Best Practices in Dam and Levee Safety Risk Analysis

V-4. Buttress Dams

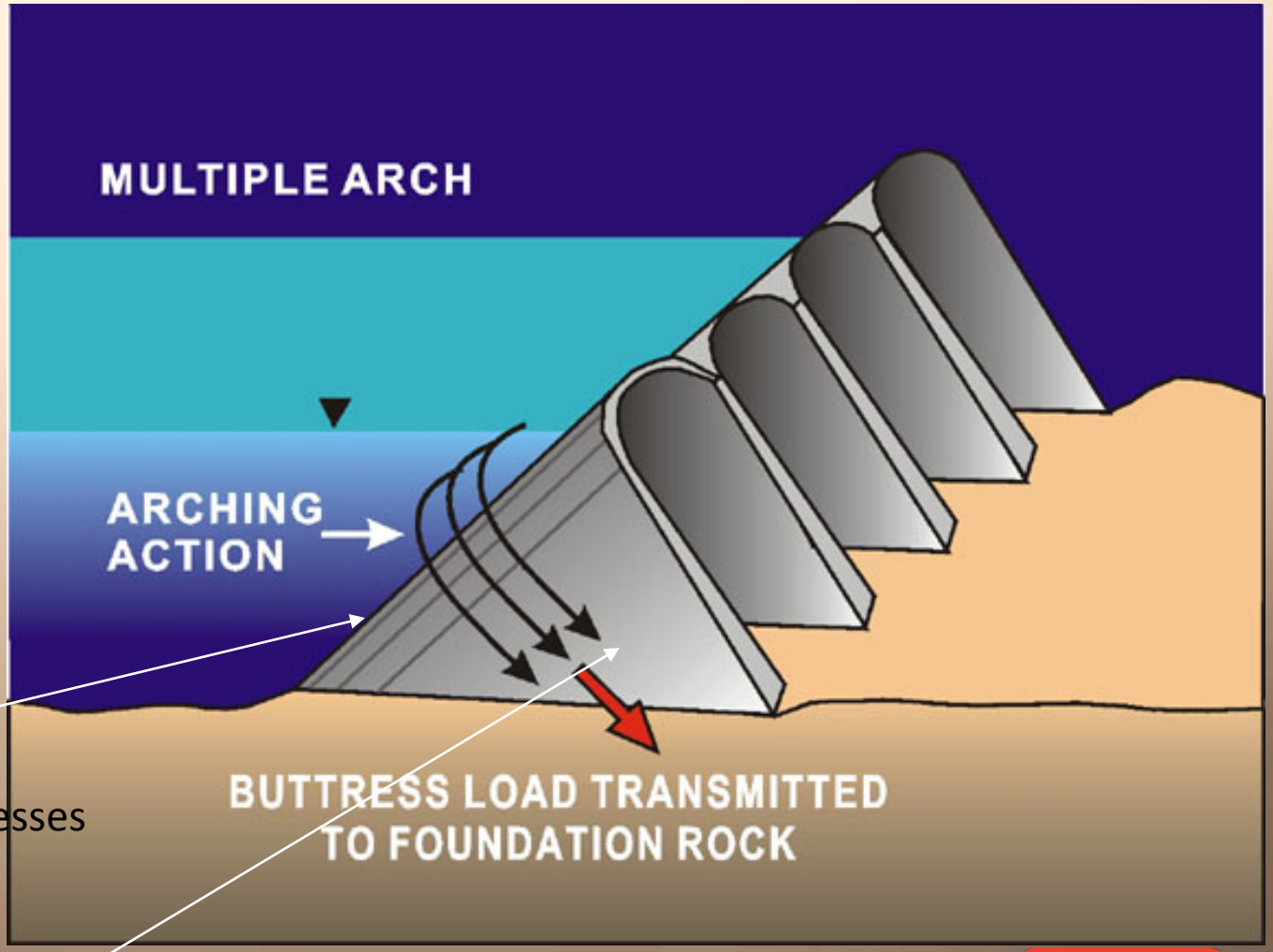
12 June 2015

RECLAMATION
Managing Water in the West

US Army Corps of Engineers
BUILDING STRONG®

Buttress Dams

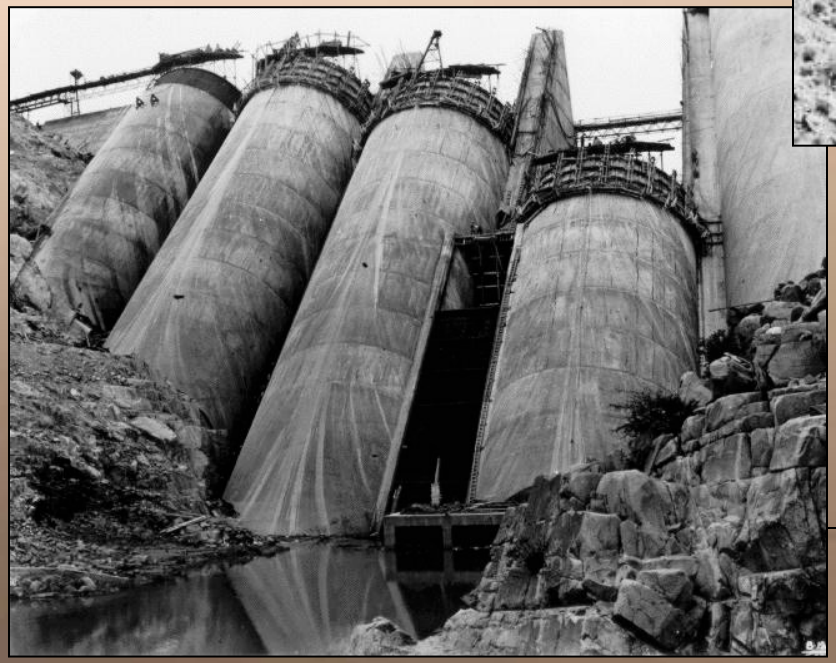
Similar to gravity dams
Center removed
Expensive materials
Cheap labor
Sloped upstream face



