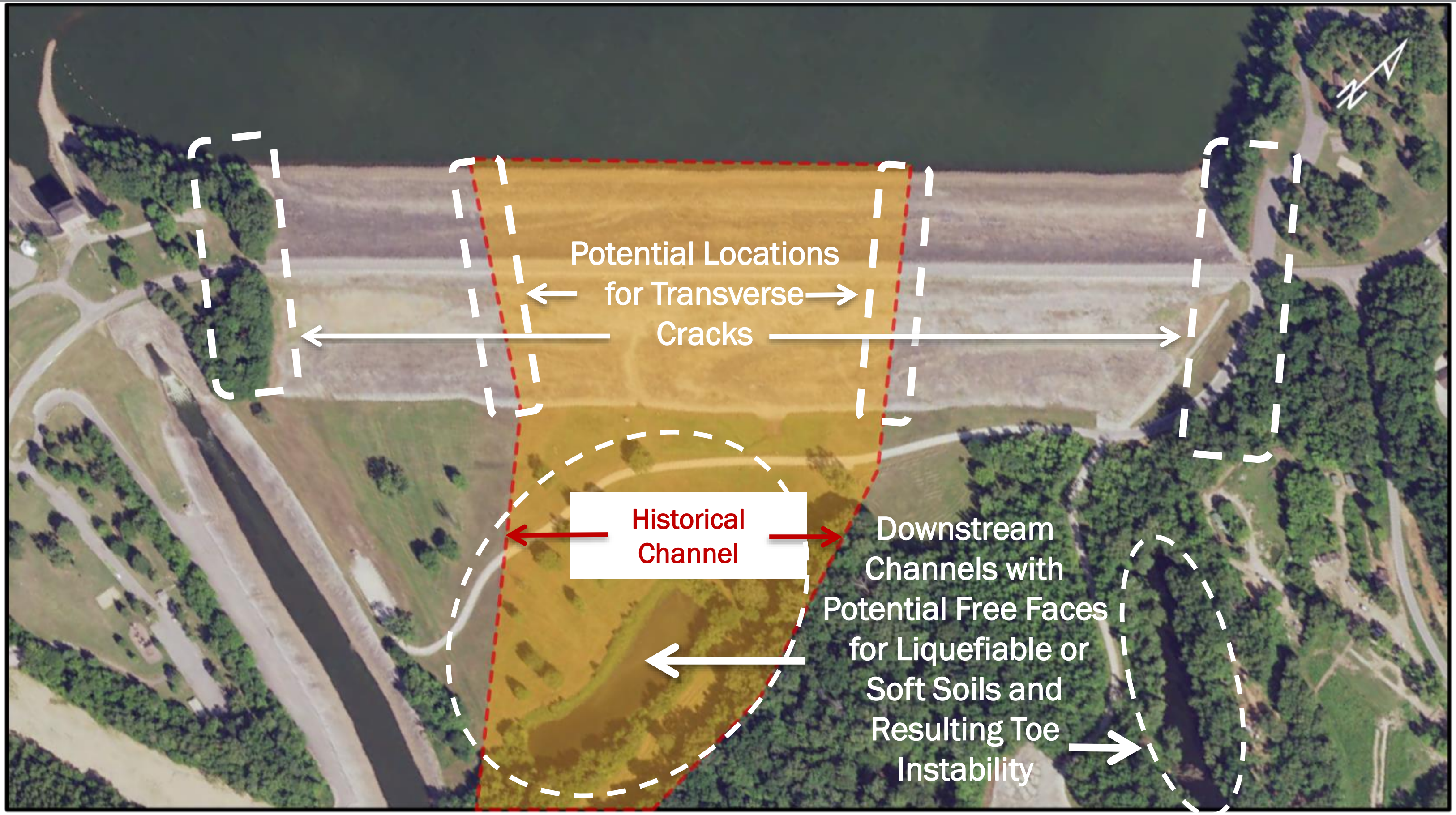
Topic 3: Foundation Conditions [Geologic and Site Preparation] [Example and Commentary] (2)

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(C). Foundation Conditions [Geologic and Site Preparation]			
C3. Presence of stream deposits, irregular rock, or other source(s) of significant geologic contrasts within the dam footprint	Many dams are constructed across rivers or streams, which likely consist of looser and/or softer deposits along the rivers/streams and denser or stiffer materials on the sides. The transition areas near the channels are locations of potentially significant stiffness contracts. These areas are potential locations for transverse crack development.	The dam was constructed across a stream without removal of all loose/soft foundation materials. The width of the stream is about 1/3rd of the dam crest length. The stream is unaltered at the downstream toe.	There are potential locations of transverse cracking near the known locations of contrasting geologic units. The existing channel is very close to the downstream toe, which provides an easier exit for deformed foundation and embankment soil movement.
C4. Presence of active or old landslides adjacent to the dam	There may be active or old landslides within the reservoir rims (distant from the dam or in proximity of the dam). An earthquake could potentially trigger these landslides. A landslide could trigger overtopping by seiche and/or direct impact on dams.	An old and active landslide with slow movement (creep) is located near the right abutment of the dam.	The potential landslide mass volume is significant to (1) deposit sediments at the upstream of the dam and block the low-level outlet and spillway gates, (2) create waves, which may result in overtopping if coincident pool is high, (3) create openings or cracks in the right abutment area, which may result in rapid erosion of materials.

