Restoration of the Salton Sea

Volume 2: Embankment Designs and Optimization Study

Appendix 2D: Risk Analysis

Attachment C: Tables with Relevant Factors used in Probability Estimates

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Table 1
Mid-Sea Sand Dam, Static – Internal Erosion of Embankment
Initiation. Does large defect exist in SCB Wall?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 1
Failure Mode Description: Static - Internal Erosion (Piping) of Embankment	
Event FM No.1a: Erosion initiates at a defect in the SCB cutoff wall What is the likelihood a panel-sized non-detected/repaired flaw exists after the SCB wall is constructed?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.0001(assumes high quality QC) 0.001 (assumes poor quality QC)		0.001(assumes high quality QC) 0.01 (assumes poor quality QC)

More Likely Factors	**Less Likely Factors**
Construction must take place over 8 miles (+7,000 panels)	Depth well known at all locations
Non-uniform foundation conditions	Slurry sets within 24 hours, gains 70% strength in 7 days
Salt water may interfere with cement setting	Stone columns in place reduce likelihood of slope instability
Magnitude 5 earthquake fairly likely at some point in the 400+ days required to build the wall	Fresh water used to mix SCB
Several mechanisms for defect.	Salt water cements exist
• side wall caves • cement bentonite mix is wrong • movement • loss of trench fluid • contractor doesn't go deep enough • contractor stops overnight etc.	Construction practice includes well established Q.C.
	Loss of trench fluid easily detected
	Construction with equal water head would result in low probability of fracturing
	Panel size is constraining length of defect

Table 2
Mid-Sea Sand Dam, Static – Internal Erosion of Embankment
Continuation. Are Type A and B materials incompatible?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 1
Failure Mode Description: Static - Internal Erosion (Piping) of Embankment	
Event FM No.1b: Filtered exit of seepage from zone A to zone B is deficient What is the likelihood of a continuous channel from the Type A/B materials to the downstream face?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.005		0.02

More Likely Factors	**Less Likely Factors**
Pluviation process will segregate Type B materials that can readily segregate	Types A & B will have similar gradations with B slightly coarser
Not controlled placement. Quality control will occur while stockpiling & handling but not during placement	Stratification in B not likely to occur over inter-connected layer 100 feet to 200 feet long
	Type A material has less than 10% fines, requiring high gradient and high velocity to move soil particles. Permeability with less than 10% fines will be high, so head would drop off quickly
	Distance from SCB wall to A/B contact is long
	Flaw in B not likely to continue to daylight at the downstream side

Table 3
Mid-Sea Sand Dam, Static – Internal Erosion of Embankment Progression. Can Type A material support roof?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 1
Failure Mode Description: Static - Internal Erosion (Piping) of Embankment	
Event FM No.1c: Materials are capable of supporting a roof What is the likelihood a roof will form in Type A material?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
	0.001	

More Likely Factors	**Less Likely Factors**
Zone of partial saturation can have some apparent cohesion to support a roof	Fines content less than 10%
	Non-plastic fines
	Lower material will be saturated and have little to no apparent cohesion
	Region of high gradient & partial saturation/apparent cohesion not likely to be extensive

Table 4
Mid-Sea Sand Dam, Static – Internal Erosion of Embankment
Unlimited Progression

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 1
Failure Mode Description: Static - Internal Erosion (Piping) of Embankment	
Event FM No.1d: Erosion can occur and flows are not limited	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.01		0.1

More Likely Factors	**Less Likely Factors**
If enough material is removed SCB wall will buckle	SCB is not easy to erode
	Type B material upstream of A serves as a crack stopper
	Stone column reinforcement

Table 5
Mid-Sea Sand Dam, Static – Internal Erosion of Embankment
Unsuccessful Intervention

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 1
Failure Mode Description: Static - Internal Erosion (Piping) of Embankment	
Event FM No.1e: Intervention is unsuccessful	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
	0.1	

More Likely Factors	Less Likely Factors
If monitoring is infrequent then sinkhole/slump won't be detected	Progressing slump or stoping will be easily observed & will take a long time
	Boil material may be observed being deposited downstream if water is low
	Fix is pretty simple