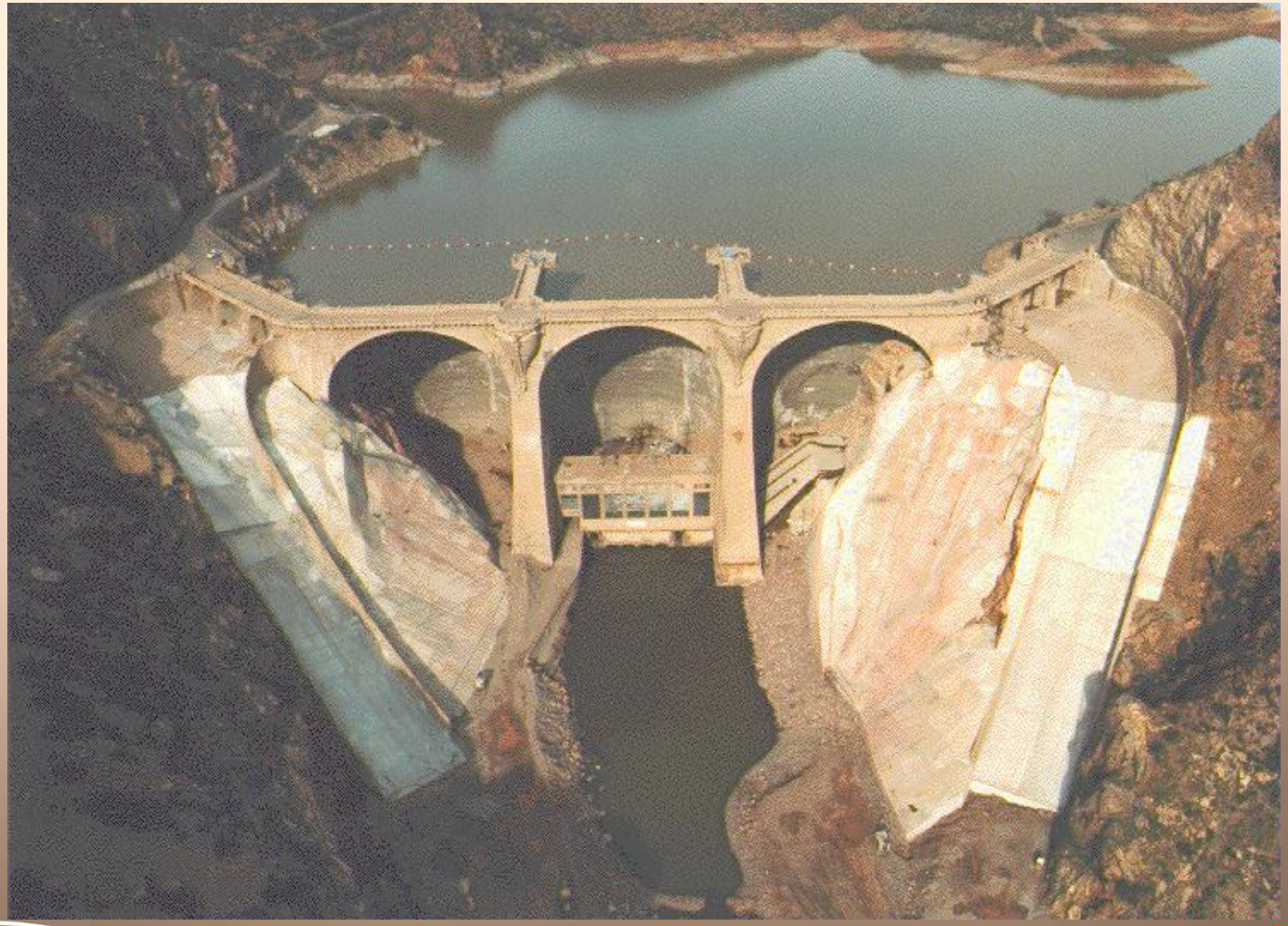
Upstream water barrier:
- Arches
- Slabs
- Massive-head buttresses
- Domes