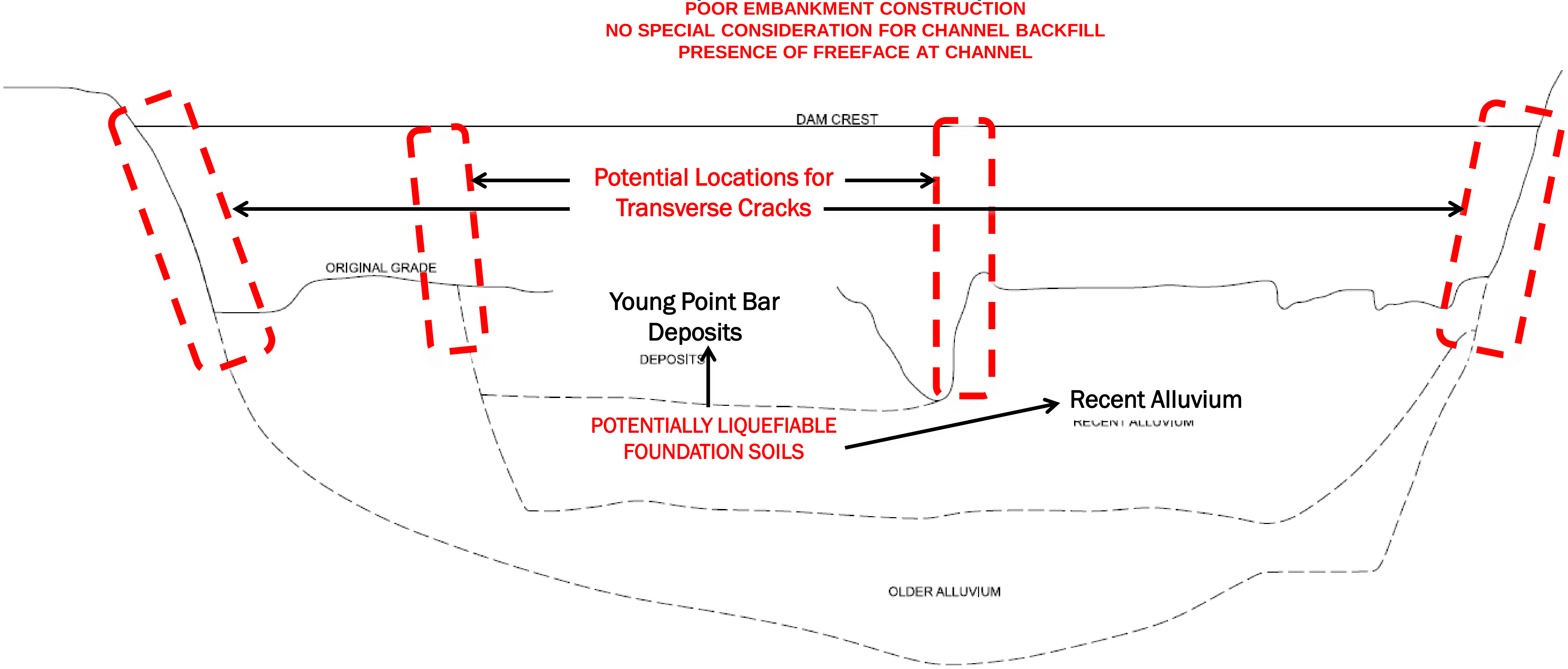
Example: Historical Channel Under Footprint of an Embankment Dam (Planview)



Potential for

- liquifiable and soft soils in foundation,
- transverse cracks, and
- Downstream/ upstream free face for deformed soil movement

Example: Historical Channel Under Footprint of an Embankment Dam (Cross Section)



Topic 3: Foundation Conditions [Geologic and Site Preparation] [Example and Commentary] (3)

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(C). Foundation Conditions [Geologic and Site Preparation]			
C5. Foundation preparation and grouting	Proper foundation preparation (compaction, removal of unsuitable materials, etc.) and multi-line sequential grouting are performed in modern dams.	Only one line of grouting was performed and the grouting operation was not well documented. Downstream seepage is a regular concern, and monitoring to detect potential accelerating seepage is not regularly performed and/or reported.	Inadequate grouting may indicate an existing deficiency for BEP-type failure modes,: conditions that may be exacerbated due to an earthquake.
C6. Abutment mapping, inspection and treatment. Monitoring of abutting fill placement. Etc.	Embankments are usually constructed with special considerations for compaction near steep abutment slopes and/or localized overhangs. Rock slopes are sculpted and prepared (e.g. trimming overhangs, slush grouting, excavation of poor materials, etc.) to provide good abutment contact conditions. with embankment materials.	The embankment was constructed on a steep rock slope without removal of rock ledges or other abutment treatments.	Seismic displacements of the embankment at and near a steep rock abutment could lead to potential for transverse through-cracking or contact gapping during an earthquake. This can lead to potential development of piping, and can be exacerbated by seismic deformations and displacements as well as post-earthquake settlements due to densification of loose/uncompacted embankment materials.

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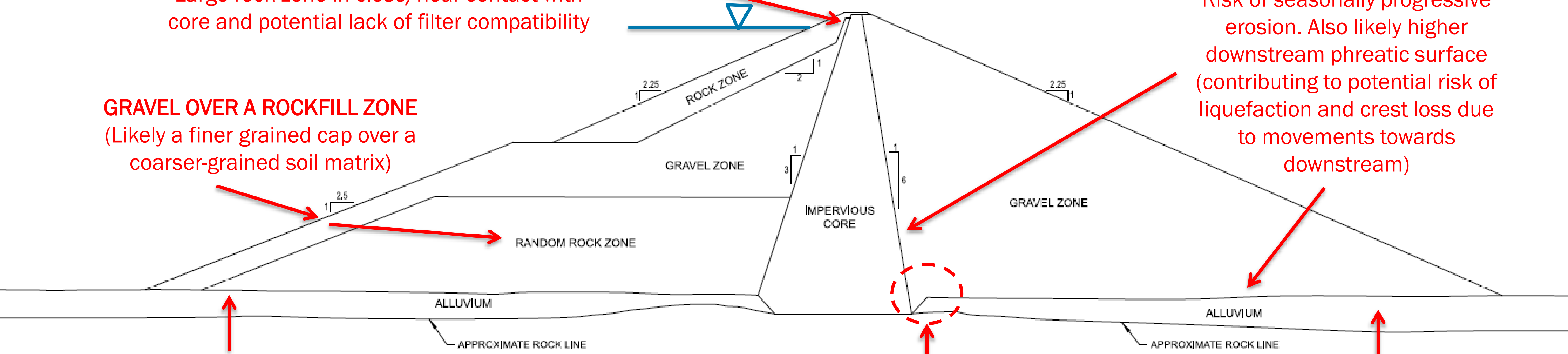
Example Embankment Dam
Some Defects Cannot Be Easily Captured by Seismic Analyses – Needs Engineering Assessment