Table 6
Mid-Sea Sand Dam, Static – Internal Erosion of Foundation Material
Initiation. Does silty sand inclusion exist in stiff lacustrine?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 2
Failure Mode Description: Static - Internal Erosion of Foundation Material	
Event FM No.2a: A constrained, high-head silty sand inclusion exists, undetected in the stiff lacustrine. What is the likelihood a two order magnitude higher (or more) permeability material exist within the stiff lacustrine or below the stiff lacustrine charged to full reservoir head and constrained downstream of the sand dam?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.0001		0.005

More Likely Factors	Less Likely Factors
8 miles of dam	Exploration will be on close centers & will likely identify problematic situations
Several mechanisms for cracking upstream - Desiccation - Lateral spreading - Erosion channels - Dunes can existed on west side	Fat clay in exploration so far shows thick & continuous
Erosion channels can fit between exploration spacing	Depositional environment implies fat clay placed continuously for long periods of time
Silty-fine-sand lenses described in fat clay	If cracks are likely upstream, they are also likely downstream
Coarser - grained inclusions evident within fat clay in all CPT's to date	

Table 7
Mid-Sea Sand Dam, Static – Internal Erosion of Foundation Material
Initiation. Does small isolated hole exist in stiff lacustrine?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 2, FM No. 8
Failure Mode Description: Static - Internal Erosion of Foundation Material	
Event FM No.2b: Erosion initiates at a hole in the stiff lacustrine from the inclusion What is the likelihood the downstream constraint will be breached into a single small isolated defect in the downstream blanket that will maintain a high head concentrated flow and create high exit velocities?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.0001		0.007

More Likely Factors	**Less Likely Factors**
Pre-sea human activity left penetrations	Upper stiff lacustrine measured 4 to 31.5 feet thick.(the thicker the layer the less likely this event would occur)
Fluid flowing through hole likely to be lightly saline (won't disperse clay)	Material surrounding defect is likely to erode
Natural penetrations • Burrows • Roots • Sand boils from liquefaction • Pressure relief wells • Mud holes	Stiff lacustrine is likely dispersive
Event FM No.8b: Likelihood of this event for Rock Fill Dam with rock notches is one order of magnitude higher. Probability estimates are 0.001 to 0.07	

Table 8
Mid-Sea Sand Dam, Static – Internal Erosion of Foundation Material
Continuation. Are velocities sufficient to start erosion?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 2, FM No. 8
Failure Mode Description: Static - Internal Erosion of Foundation Material	
Event FM No.2c: Velocity is sufficient to start erosion in the inclusion What is the likelihood that velocity is sufficient for transporting silty sand up through the hole in the stiff lacustrine at or beyond the downstream toe?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.05		0.5

More Likely Factors	**Less Likely Factors**
Silty fine sand is highly erodible	Permeability of inclusion is low, limiting velocity/quantity
Many such layers identified	Flow path is more than 1200 feet long and flow is limited
Only takes 1 to 2 ft/sec velocity to start erosion	Flow has to travel vertically
	Removed material builds cone around hole
Event FM No.8c: Seepage path length of inclusion from upstream notch to downstream notch is approximately 400 feet (instead of 1200 feet with sand dam) and full head will dissipate over a much shorter distance. Therefore, probability of this event is higher for rock notches (0.1 to 0.7).	

Table 9
Mid-Sea Sand Dam, Static – Internal Erosion of Foundation Material
Unlimited Progression

Dam: Mid-Sea Sand Dam with Stone Columns		**Failure Mode:** FM No. 2, FM No. 8
Failure Mode Description: Static - Internal Erosion of Foundation Material		
Event FM No.2d: Materials are capable of supporting a roof, erosion can occur and progression is not limited.		
Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.001		0.01

More Likely Factors	**Less Likely Factors**
Depositional environment indicates that a layer of silty sand can be uniformly graded over extensive distances ↔	Very unlikely to have perfectly erodible material for 1200 feet
Stiff lacustrine has higher resistance than fine sand (hole will not expand larger than necessary to handle the available flow)	Layers within stiff lacustrine not likely to be greater than a few inches to a couple of feet thick
Unlimited reservoir supply	As eroded area enlarges, overlying stiff lacustrine will collapse into void, limiting failure progression. However, this in only true if layers are thin
Event FM No.8d: Seepage path is shorter for Rock Fill Dam with rock notches, making conditions for unlimited progression more likely, however rock fill is less erodible than sand. Accordingly, probability of this event for rock notches is estimated to be the same as for Sand Dam (0.001 to 0.01).	