Buttresses

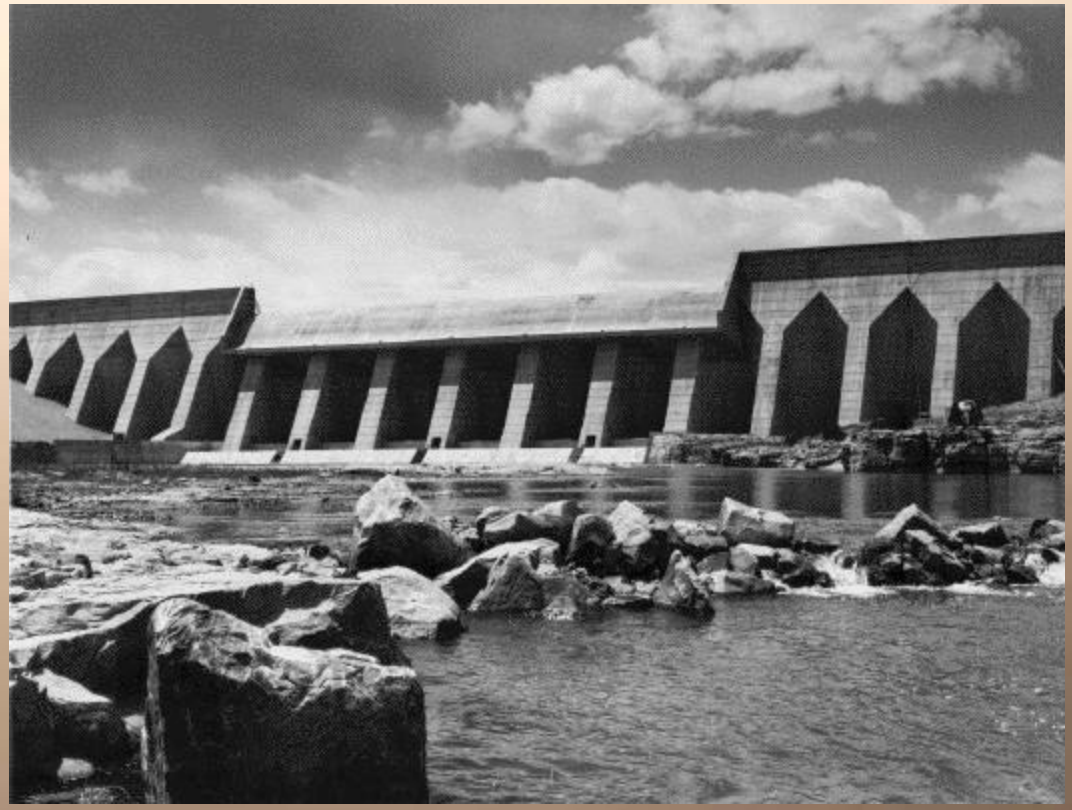
Multiple Arch Buttress



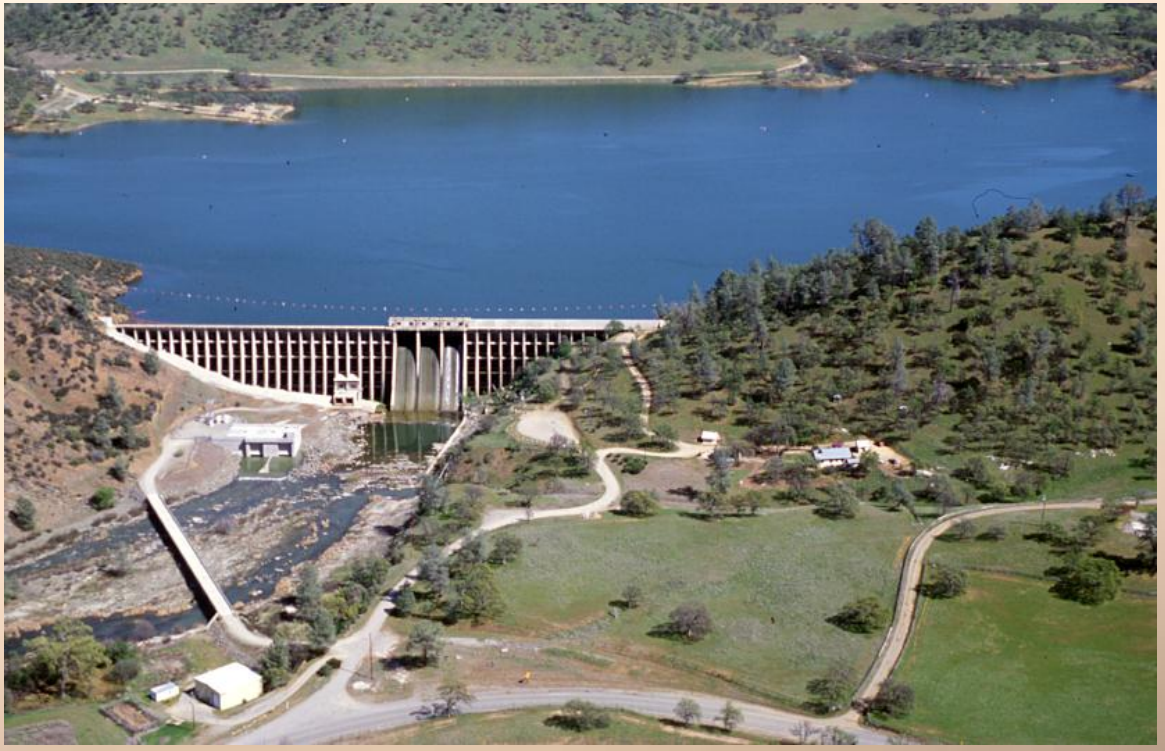
Dome and Buttress



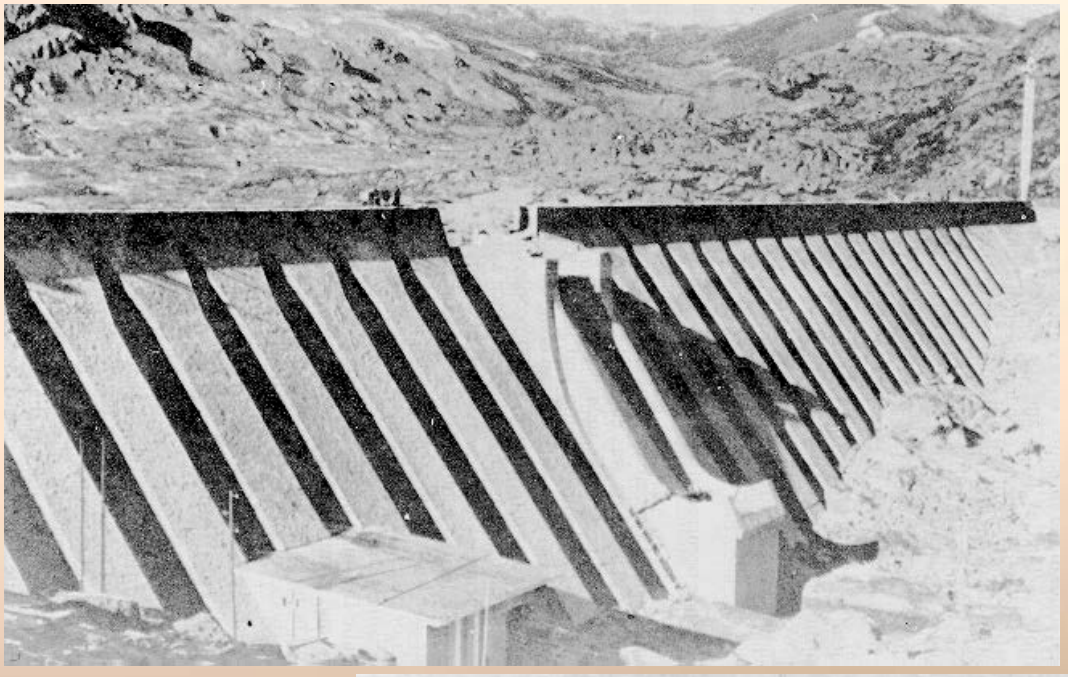
Massive-Head Buttress



Slab and Buttress



Vega de Tera Dam, Northwest Spain



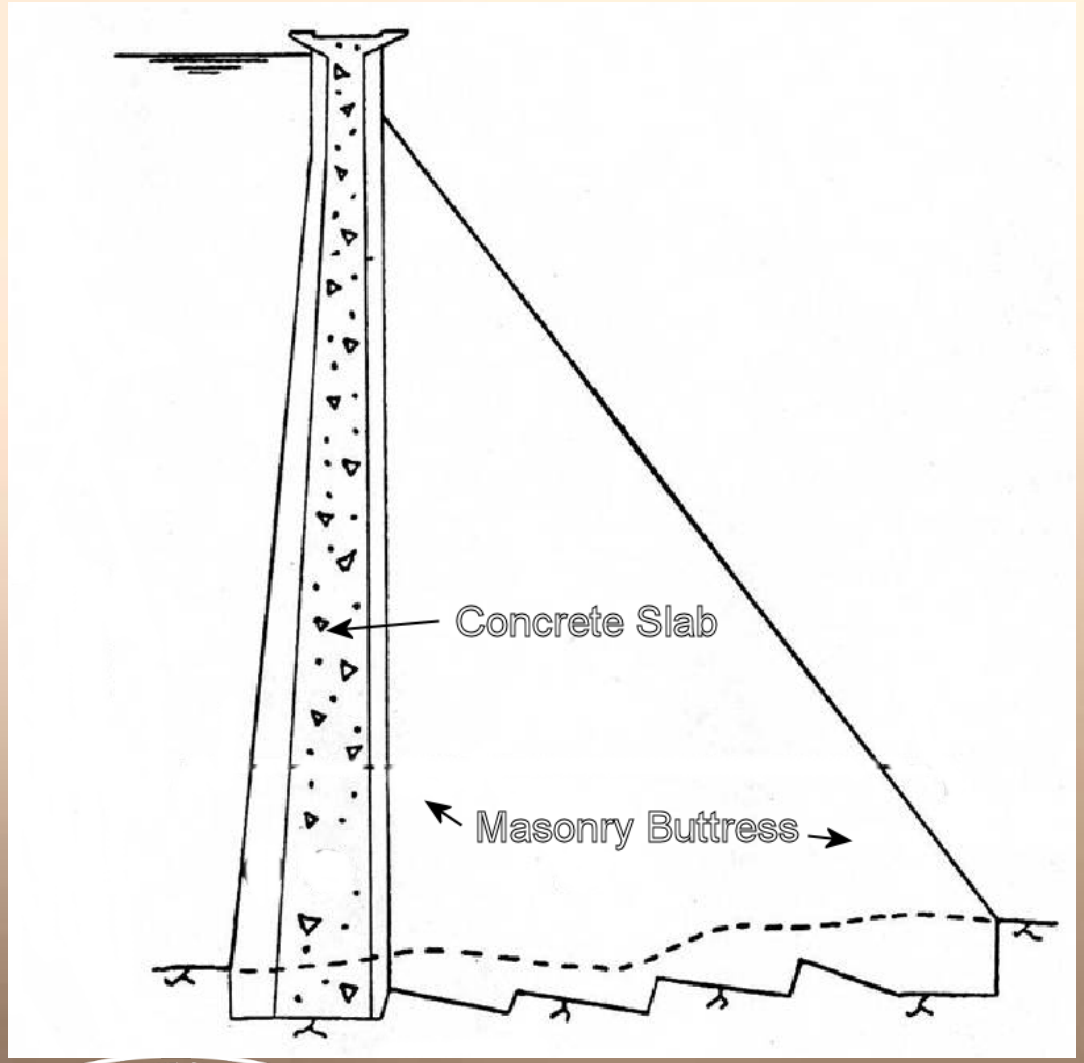
112’ high buttress dam completed 1957

Winter shutdown, little attention to lift joints

Failed January 10, 1959

144 fatalities

Vega de Tera Dam



Buttresses cement mortared masonry

Grouting in 1956 to control leakage

Reservoir full in 1958

Empty in October 1958

In January, heavy rains filled reservoir

17 buttresses failed in rapid succession

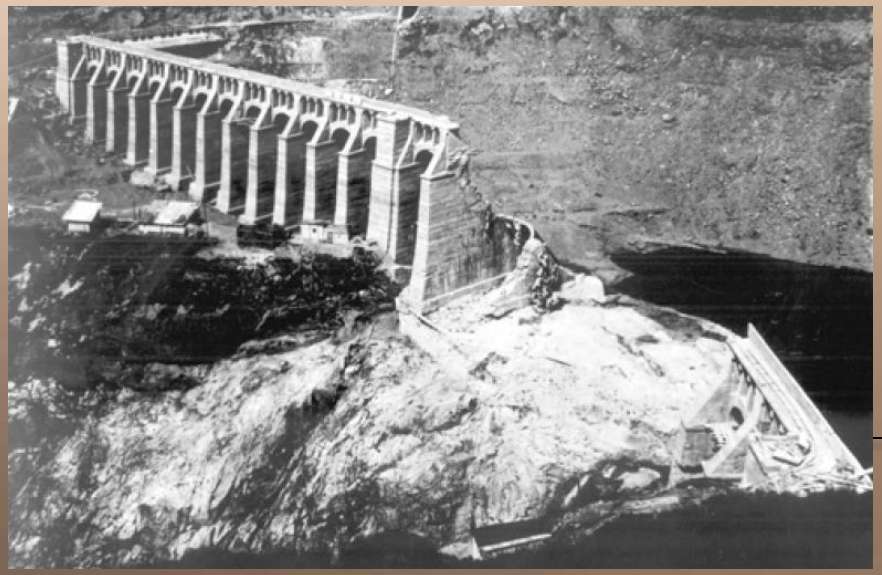
Failure initiated between masonry and concrete on sloping portion of foundation

Modulus of masonry = 140,000 lb/in^2

Official cause of failure attributed to large deformations due to low modulus masonry

But not much slope on u/s face!

Gleno Dam, Italy