NARROW GRAVEL ZONE
(likely lack of compaction)
Large rock zone in close/near contact with core and potential lack of filter compatibility

NO FILTER AND BLANKET DRAIN
Risk of seasonally progressive erosion. Also likely higher downstream phreatic surface (contributing to potential risk of liquefaction and crest loss due to movements towards downstream)

GRAVEL OVER A ROCKFILL ZONE
(Likely a finer grained cap over a coarser-grained soil matrix)



POTENTIALLY LIQUEFIABLE FOUNDATION SOILS
(upstream saturated zone)

POTENTIAL PONDING AREA

POTENTIALLY LIQUEFIABLE FOUNDATION SOILS
(Shallow alluvium not removed or treated)

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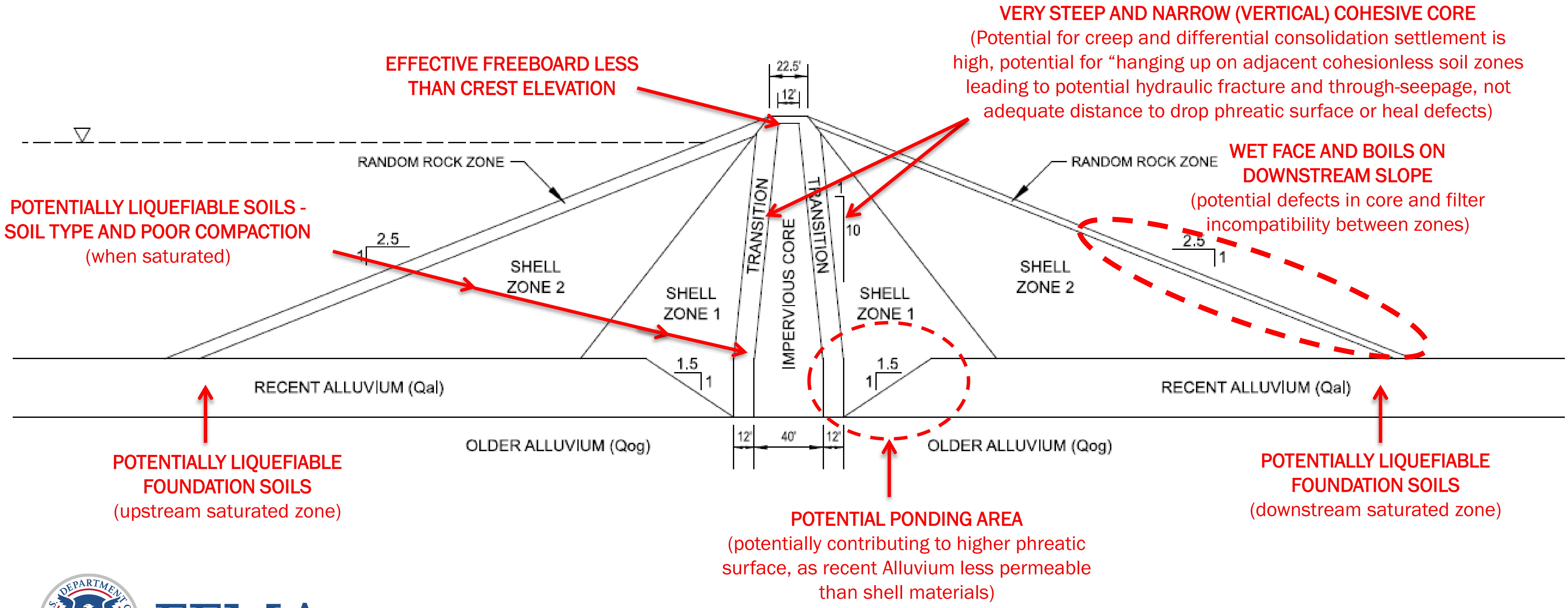
Example Embankment Dam
Some Defects Cannot Be Easily Captured by Seismic Analyses – Needs Engineering Assessment (2)



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Topic 4: Embankment Core [Construction and Performance]

Evaluation Topic	Current Criteria or State of Practice with Significance on Seismic Performance	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Difference Between Current Criteria/State of Practice and the Existing Dam on Evaluation Topics
(D). Embankment Core [Construction and Performance]			
D1. Embankment Core – material type, lift thickness, compaction equipment, moisture conditions			
D2. Embankment Core – width at top, upstream and downstream slopes			
D3. Embankment core - presence of potentially liquefiable materials			
D4. Etc (Site Specific)			

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Topic 4: Embankment Core [Construction and Performance] [Example/Commentary]

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(D). Embankment Core [Construction and Performance]			
D1. Embankment Core: material type, lift thickness, compaction equipment, moisture conditions	Clayey materials (not too plastic or too low plasticity) placed in thinner lifts (≤ 12 -inches), compaction moisture conditions with slightly higher than optimum moisture content (OMC) (< +5 percent of OMC) and “kneading” compaction (compacted with sheeps foot roller.).	Clayey core was constructed with moisture +10 percent of optimum with thick lifts (24-inches) and spread-compacted with 1-pass of tracks of D8 dozer.	The embankment core very high water content compacted poorly.-Potential for deformations during an earthquake may be high due to low strength. It may also be potentially prone to shrinkage and cracking upon drying. Seismic loading might exacerbate cracking.
D2. Embankment Core: width at top, upstream and downstream slopes	Core with wider crest width (such as 30 feet or more) and flatter slope (such as 0.5H:1V or flatter).	Core has a relatively narrow crest width (12 feet) with very steep slope (0.17H:1V or 1H:6V).	Narrow vertical core may “hang up” on adjacent cohesionless soil zones, increasing risk of cracking and/or hydraulic fracture. Core with wider crest and flatter slope would provide additional protection against potential cracking, creep and BEP (pre- and post-earthquake) after an earthquake. Also, wider core with flatter slope would provide additional protection against erosion if shell materials are removed during an earthquake (exposed core slope).