Table 10
Mid-Sea Sand Dam, Static – Internal Erosion of Foundation Material
Unsuccessful Intervention

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 2, FM No. 8
Failure Mode Description: Static - Internal Erosion of Foundation Material	
Event FM No.2e: Intervention is unsuccessful	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.1		0.7

More Likely Factors	**Less Likely Factors**
With high tail water (such as during first filling) erosion isnot so easy to detect visually.	Under seepage is easy to detect, if no or little water downstream. Transported material is likely to be noted.
Magnitude of subsidence due to internal erosion will be on the order of typical settlement (if layer is few inches to 1 or 2 feet thick)	Slow development means more time to construct modifications
Slow load with decreased vigilance	Multiple instrumentation ways to detect
Reliable prediction from instrumentation of seepage not well established	If silty-sand layer is thick, a large volume of material must be eroded (slow development and easy to detect)
Event FM No.8e: Transported material more likely to be hidden in Rock Fill Dam with rock notches and erosion may continue undetected for a long period of time. Probability of unsuccessful intervention is estimated to be between 0.2 and 0.9.	

Table 11
Mid-Sea Sand Dam, Seismic- Deformation and Overtopping of Embankment
Estimated Deformations

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 3

Failure Mode Description: Seismic – Deformation and Overtopping of Embankment

Event FM No.3a: Type A material Strength Distribution
Event FM No.3b: Deformations under various seismic loads

Estimates of Deformations for various loads

Sand Dam Strength, psf	Deformation, ft						
	greater 0.9g (load 4)		0.7g to 0.9g (load 3)		0.26g to 0.7g (load 2)		0g to 0.26g (load 1)
	max	min	max	min	max	min	expected
1000	6	4	4	2	1	0.1	0
2000	2	1	0.8	0.5	0.1	0.01	0
3000	0	0	0	0	0	0	0

Strength Distribution for Type A material - The group agreed to use an equivalent Su convention to represent the strength of the Type A material. The lower bound of the strength was set as the lower bound of the Seed and Harder curve with an equivalent N1-60 blowcount of 20, or 1000 psf. A middle bound of 1600 psf was adopted based on a calculation of the average strength along the failure surface and the calculation: 40 feet by 65 pcf x tan 32. The upper bound was set at 3000 based on similar calculation of 40 feet by 125 pcf x tan 32. The corresponding deformations estimate with FLAC suggests that no deformations are expected from Load 1, and if the strength is 3000 psf no deformations are expected for any earthquake loads. For strength between 1000 and 2000 psf deformations for Load 2 range from 0.01 to 1 foot, for Load 3 they range from 0.5 to 4 feet and for Load 4 from 1 to 6 feet.

Table 12
Mid-Sea Sand Dam, Seismic- Deformation and Overtopping of Embankment
Overtopping failure potential versus freeboard

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 3
Failure Mode Description: Seismic – Deformation and Overtopping of Embankment	
Event FM No.3c: Overtopping potential as a function of residual freeboard What is the probability the dam will continue to breach if the post-earthquake freeboard is X?	

Estimates		
Probability of failure at this residual freeboard	**Minimum Freeboard**	**Maximum Freeboard**
0	1.5	4
0.1	1	3
0.5	-0.1	1.5
0.9		1
0.95	-0.75	
1	-1	0.5

More Likely Factors	**Less Likely Factors**
Wave runup can be several feet	SCB wall blocks transverse, open, deep upstream/downstream cracks
Wind that can produce significant waves is relatively frequent in the areas	SCB wall does not deform
Very long dam, large fetch	Sandbags or geotube intervention is included in estimates
Sand on both sides of the wall will be prone to erosion under conditions of overflow that is more than 3 to 6 inches	
Mitigation measures such as additional crest armoring with rock, reinforcement of the upper portion of the SCB wall are not included in estimates	