164-ft high multiple arch

52-foot high masonry plug constructed in deep central gorge (lime mortar instead of specified cement mortar)

Original design called for gravity dam; design changed and dam built prior to approval

Poor concrete quality

Failed October 22, 1923

100-foot high wave, widespread destruction in Dezzo River Valley

356 fatalities

Gleno Dam

Key facts

Dam survived full reservoir for nearly 2 months

Masonry plug survived nearly intact

Cracking in buttresses followed direction of maximum shear

Gleno Dam

Official report on cause of failure

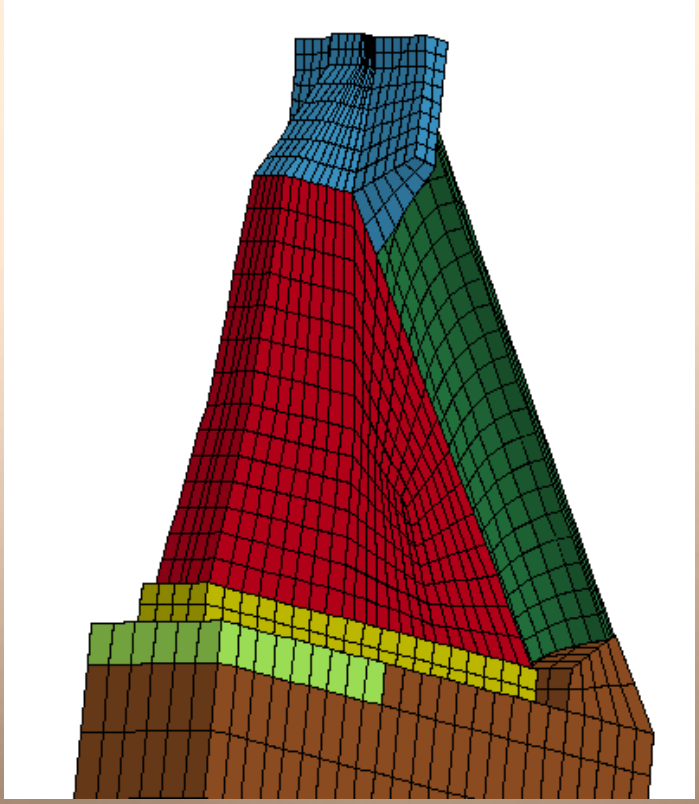
- Continued leakage progressively weakened (leached lime mortar) masonry plug (dam was stable for over a month)
- Plug unable to “arch” due to outlet
- Plug did not extend downstream far enough
- Deformation occurred
- Buttresses and Arches unable to accommodate movement

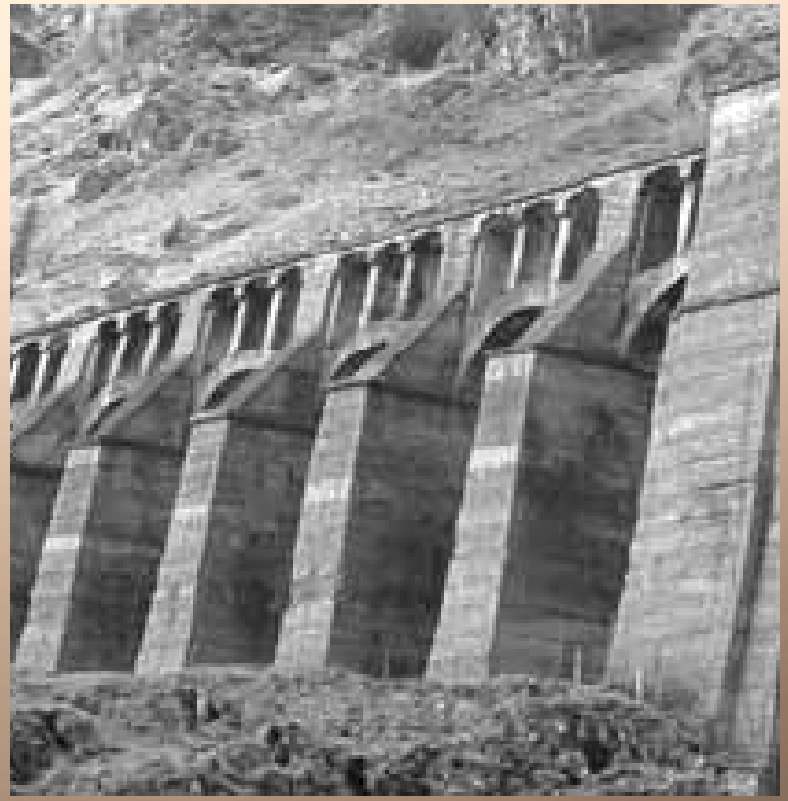
Other reports suggest alternate mechanisms