Topic 4: Embankment Conditions [Construction and Performance] [Example/Commentary]

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(D). Embankment Conditions [Construction and Performance]			
D3. Embankment core - presence of potentially liquefiable materials	Dam cores are constructed of potentially liquefiable soils such as sandy and gravelly soils due to lack of ideal plastic fine-grained soil in borrows.	Embankment core of a portion of the dam was constructed with low plasticity Silt to Silty Sand with poor compaction effort and thicker lifts	Potentially liquefiable core would have higher potential for deformations including freeboard loss, cracking, etc.
D4. Etc (Site Specific)			

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Topic 5: Filter and Drainage Zones

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(E). Filter and Drainage Zones			
E1. Presence of downstream filter, and filter geometry and location.			
E2. Downstream filter – material type, lift thickness, compaction equipment, moisture conditions			
E3. Filter compatibility between filter zone and adjacent transition and/or shell zone materials. Full continuity of filter compatibility from core to exit drain.			
E4. Presence of downstream blanket drain and collection system			
E5. Filter compatibility between foundation-drain and between drain and shell			
E6. Presence of upstream filter/transition zone			
E7. Upstream filter/transition zone – material type, lift thickness, compaction equipment, moisture conditions			
Etc. (Site Specific)			

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Topic 5: Filter and Drainage Zones [Example]

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(E). Filter and Drainage Zones			
E1. Presence of downstream filter, and filter geometry and location.	Downstream filter and blanket drains are essential components of modern embankment dams.	Downstream filter zone is available.	
E2. Downstream filter – material type, lift thickness, compaction equipment, moisture conditions	Coarse-grained soils compacted with vibratory roller with adequate relative compaction such that particle breakage (and increase of finer particles) is prevented, and liquefaction potential is low. A wider filter zone indicates that proper compaction equipment can be used. A wider filter zone may have materials to prevent cracks to widen and deteriorate.	Filter layer is narrow (7 feet), constructed with thicker lifts of 24-inches and spread compacted using one pass of a D8 dozer.	Poorly compacted filter layer would have potential for liquefaction and deformations.
E3. Filter compatibility between filter zone and adjacent transition and/or shell zone materials. Full continuity of filter compatibility from core to exit drain.	Filter material gradations should have compatibility with both core and shell materials.	Even though the particles are progressively larger from core to filter to shell, these layers do not meet modern filter compatibility criteria.	In the absence of filter compatibility, migration of particles from core to filter and filter to shell may occur. Finer particle migration may result in downstream higher phreatic surface (e.g. higher potential for liquefaction) and potential BEP conditions.

Topic 5: Filter and Drainage Zones [Example] (2)

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(E). Filter and Drainage Zones			
E4. Presence of downstream blanket drain and collection system	Blanket drains safely convey water that seeps through core and filter to downstream toe area.	Downstream blanket drain is not available.	In the absence of a properly designed blanket drain, potential of higher phreatic surface in downstream can lead to potential for liquefaction and other conditions that contribute to seismic deformations and freeboard loss.
E5. Filter compatibility between foundation-drain and between drain and shell	Filter compatibility between foundation and blanket drain materials is an important modern criteria	Filter compatibility between the foundation and blanket drain materials and between drain and shell do not meet modern filter criteria.	In the absence of filter compatibility between blanket drain and foundation layer and between blanket drain and shell, banket drain may get clogged and the downstream phreatic surface may rise, leading to potential for liquefaction and other conditions that can contribute to seismic deformations and potential for freeboard loss.

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Topic 5: Filter and Drainage Zones [Example] (3)

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(E). Filter and Drainage Zones			
E6. Presence of upstream filter/transition zone	Upstream filter/transition layer is not essential, if shell materials are filter compatible with core. A transition layer may allow use of coarser shell materials (such as rockfill), which might otherwise not be filter compatible with the core.	An upstream transition/filter layer is present.	The transition/filter layer that is present is susceptible for deformations, which could create longitudinal cracking along the core-transition interface and may potentially expose the core, if soil deforms.
E7. Upstream filter/transition zone – material type, lift thickness, compaction equipment, moisture conditions	Coarse-grained soils compacted with vibratory roller with adequate relative compaction such that particle breakage (and increase of finer particles) is prevented, and liquefaction potential is low. A wider filter zone indicates that proper compaction equipment can be used. A wider filter zone may have materials to prevent cracks to widen and deteriorate.	Filter layer is narrow (7 feet), constructed with thicker lifts of 24-inches and spread compacted using one pass of D8 dozer.	Poorly compacted filter layer would have potential for liquefaction. Subsequent static settlement may result differential deformations. Differential settlements between the narrow filter and the two adjacent zones can lead to cracking.
Etc. (Site Specific)			

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Topic 6: Embankment Shell Zones

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(F). Embankment Shell Zones			
F1. Upstream shell – material type, lift thickness, compaction equipment, moisture conditions, numbers of passes, etc.			
F2. Presence of different sub-layers within upstream shell			
F3. Downstream shell – material type, lift thickness, compaction equipment, moisture conditions, numbers of passes, etc.			
F4. Presence of different sub-layers within upstream shell			