Table 13
Mid-Sea Sand Dam, Seismic – Internal Erosion of Embankment
Initiation. Does large defect exist in SCB wall?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 4
Failure Mode Description: Seismic - Internal Erosion of Embankment	
Event FM No.4a: Erosion initiates at a defect in the SCB cutoff wall What is the likelihood the SCB wall will be damaged by an earthquake such that large seepage quantities flow through the wall?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
Load 2 - 0.01 Load 3 - 0.9	Load 1 - 0 Load 4 - 1	Load 2 - 0.1 Load - 0.99

More Likely Factors	**Less Likely Factors**
Load 1 - No damage would occur	
Load 2 - Some fracturing. 1 mile of wall would be damaged	For less than 5% shear, elastic behavior sustainable without fracture
Load 3 - More fracturing. 1 to 3 miles of wall would be damaged	For shear between 5 and 100% fracturing zone. Block size decreases and aperture size increases as shear increases (rubble-ize)
Load 4 - Wall crumbles (rubble-ized) whole structure damaged	For 100% shear, offset region

Large defect forms in SCB wall due to earthquake. FLAC results suggest that the highest strains in the wall will be at the contact between the dam and stiff lacustrine material. Strains are large enough to induce cracking but not a complete offset of the wall. Permeability in this zone would likely increase in by 2 orders of magnitude (i.e. from 1x 10-6 to 1 x10-4 cm/sec). Defect development was discussed at three possible locations.

- Shear near crest of the dam
- Shear at base
- Shear in weak area or defect constructed in wall

Overall, the group postulated the most likely location for a significant defect was at the base of the wall. Assuming that the base of the wall was damaged to cause two orders of magnitude change in permeability the unit rate of seepage through the wall could change from about 0.0001 to 0.01 cfs.ft. Over a three-mile length, the leakage would increase from about 2 cfs to 200 cfs. This amount of seepage would be judged a failure of the system.

Table 14
Mid-Sea Sand Dam, Seismic – Internal Erosion of Embankment
Continuation. Are Type A and B materials incompatible?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 4
Failure Mode Description: Seismic - Internal Erosion of Embankment	
Event FM No.4b: Filtered exit of seepage from zone A to zone B is deficient What is the likelihood of a continuous channel from the Type A/B materials to the downstream face?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.01		0.04

More Likely Factors	**Less Likely Factors**
Pluviation process will segregate B materials that can readily segregate	Types A & B will have similar gradations with B slightly coarser
Not controlled placement. Quality control will occur while stockpiling & handling but not during placement.	Stratification in Type B material not likely to occur over inter-connected layer 100' to 200 feet long.
During an earthquake some B material will move away reducing the distance from A/B interface to seepage exit face.	Type A material has less than 15% fines, requiring high gradient and high velocity to move soil particles. Permeability with less than 15% fines will be high so head would drop off quickly
	Distance from SCB wall to A/B contact is large
	Flaw in B not likely to continue to daylight at the downstream side.

Table 15
Mid-Sea Sand Dam, Seismic – Internal Erosion of Embankment Progression. Can Type A material support roof?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 4
Failure Mode Description: Seismic - Internal Erosion of Embankment	
Event FM No.4c: Materials are capable of supporting a roof What is the likelihood a roof will form in Type A material?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
	0.001	

More Likely Factors	Less Likely Factors
Zone of partial saturation can have some apparent cohesion to support a roof	Fines content less than 15%
	Non-plastic fines
	Lower material will be saturated and have little to no apparent cohesion
	Region of high gradient & partial saturation/apparent cohesion not likely to be extensive

Table 16
Mid-Sea Sand Dam, Seismic – Internal Erosion of Embankment
Unlimited Progression

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 4
Failure Mode Description: Seismic - Internal Erosion of Embankment	
Event FM No.4d: Erosion can occur and flows are not limited	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.01 (loads 1, 2, 3) 0.02 (load 4)		0.1 (loads 1, 2, 3) 0.15 (load 4)

More Likely Factors	**Less Likely Factors**
If enough material is removed SCB wall will buckle	SCB is not easy to erode.
During an earthquake SCB material may crumble above water table increasing likelihood of erodibility	Type B upstream of A serves as a crack stopper
	Stone column reinforcement
	If SCB does not crumble there will not be a change in erodibility

Table 17
Mid-Sea Sand Dam, Seismic – Internal Erosion of Embankment
Unsuccessful Intervention