- Masonry plug survived nearly intact
- Sliding at base of buttresses (smooth surface, cleanup unknown, anchor bars inadequate)
- Shear failure of buttresses (calculated shear stress exceeded concrete strength, cracks followed planes of maximum shear)

Gleno Dam Failure – FE Model

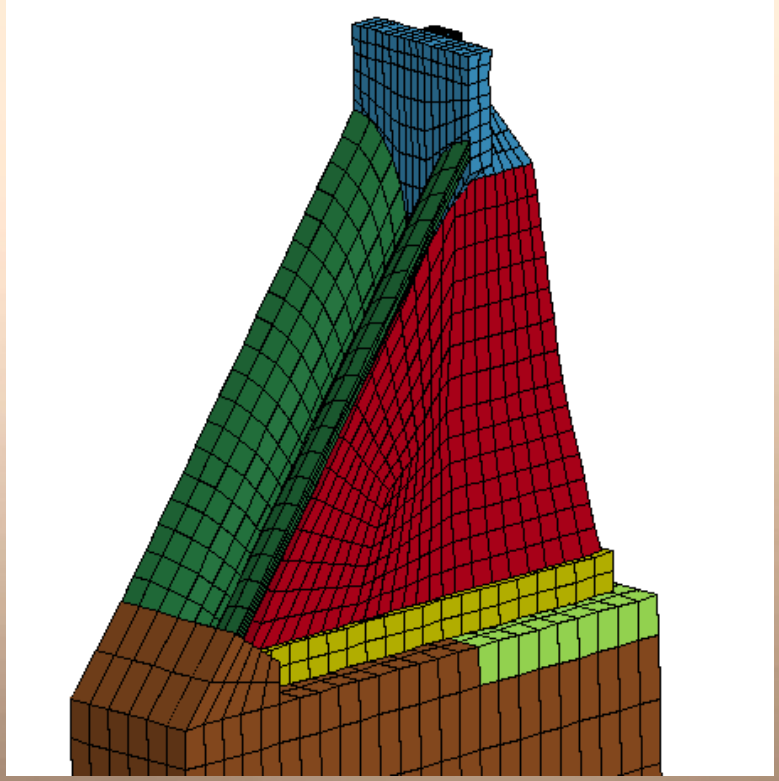
- General views of the model





Gleno Dam Failure – FE Model

- General views of the model

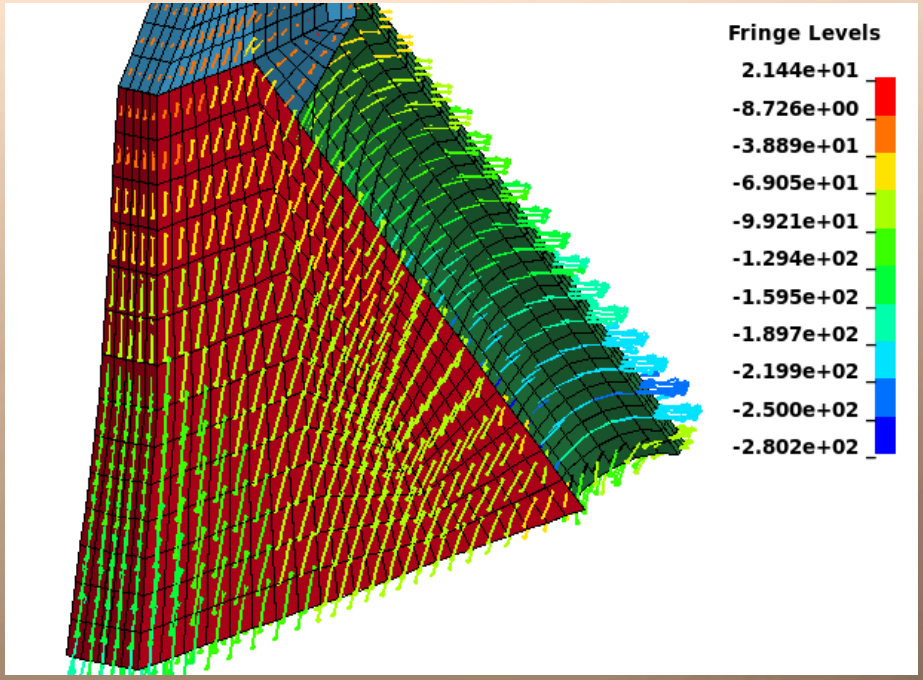


Gleno Dam Failure – FE Model

- Buttress is modeled with a nonlinear concrete material model
- f'_c = 1,500 psi
- f_{crack} = 75 psi
- Buttress contact with foundation is given a 0.9 friction value for sliding
- Assume 35 ft of foundation in front of buttress allowed to settle and eventually lose contact
- Static water load applied as pressure loads

Gleno Dam Failure – FE Model

- First run done with foundation assumed to be sound.
- Results indicate stability with most of the dam in compression