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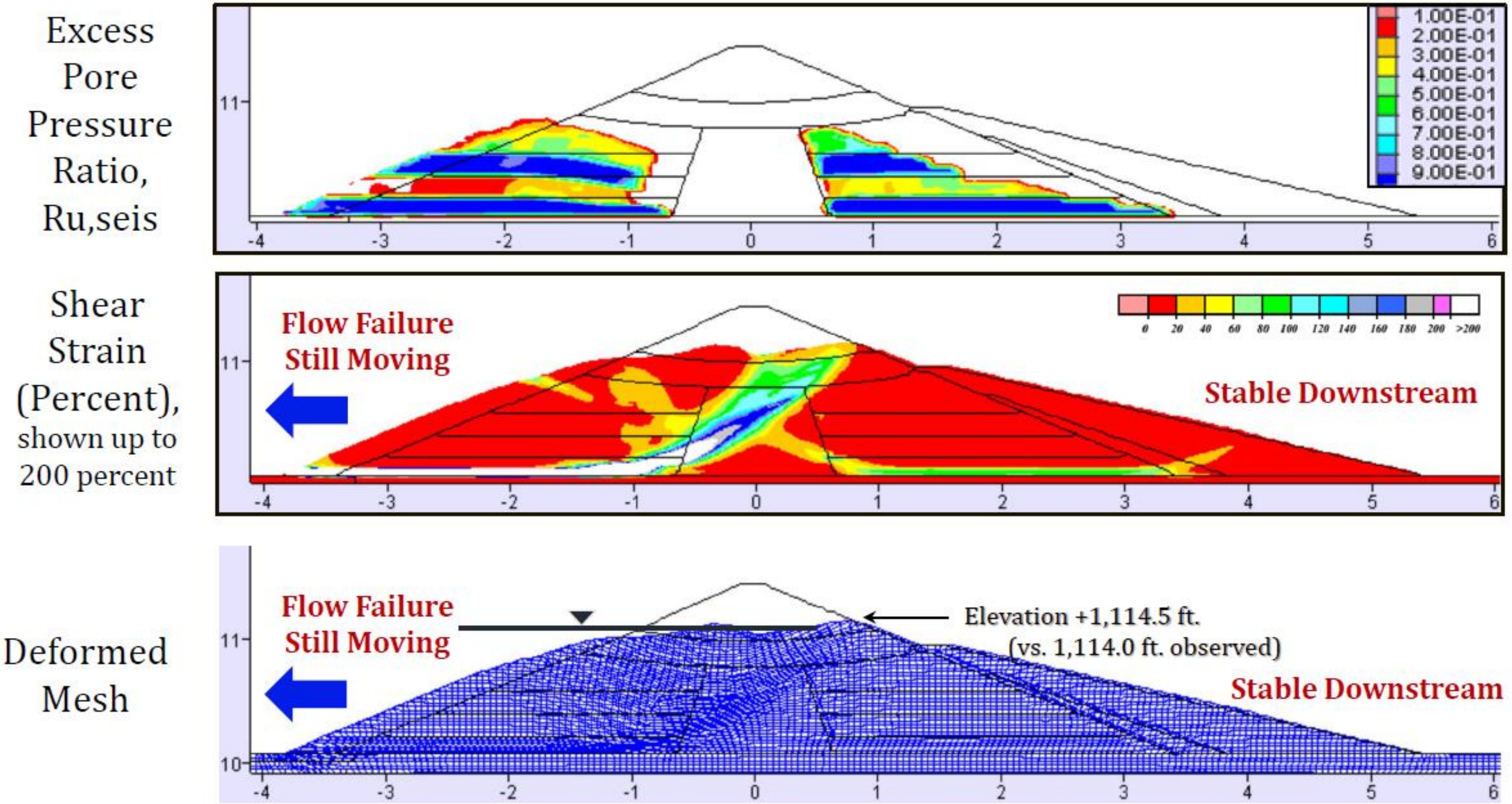
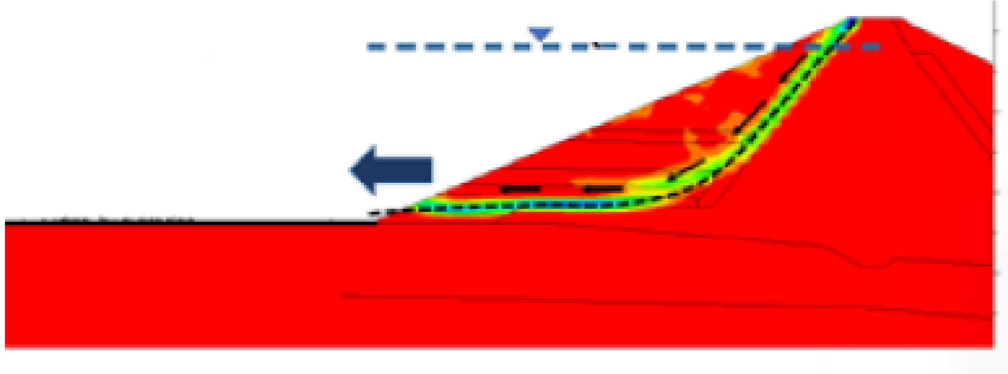
LSFD Analysis 1: Roth Model - Cetin et al. (2018) Triggering and Weber et al. (2015) Undrained and Residual S_r - Conditions at End of Analysis