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 4
Failure Mode Description: Seismic - Internal Erosion of Embankment	
Event FM No.4e: Intervention is unsuccessful	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.2 (load 2) 0.4 (load 3) 0.7 (load 4)		0.4 (load 2) 0.6 (load 3) 0.9 (load 4)

More Likely Factors	Less Likely Factors
If monitoring is infrequent then sinkhole/slump won't be detected	Progressing slump or stoping will be easily observed & will take a long time
Fix would require replacing the wall and regrading crest , which may take longer than the time for reservoir to empty	Boil material may be observed being deposited downstream if water is low
	Fix is pretty simple

Table 18
Mid-Sea Sand Dam, Seismic – Internal Erosion of Foundation
Initiation. Does silty sand inclusion exist in stiff lacustrine?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 5
Failure Mode Description: Seismic - Internal Erosion of Foundation	
Event FM No.5a: A constrained, high-head silty sand inclusion exists, undetected in the stiff lacustrine. What is the likelihood a two order magnitude (or more) material exist within the stiff lacustrine or below the stiff lacustrine charged to full reservoir head and constrained downstream of the sand dam?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.0001		0.005

More Likely Factors	**Less Likely Factors**
Explorations for seismic fix would increase likelihood of connection with reservoir ↔	Exploration for seismic fix would decrease likelihood of downstream toe being constrained
8 miles of dam	Exploration will be on close centers & will likely identify problematic situations
Several mechanisms for cracking upstream - Desiccation - Lateral spreading - Erosion channels - Dunes can existed on west side	Fat clay in exploration so far shows thick & continuous
Erosion channels can fit between exploration spacing	Depositional environment implies fat clay placed continuously for long periods of time.
Silty-fine-sand lenses described in fat clay	If cracks are likely upstream, they are also likely downstream.
Coarser - grained inclusions evident within fat clay in all CPT's to date	

Table 19
Mid-Sea Sand Dam, Seismic – Internal Erosion of Foundation
Initiation. Does small isolated hole exist in stiff lacustrine?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 5, FM No.11
Failure Mode Description: Seismic - Internal Erosion of Foundation	
Event FM No.5b: Erosion initiates at a hole in the stiff lacustrine from the inclusion What is the likelihood the downstream constraint will be breached into a single small isolated defect in the downstream blanket that will maintain a high head concentrate flow create high exit velocities?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.001		0.07

More Likely Factors	**Less Likely Factors**
Pre-sea human activity left penetrations	Upper stiff lacustrine measured 4 to 31.5 feet thick (the thicker the layer the less likely this event will occur)
Fluid flowing through hole likely to be highly saline (won't disperse clay)	Material surrounding defect is likely to erode.
Natural penetrations Burrows Roots Sand boils from liquefaction Pressure relief wells Mud holes	Stiff lacustrine is likely to dispersive.
Earthquake can damage grout in exploration holes	
Earthquake can build up pressure in silty sand layer that may blow out	
Event FM No. 11b: Likelihood of this event for Rock Fill Dam with rock notches is the same. Probability estimates are 0.001 to 0.07	

Table 20
Mid-Sea Sand Dam, Seismic – Internal Erosion of Foundation
Continuation. Are velocities sufficient to start erosion?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 5, FM No.11
Failure Mode Description: Seismic - Internal Erosion of Foundation	
Event FM No.5c: Velocity is sufficient to start erosion in the inclusion What is the likelihood that velocity is sufficient for transporting silty sand up through the hole in the stiff lacustrine at or beyond the downstream toe?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.05		0.5

More Likely Factors	**Less Likely Factors**
Silty fine sand is highly erodible	Permeability of inclusion is low, limiting velocity/quantity approximately 10^{-3} - 10^{4} cm/sec
Many such layers identified	Flow path is more than 1200 feet and flow is small
Only takes 1 to 2 ft/sec velocity to start erosion	Flow has to travel vertically
Pressure might be higher to initiate velocities and start flow (pressure relief liquefaction phenomenon)	Removed material builds cone around hole
	Earthquake might cause hole to collapse

Event FM No. 11c: Seepage path length of inclusion from upstream notch to downstream notch is approximately 400 feet (instead of 1200 feet with sand dam) and full head will dissipate over a much shorter distance. Therefore, probability of this event is higher for rock notches (0.1 to 0.7)

Table 21
Mid-Sea Sand Dam, Seismic – Internal Erosion of Foundation
Progression unlimited?