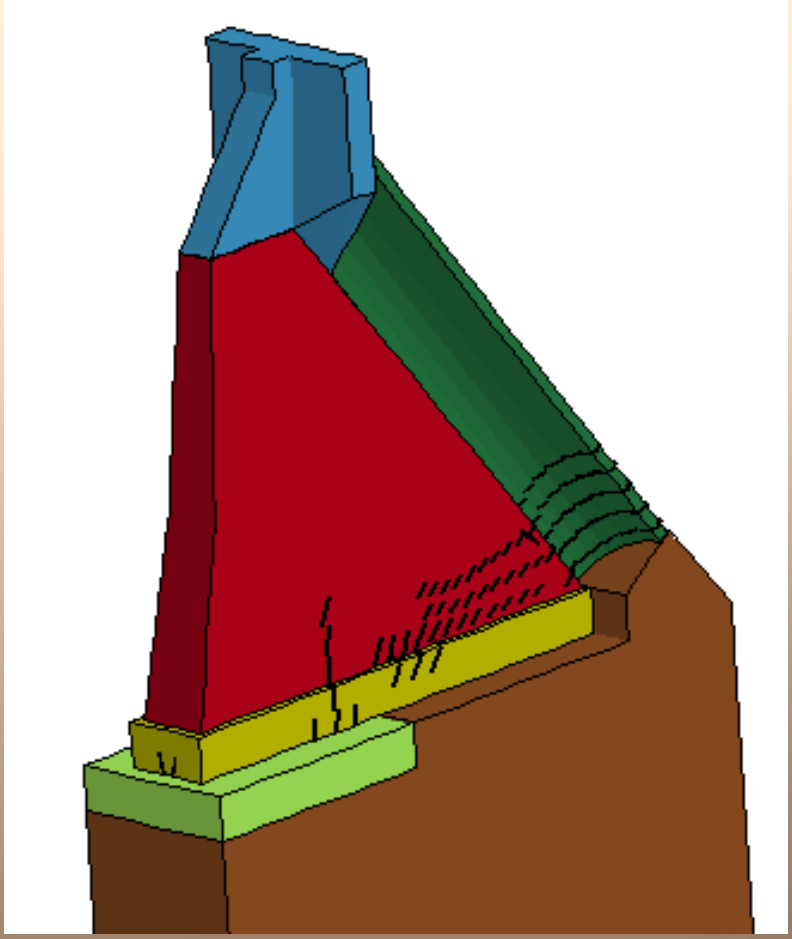


Gleno Dam Failure – FE Model

- Next a run was done simulating the onset of foundation settlement.
- This was done by softening the front 35 ft of the foundation by 100 times

Gleno Dam Failure – FE Model

- One can observe the onset of cracks near the foundation

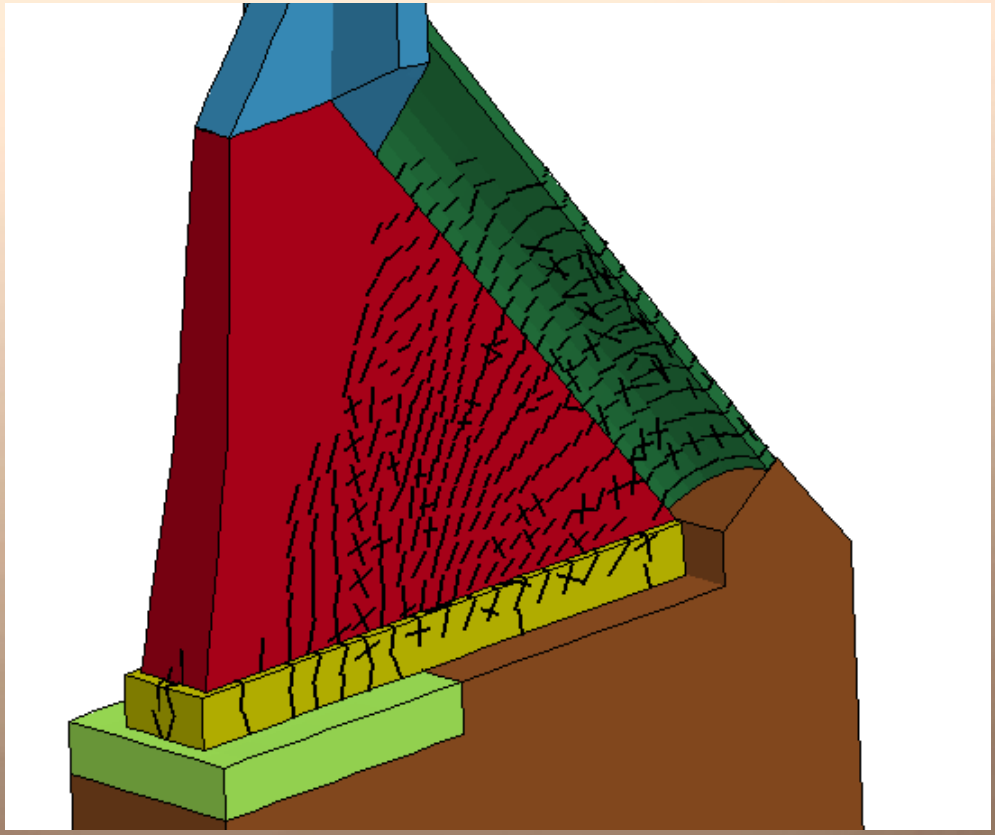


Gleno Dam Failure – FE Model

- The final run simulated the settlement process well underway with eventual complete loss of contact over the front 35 ft of foundation

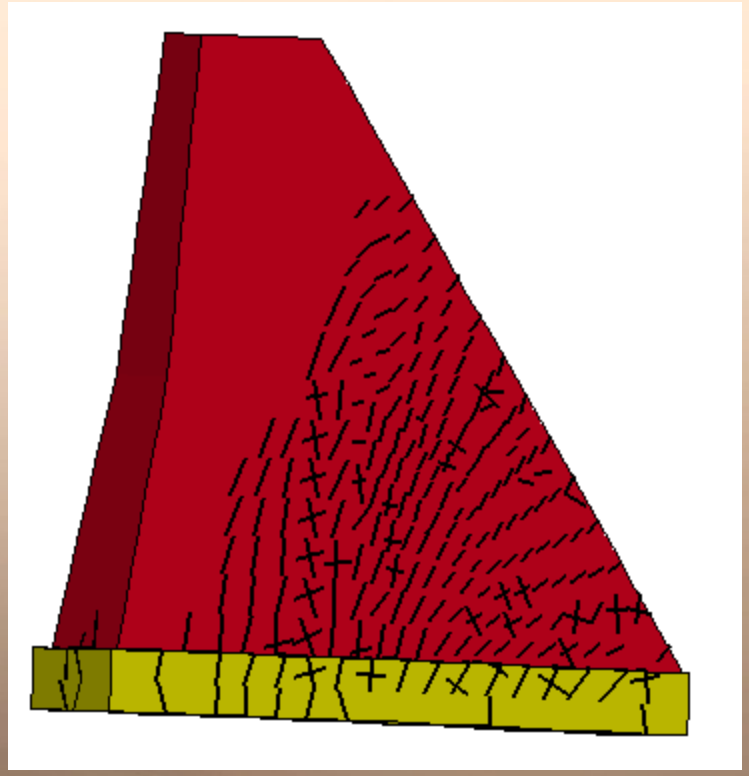
Gleno Dam Failure – FE Model

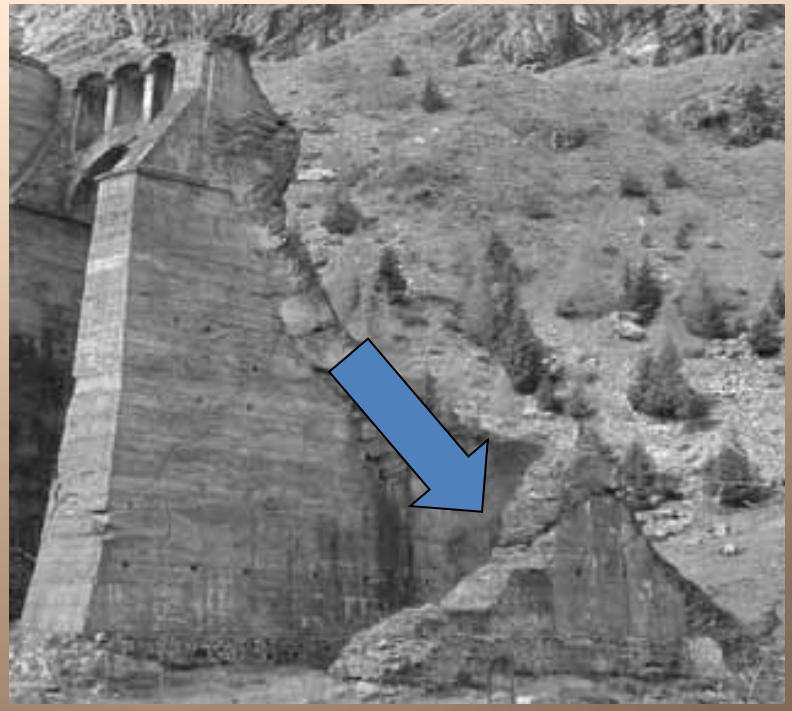
- One can observe a well developed cracking pattern with major damage to the buttress