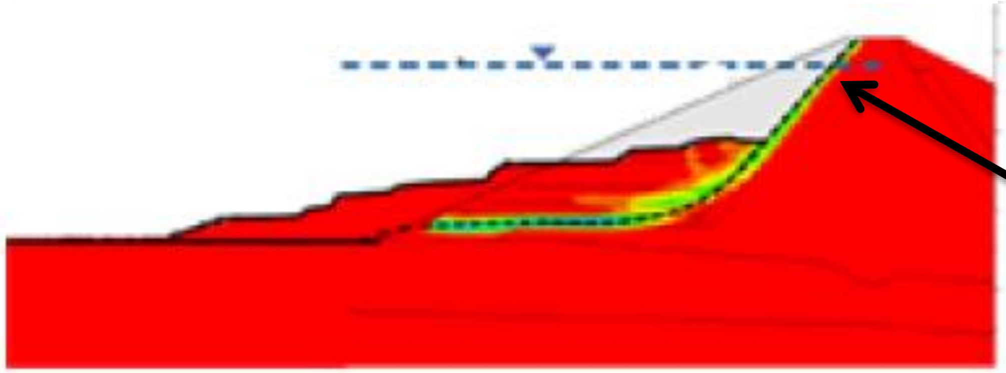


Chowdhury et al., 2019

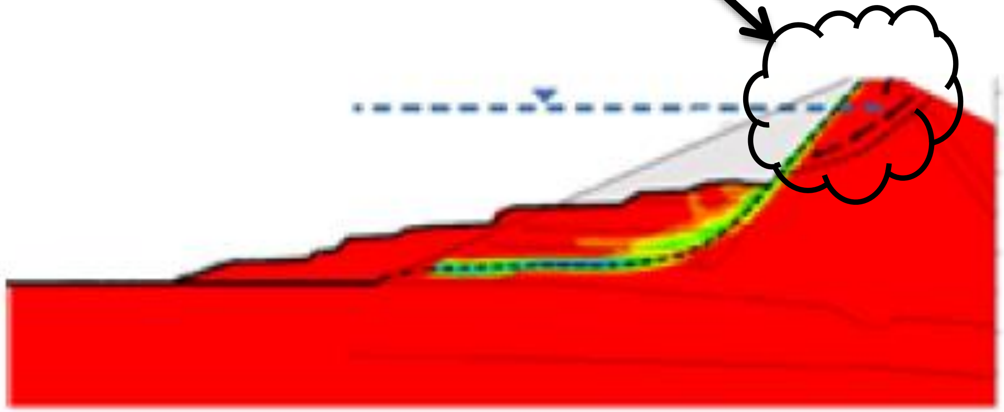
Upstream Flow Slide in Shell and Secondary Deformations in Core



1. Earthquake occurs
2. Initiation of liquefaction-induced upstream flow slide occurs



Secondary Crest Sliding, Cracking, and Remaining Crest Exposed to Reservoir



Upstream Flow Slide in Shell
(Final residual flow slide geometry after runout)

Topic 6: Embankment Shell Zones [Example]

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(F). Embankment Shell Zones			
F1. Upstream shell – material type, lift thickness, compaction equipment, moisture conditions, numbers of passes, etc.	Coarse-grained soils compacted with vibratory roller such that materials are suitably densified with relatively thinner lifts (12-inches to 18-inches) and sufficient "passes". Adequate compaction provides dense packing, which helps reducing seepage concerns, erosion potential, liquefaction potential, and seismic deformation potential.	Shell was constructed with thicker lifts of 36-inches to 48-inches and spread compacted using one "levelling" pass of D8 dozer. Materials are Sandy Gravel to Gravelly Sand.	Poorly compacted shell zone would have potential for liquefaction and resulting deformations. Large deformations (movements) may expose and/or unbrace the core, which usually has steep slopes and may not be stable once exposed. Larger slide displacements can carry away the crest section of the dam. Lesser sliding displacements can cause crest loss accompanied with cracks and blocky failures occur. Case history: Lower San Fernando Dam in 1971.
F2. Presence of different sub-layers within upstream shell	Construction of shell zones with thinner lifts with vibratory roller should reduce potential for looser sub-layers. Suitable compaction should be performed for all lifts during construction; one or more "looser" lifts could pose a potential hazard.	Construction techniques of shell zone (thicker lifts with inadequate compaction efforts) indicates that potential for looser sub-layers is high.	In is common to find denser and looser soil sub-layers with varying thicknesses in upnstream shells due to poor compaction efforts in older dams compacted with tracked or rubber tired non-vibratory compaction equipment which produces poor compaction of potentially liquefiable soil types, especially in lower portions of a compaction "lift". This often results in loose and potentially liquefiable soils, and also to layered soils potentially vulnerable to void redistribution and resulting low post-liquefaction residual strengths.

Topic 6: Embankment Shell Zones [Example] (2)

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
		(F). Embankment Shell Zones	
F3. Downstream shell – material type, lift thickness, compaction equipment, moisture conditions, numbers of passes, etc.	Coarse-grained soils compacted with vibratory roller such that materials are suitably densified with relatively thinner lifts (12-inches to 18-inches) and sufficient "passes". Adequate compaction provides dense packing, which helps reducing seepage concerns, erosion potential, liquefaction potential, and seismic deformation potential.	Shell was constructed with thicker lifts of 36-inches to 48-inches and spread compacted using one "levelling" pass of D8 dozer. Materials are Sandy Gravel to Gravelly Sand.	Poorly compacted shell zone would have potential for liquefaction and resulting deformations. Large deformations (movements) may expose and/or unbrace the core, which usually has steep slopes and may not be stable once exposed. Larger slide displacements can carry away the crest section of the dam. Lesser sliding displacements can cause crest loss accompanied with cracks and blocky failures occur. Downstream deformations may be less than upstream; however, would depend on site-specific conditions.
F4. Presence of different sub-layers within downstream shell	Construction of shell zones with thinner lifts with vibratory roller should reduce potential for looser sub-layers. Suitable compaction should be performed for all lifts during construction; one or more "looser" lifts could pose a potential hazard.	Construction techniques of shell zone (thicker lifts with inadequate compaction efforts) indicates that potential for looser sub-layers is high. Due to absence of filter and proper drainage, downstream phreatic surface is higher than expected.	In is common to find denser and looser soil sub-layers with varying thicknesses in downstream shells due to poor compaction efforts in older dams compacted with tracked or rubber tired non-vibratory compaction equipment which produces poor compaction of potentially liquefiable soil types, especially in lower portions of a compaction "lift". This often results in loose and potentially liquefiable soils, and also to layered soils potentially vulnerable to void redistribution and resulting low post-liquefaction residual strengths.