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 5, FM No.11
Failure Mode Description: Seismic - Internal Erosion of Foundation	
Event FM No.5d: Materials are capable of supporting a roof, erosion can occur and progression is not limited.	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.001		0.01

More Likely Factors	**Less Likely Factors**
Depositional environment indicates that a layer of silty sand can be uniformly graded over extensive distances	Very unlikely to have perfectly erodible material for 1200 feet
Stiff lacustrine has higher resistance to erosion than fine sand (hole will not expand larger than necessary to handle the available flow)	Layers within stiff lacustrine not likely to be greater than a few inches to a couple of feet thick
Unlimited reservoir supply	As eroded area enlarges, overlying stiff lacustrine will collapse into void, limiting failure progression. However, this is only true if layers are thin
Event FM No. 11d: Seepage path is shorter for Rock Fill Dam with rock notches, making conditions for unlimited progression more likely, however rock fill is less erodible than sand. Accordingly, probability of this event for rock notches is estimated to be the same as for Sand Dam (0.001 to 0.01).	

Table 22
Mid-Sea Sand Dam, Seismic – Internal Erosion of Foundation
Intervention Unsuccessful?

<table>
<tr><td colspan="3">Dam: Mid-Sea Sand Dam with Stone Columns</td><td colspan="3">Failure Mode: FM No. 5, FM No.11</td></tr>
<tr><td colspan="6">Failure Mode Description: Seismic - Internal Erosion of Foundation</td></tr>
<tr><td colspan="6">Event FM No.5e: Intervention is unsuccessful</td></tr>
<tr><td colspan="6">Estimates</td></tr>
<tr><td colspan="2">Reasonable Low</td><td colspan="2">Best Estimate</td><td colspan="2">Reasonable High</td></tr>
<tr><td colspan="2">0.5</td><td colspan="2"></td><td colspan="2">0.9</td></tr>
<tr><td colspan="3">More Likely Factors</td><td colspan="3">Less Likely Factors</td></tr>
<tr><td colspan="3">With high tail water (such as during first filling) not so easy to detect visually</td><td colspan="3">Under seepage is easy to detect, if no or little water downstream. Transported material is likely to be noted</td></tr>
<tr><td colspan="3">If layer is few inches to 1 or 2 feet thick magnitude of subsidence due to internal erosion will be on order of typical settlement</td><td colspan="3">Slow development means more time to construct modifications</td></tr>
<tr><td colspan="3">Slow load with decreased vigilance</td><td colspan="3">Multiple instrumentation ways to detect</td></tr>
<tr><td colspan="3">Reliable prediction from instrumentation of seepage not well established</td><td colspan="3">If silty-sand layer is thick, a large volume of material must be eroded (slow development and easy to detect)</td></tr>
<tr><td colspan="3">Possibly extensive infrastructure damage due to and earthquake may distract from implementing remedial actions</td><td colspan="3">Increased awareness immediately after and earthquake</td></tr>
<tr><td colspan="6">Event FM No. 11e: Probability of unsuccessful intervention for Rock Fill Dam with rock fill notches is estimated to be the same as for Sand Dam (0.5 to 0.9)</td></tr>
</table>

Table 23
Mid-Sea Sand Dam, Seismic- Liquefaction of Stiff Lacustrine
Estimated Deformations

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 6
Failure Mode Description: Seismic – Liquefaction of Stiff Lacustrine, Seismic Deformation and Overtopping of Embankment	
Event FM No.6a: Deformations under various seismic loads	

Estimates of Deformations for various loads

Deformation, ft						
greater 0.9g (load 4)		0.7g to 0.9g (load 3)		0.26g to 0.7g (load 2)		0g to 0.26g (load 1)
max	min	max	min	max	min	expected
11	5	9	5	6	5	5

This failure mode is similar to FM No.3 with one key difference. The embankment yield acceleration with liquefied stiff lacustrine will be approximately 0.03 to 0.05 g, which is significantly lower than the design criteria of 0.17g, assumed to be met for FM No.3. The RET judged that embankment deformations due to liquefaction in the stiff lacustrine will be greater than 5 feet (available freeboard) for all seismic loads. Actual deformations may be significantly higher. Based on the Newmark analysis, deformations for yield acceleration of 0.05g would be between 15 and 30 feet.