Gleno Dam Failure – FE Model

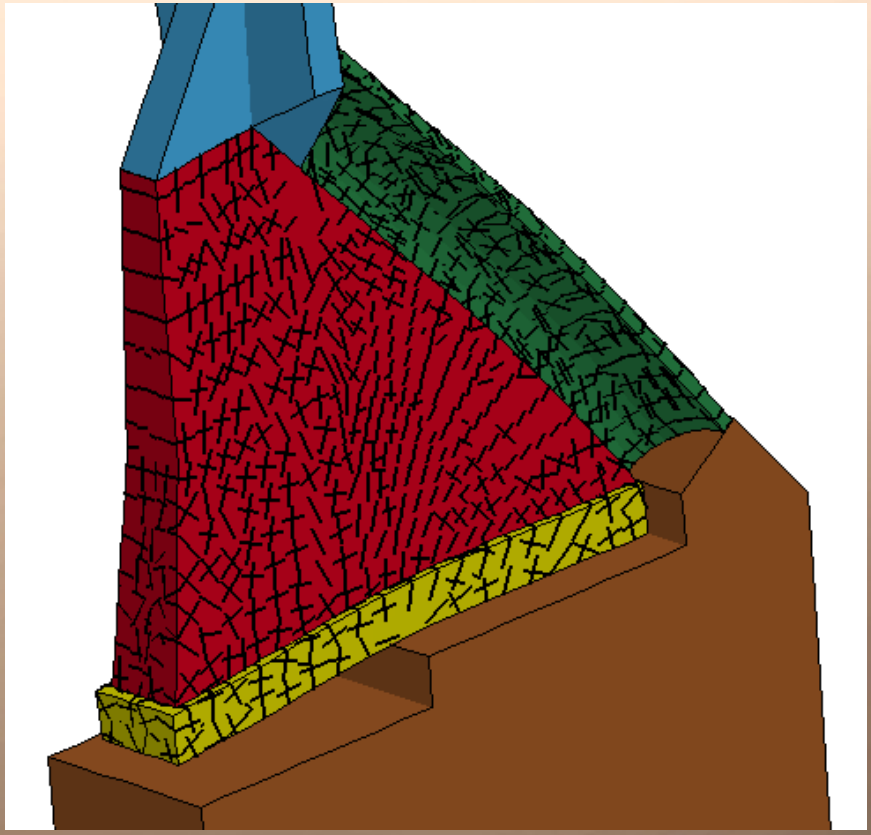
- The cracking pattern orientation is indicative what was observed at the site after failure



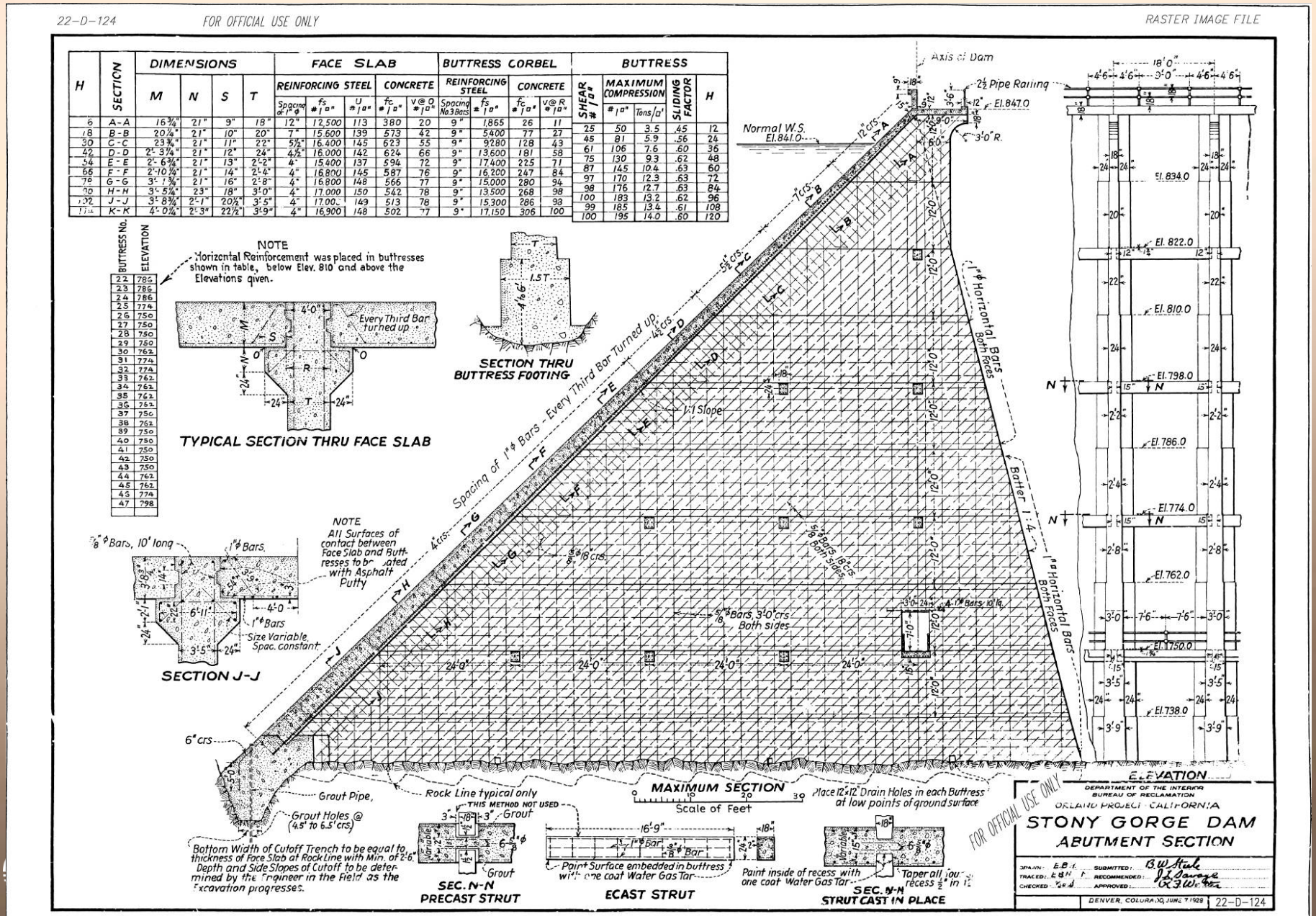


Gleno Dam Failure – FE Model

- Finally, with complete loss of contact over the front 35 ft of foundation, the dam fails catastrophically!