Topic 7: Embankment-Abutment Contact Area and Soil-Structure Interactions

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(G). Embankment-Abutment Contact Areas and Soil-Structure Interactions			
G1. Embankment-abutment contact area design and construction measures			

Topic 7: Embankment-Abutment Contact Area and Soil-Structure Interactions [Example]

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(G). Embankment-Abutment Contact Areas and Soil-Structure Interactions			
G1. Embankment-abutment contact area design and construction measures	Contact areas should (1) be free of overhangs, (2) have voids filled (dental treatment), (3) be compacted well, (4) have weathered and/or fractured rock from abutment surfaces excavated or grouted, and (5) have expected overall well functioning filter-drainage performance after seismic shaking and resulting embankment deformations.	Rock ledges were not removed; surface preparation at abutment was poor; downstream drainage feature is absent.	Embankment-abutment contact areas could be potential locations for transverse crack development.

Topic 8: Existing Distress Conditions (Static and Hydraulic)

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(H). Existing Distress Conditions			
H1. Development of sand boils, seepage distress with increasing pool			
H2. Instrumentation data for phreatic surface			
H3. Instrumentation data for deformations			
H4. Instrumentation data for settlement			
H5. Observations from dam site			
Etc. (Site Specific)			

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Topic 8: Existing Distress Conditions (Static and Hydraulic) [Example]

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(H). Existing Distress Conditions			
H1. Development of sand boils, seepage distress with increasing pool	Existing sand boils and seepage distress indicates presence of existing defects.	Sand boils and wet areas are present on downstream.	An earthquake event would likely exacerbate existing seepage conditions.
H2. Instrumentation data for phreatic surface	Instrumentation on crest, downstream, and toe are important to evaluate phreatic surface on downstream of a dam.	Existing (limited) piezometers indicate higher than expected phreatic surface on downstream slope.	Higher phreatic surface, even with filter and blanket drain, may indicate filter incompatibility and clogging of filters and blanket drains. Higher downstream phreatic surface may increase liquefaction potential and increased crest loss due to contributions of embankment deformations towards downstream.
H3. Instrumentation data for deformations	Instrumentation data for deformations may help monitor any slope stability issues prior to an earthquake and identify internal damage due to an earthquake. Some damage may not manifest on surface.	Existing instruments indicate a deeper shear plane with slow movements.	The existing instrument data may indicate slower movement of the sliding mass in static conditions, however, any movement along pre-existing sliding plane may be exacerbated due to an earthquake.

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Topic 8: Existing Distress Conditions (Static and Hydraulic) [Example] (2)

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(H). Existing Distress Conditions			
H4. Instrumentation data for settlement	Settlement monitors near the abutments, and along the crest (along interfaces of different zones), and transverse to the dam axis are important to monitor and characterize settlements in different zones.	Existing settlement monitors indicate settlement of upstream transition and shell zones. Cracks are also visible on surface near these differential settlement locations.	Differential settlement across the interface and cracks on surface indicate post-construction settlements. These may indicate pre-earthquake existing shear planes with potential weaker interfaces . Transverse cracks across different zones and abutment may be exacerbated during an earthquake.
H5. Observations from dam site	Detailed observations and recording by experienced personnel may help to identify issues that may require further inspection, data collection and instrumentation, and evaluation.	A hummocky slope surface of a poorly constructed dam.	This may be an indication of poor compaction of the dam, which with cycles of saturated conditions and subsequent drying may create uneven settlement of the surficial portions of the shell. However, in some cases, these may indicate material loss (such as development of piping erosion, segregation of finer particles, etc.)
Etc. (Site Specific)			

Topic 9: Seismic Freeboard

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(I). Seismic Freeboard			
I1. Allowable lowest freeboard			
I2. Continuity of low permeability core up safely above the maximum reservoir elevation.			

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Topic 9: Seismic Freeboard [Example]

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(I). Seismic Freeboard			
I1. Allowable lowest freeboard	Available seismic freeboard should be demonstrated (by analyses) to be able to safely retain to the reservoir after potential seismic deformations (deviatoric and volumetric) and seismic cracking, etc. for design-level seismic events. [Note: CA DSOD recommends 0.05H+5 freeboard for new dams]	Only 10 feet (~3 percent of height) freeboard available for this 300 feet tall dam for 3 to 6 months of a year.	Freeboard is inadequate and potential for overtopping due to earthquake-induced crest loss and cracking is high.
I2. Continuity of low permeability core up safely above the maximum reservoir elevation.	Low permeability core materials are usually extended up to the crest to slow down erosional damage due to overtopping.	Crest and top of core is 7 feet apart and erodible sand and gravel materials are in this area.	Available freeboard after an earthquake should be measured from top of impervious core, i.e., 7 feet less than crest level.

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Topic 10: Appurtenant Structures and Systems with Significance for Post-Earthquake Response and Performance

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(J). Appurtenant Structures and Equipment with Significance for Post Earthquake Response and Performance			
J1. Spillway with capability to lower reservoir elevation in an emergency scenario			
J2. Location of outlet towers/inlet tower compared to spillway			
J3. Presence of low elevation outlet tunnel/conduit [elevation, condition, and expected survivability/availability after EQ]			
J4. Special care around tunnel, pipe, outlet, etc. [such as backfill]			
J5. Expected post-EQ operational capability of control tower equipment, etc. at MDE-GM			
J6. Planning of post-earthquake response protocols and material supply			
J7. Etc. (Site Specific)			

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Topic 10: Appurtenant Structures and Systems with Significance in Post-Earthquake Response and Performance [Example]