Table 24
Mid-Sea Sand Dam, Seismic- Deformation and Overtopping of Embankment
Overtopping failure potential versus freeboard

Dam: Mid-Sea Sand Dam with Stone Columns	**Failure Mode:** FM No. 6
Failure Mode Description: Seismic – Liquefaction of Stiff Lacustrine, Seismic Deformation and Overtopping of Embankment	
Event FM No.6b: Overtopping potential as a function of residual freeboard What is the probability the dam will continue to breach if the post-earthquake freeboard is X?	

Estimates		
Probability of failure at this residual freeboard	**Minimum Freeboard**	**Maximum Freeboard**
0	1.5	4
0.1	1	3
0.5	-0.1	1.5
0.9		1
0.95	-0.75	
1	-1	0.5

More Likely Factors	**Less Likely Factors**
Wave runup can be several feet	SCB wall blocks transverse, open, deep upstream/downstream cracks
Wind that can produce significant waves is relatively frequent in the areas	SCB wall does not deform
Very long dam, large fetch	Sandbags or geotube intervention is included in estimates
Sand on both sides of the wall will be prone to erosion under conditions of overflow that is more than 3 to 6 inches	
Mitigation measures such as additional crest armoring with rock, reinforcement of the upper portion of the SCB wall are not included in estimates	

Table 25
Mid-Sea Rockfill Dam with Rock Notches, Static – Internal Erosion of Foundation Material
Initiation. Does silty sand inclusion exist in stiff lacustrine?

Dam: Mid-Sea Rockfill Dam with Rock Notches	**Failure Mode:** FM No. 8
Failure Mode Description: Static - Internal Erosion of Foundation Material	
Event FM No.8a: A constrained, high-head silty inclusion exists, undetected in the stiff lacustrine What is likelihood a silty sand inclusion exists close to the bottom of the downstream rock notch that has a connection to the upstream rock notch?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.0005		0.01

More Likely Factors	**Less Likely Factors**
8 mile long dam	Exploration on close centers will likely detect inclusion
Silty-sand layers described in stiff lacustrine	Depositional environment implies fat clay placed continuously for long periods of time
CPT's show inclusions in each borehole	If cracks are likely upstream, they are also likely downstream.
Seepage path length of inclusion from upstream to downstream is approximately 400 feet (instead of 1200 feet with sand dam)	Fat clay in exploration so far shows thick & continuous
Depositional environment indicates that a layer of silty sand can be uniformly graded over extensive distances	Vertical distance from bottom of upstream rock notch to pervious inclusion at bottom of downstream rock notch is approximately 40 feet. A connection of inclusion to full reservoir head is unlikely at this depth

Table 26
Mid-Sea Rockfill Dam with Rock Notches, Seismic –Overtopping of Embankment
Estimated Deformations

Dam: Mid-Sea Rockfill Dam with Rock Notches

Failure Mode: FM No. 9

Failure Mode Description: Seismic – Deformation and Overtopping of Embankment

Event FM No.9a: Upper Stiff Lacustrine Strength Distribution

Event FM No.9b: Deformations under various seismic loads

Estimates of Deformations for various loads

Sand Dam Strength, psf	Deformation, ft						
	greater 0.9g (load 4)		0.7g to 0.9g (load 3)		0.26g to 0.7g (load 2)		0g to 0.26g (load 1)
	max	min	max	min	max	min	expected
1000	6	4	4	2	1	0.1	0
2000	2	1	0.8	0.5	0.1	0.01	0
3000	0	0	0	0	0	0	0

Strength Distribution for Upper Stiff Lacustrine - S_u convention was used to represent the strength of the stiff lacustrine material. The lower bound of the strength 1,000 psf. Assuming a linear increase of strength with depth (s_u/σ'_v of 0.3) and an average depth of a failure surface of 60 feet. The upper bound value 2,700 psf, assuming frictional resistance of 32 degrees: Su=60 ft x 65 psf x tan (32°). The most likely value was estimated at 1,500 psf. The range of deformations fro this embankment configuration would be the same as predicted for Sand Dam (FM No. 5) because cross section has same yield accelerations (0.17)

Table 27
Mid-Sea Rockfill Dam with Rock Notches, Seismic –Overtopping of Embankment
Overtopping failure potential versus freeboard

Dam: Mid-Sea Rockfill Dam with Rock Notches	**Failure Mode:** FM No. 9
Failure Mode Description: Seismic – Deformation and Overtopping of Embankment	
Event FM No.9c: Overtopping potential as a function of residual freeboard What is the probability the dam will continue to breach if the post-earthquake freeboard is X.	