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(J). Appurtenant Structures and Equipment with Significance in Post Earthquake Response			
J1. Spillway with capability to lower reservoir elevation in an emergency scenario	Regular side channel spillway is an important feature of embankment dams to provide flood control	Gated spillway system is available. Spillway capacities are suitably adequate.	An earthquake may damage spillway capability, if not properly designed and constructed (such as crack in rock-concrete lining)
J2. Location of outlet towers/inlet tower compared to spillway	Ideally intake tower or outlet tower with tunnels should not be in close proximity of spillway.	Intake tower in the dam is in close proximity to spillway gates.	Earthquake damage to intake tower may impact the gates spillway.
J3. Presence of low elevation outlet tunnel/conduit [elevation, condition, and expected survivability/availability after EQ]	A low level outlet is important for lowering reservoir pool in case of emergency.	No existing low level outlet available.	The ability of lowering reservoir pool to prevent further damage of the dam using low level outlet is not available.
J4. Special care around tunnel, pipe, outlet, etc. [such as backfill]	Any tunnel, utility crossing, etc. require special considerations such as backfill type, compaction, grouting, etc.	Tunnel backfill is granular even in core and poor compaction due to shape of the tunnel, etc.	Potential for liquefaction, differential settlement, and backward erosion piping (BEP).

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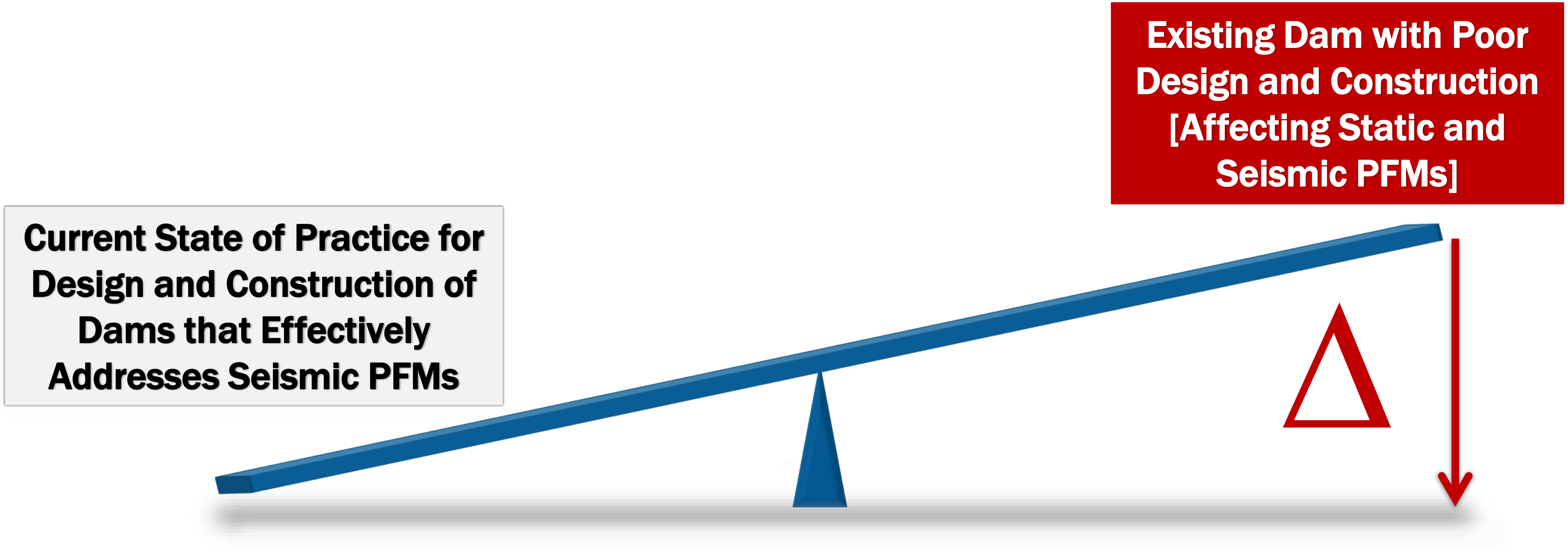
Topic 10: Appurtenant Structures and Systems with Significance in Post-Earthquake Response and Performance [Example] (2)

Evaluation Topic	Current Criteria or State of Practice [with Potential Significance for Seismic Performance]	Existing Dam Design, Construction, and Performance	Remarks on Potential Impacts of Differences Between Current Criteria/State of Practice and the Existing Dam
(J). Appurtenant Structures and Equipment with Significance in Post Earthquake Response			
J5. Expected post-EQ operational capability of control tower equipment, etc. at MDE-GM	Equipment in an intake tower or outlet tower needs to be operational after an earthquake and the outlet facility should be reliably safe for use in the immediate aftermath of a seismic event. Equipment should be anchored to provide assured operational capability after an earthquake.	No assessment of equipment suitability was performed and these are not anchored.	Loss of ability to operate an outlet tower could happen after an earthquake
J6. Planning of post-earthquake response protocols and material supply	Post-earthquake response protocols are important to identify resources and actions in case of emergency. It could be critical to minimize damage (sometimes prevent uncontrolled release).	No emergency action plan is available to address earthquake damage.	
J7. Etc. (Site Specific)			

Assessment of Aging Dams for Seismic Potential Failure Modes: A Delta (Δ) Approach



Summary

- A qualitative tool to assess the contributing factors for potential performance of an existing dam during an earthquake. It requires a comprehensive qualitative evaluation of the system including dam foundation, embankment, abutments, spillway capacity, consequences, etc.
- It requires the practitioners to understand the historical dam design and construction practices and techniques that are inadequate, and the current state of practice that appropriately account for potential seismic PFMs. It provides a transparent communication platform between practitioners and decision makers.
- Findings can be used to (a). evaluate which contributing factors can be further investigated and analyzed using current state of practice investigations and analytical tools (such as foundation and embankment conditions) and
  (b). Evaluate which conditions require modification decisions based on engineering judgment (such as need to anchor the electrical and mechanical equipment in an inlet or outlet tower to provide post-earthquake functional capability).

Thank You

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