Estimates		
Probability of failure at this residual freeboard	**Minimum Freeboard**	**Maximum Freeboard**
0	1.5	1
0.1	-3.5	-0.5
0.5	-6.5	-3
0.9	-7.5	-4
1	-10	-6

More Likely Factors	**Less Likely Factors**
	SCB wall blocks transverse, open, deep upstream/downstream cracks
	Rock fill shells not erodible
	Rock fill with 1 to 4 feet rocks has large through-flow capacity
	Rock fills historically perform well under overtopping (Hell Hole Dam overtopped by approximately 20 feet before significant damage has occurred)
	Wave action not likely to lead to a breach

Table 28
Mid-Sea Rockfill Dam with Rock Notches, Seismic –Internal Erosion of Foundation Initiation. Does silty san inclusion exist in stiff lacustrine?

Dam: Mid-Sea Rockfill Dam with Rock Notches	**Failure Mode:** FM No. 11
Failure Mode Description: Seismic - Internal Erosion of Foundation Material	
Event FM No.11a: A constrained, high head silty sand inclusion exists undetected in the stiff lacustrine What is likelihood a silty sand inclusion exists close to the bottom of the downstream rock notch that has a connection to the upstream rock notch?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
0.0005		0.01

More Likely Factors	**Less Likely Factors**
8 mile long dam	Exploration on close centers will likely detect inclusion
Silty-sand layers described in stiff lacustrine	Depositional environment implies fat clay placed continuously for long periods of time
CPT's show inclusions in each borehole	If cracks are likely upstream, they are also likely downstream.
Seepage path length of inclusion from upstream to downstream is approximately 400 feet (instead of 1200 feet with sand dam)	Fat clay in exploration so far shows thick & continuous
Depositional environment indicates that a layer of silty sand can be uniformly graded over extensive distances	Vertical distance from bottom of upstream rock notch to pervious inclusion at bottom of downstream rock notch is approximately 40 feet. A connection of inclusion to full reservoir head is unlikely at this depth

Table 29
South Sea Dam Fault Offset/Translation

Dam: South Sea Dam	**Failure Mode:** FM No. 12
Failure Mode Description: Seismic – Offset and Translation of Embankment Foundation Material	
Event FM 12a: Displacements exceeding 1 m What is the likelihood of displacement on the Imperial San Andreas step-over translation exceeding 1 m?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
	1/80 chance (0.0125)	

More Likely Factors	Less Likely Factors
Fault offsets as high as 6.5 meters may occur under the South Sea Dam	Shear zone can be 50 feet wide. Offsets can be distributed such that any one offset is less than 1 m
Any characteristic seismic event on Imperial and/or San Andreas faults could cause large displacements	

Table 30
South Sea Dam Fault Offset/Translation

Dam: South Sea Dam	**Failure Mode:** FM No. 12
Failure Mode Description: Seismic – Offset and Translation of Embankment Foundation Material	
Event FM 12b: Embankment failure by translation If there is more than 1 meter of displacement on the Imperial San Andreas step-over translation, what is the likelihood the South Sea dam will fail?	

Estimates		
Reasonable Low	**Best Estimate**	**Reasonable High**
	0.9	

More Likely Factors	Less Likely Factors
Velocities likely to start erosion at downstream end of Type A material	Shear zone can be 50 feet wide. Offsets can be distributed such that any one offset is less than wall thickness
Wall no longer there to limit progression	
Intervention can not happen because failure develops too quickly	
With this much displacement significant shaking is very likely and Type B material is likely to slide away from Type A, removing filter	
Strike/slip movement is oriented approximately 45 degrees to dam and would cause wall to fail in compression	
Channel flow velocities rather than Darcy flow	
Strike/slip has vertical component, crest settlement of 2 to 4 feet is likely	