Exposure and corrosion of reinforcing steel can reduce capacity



H	SECTION	DIMENSIONS M	N	S	T	FACE SLAB REINFORCING STEEL Spacing of 1"φ	fs #/□"	U #/□"	CONCRETE fc #/□"	V@O #/□"	BUTTRESS CORBEL REINFORCING STEEL Spacing No.3 Bars	fs #/□"	CONCRETE fc #/□"	V@R #/□"
6	A-A	16¾"	21"	9"	18"	12"	12,500	113	380	20	9"	1,865	26	11
18	B-B	20¾"	21"	10"	20"	7"	15,600	139	573	42	9"	5400	77	27
30	C-C	23¾"	21"	11"	22"	5½"	16,400	145	623	55	9"	9280	128	43
42	D-D	2'-3¾"	21"	12"	24"	4½"	16,000	142	624	66	9"	13,600	181	58
54	E-E	2'-6¾"	21"	13"	2'-2"	4"	15,400	137	594	72	9"	17,400	225	71
66	F-F	2'-10¼"	21"	14"	2'-4"	4"	16,800	145	587	76	9"	16,200	247	84
78	G-G	3'-1¾"	21"	16"	2'-8"	4"	16,800	148	566	77	9"	15,000	280	94
90	H-H	3'-5¾"	23"	18"	3'-0"	4"	17,000	150	542	78	9"	13,500	268	98
102	J-J	3'-8¾"	2'-1"	20½"	3'-5"	4"	17,000	149	513	78	9"	15,300	286	93
114	K-K	4'-0¾"	2'-3"	22½"	3'-9"	4"	16,900	148	502	77	9"	17,150	306	100

BUTTRESS SHEAR #/□"	MAXIMUM COMPRESSION #/□"	Tons/□'	SLIDING FACTOR	H
25	50	3.5	.45	12
45	81	5.9	.56	24
61	106	7.6	.60	36
75	130	9.3	.62	48
87	145	10.4	.63	60
97	170	12.3	.63	72
98	176	12.7	.63	84
100	183	13.2	.62	96
99	185	13.4	.61	108
100	195	14.0	.60	120

BUTTRESS No.	ELEVATION
22	786
23	786
24	786
25	774
26	750
27	750
28	750
29	750
30	762
31	774
32	774
33	762
34	762
35	762
36	762
37	750
38	762
39	750
40	750
41	750
42	750
43	750
44	762
45	762
46	774
47	798

Hydrodynamic Interaction

Reduced on sloping face

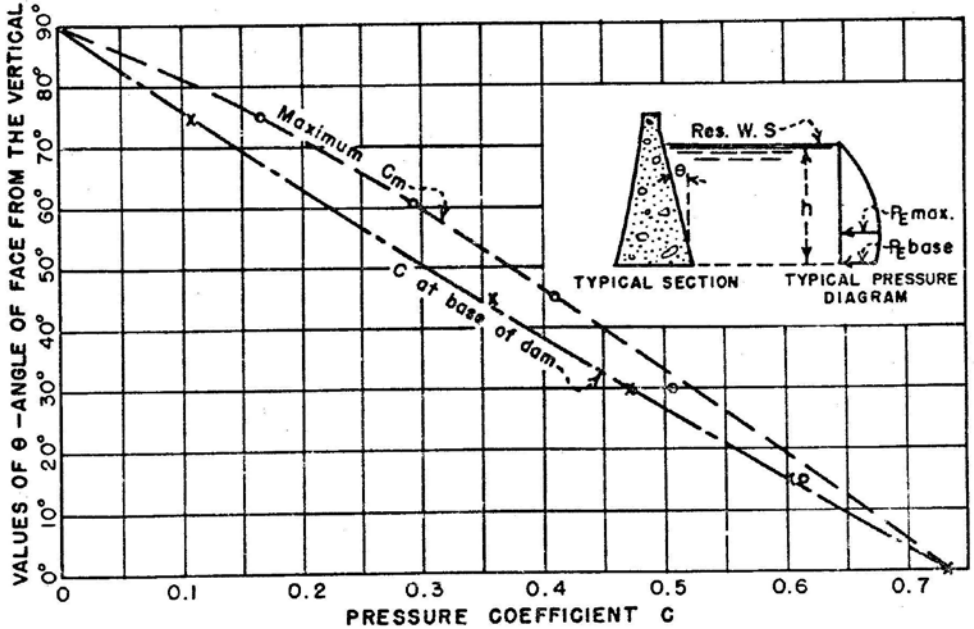


FIGURE 5 - Pressure coefficients for constant sloping faces.

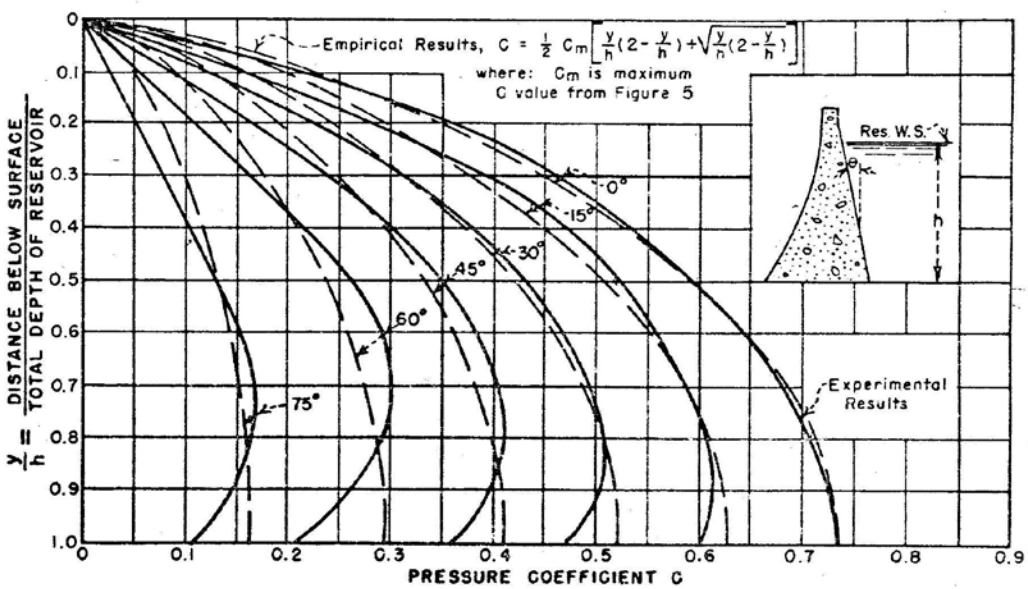


FIGURE 6 - Comparison of experimental and empirical pressure distribution curves.

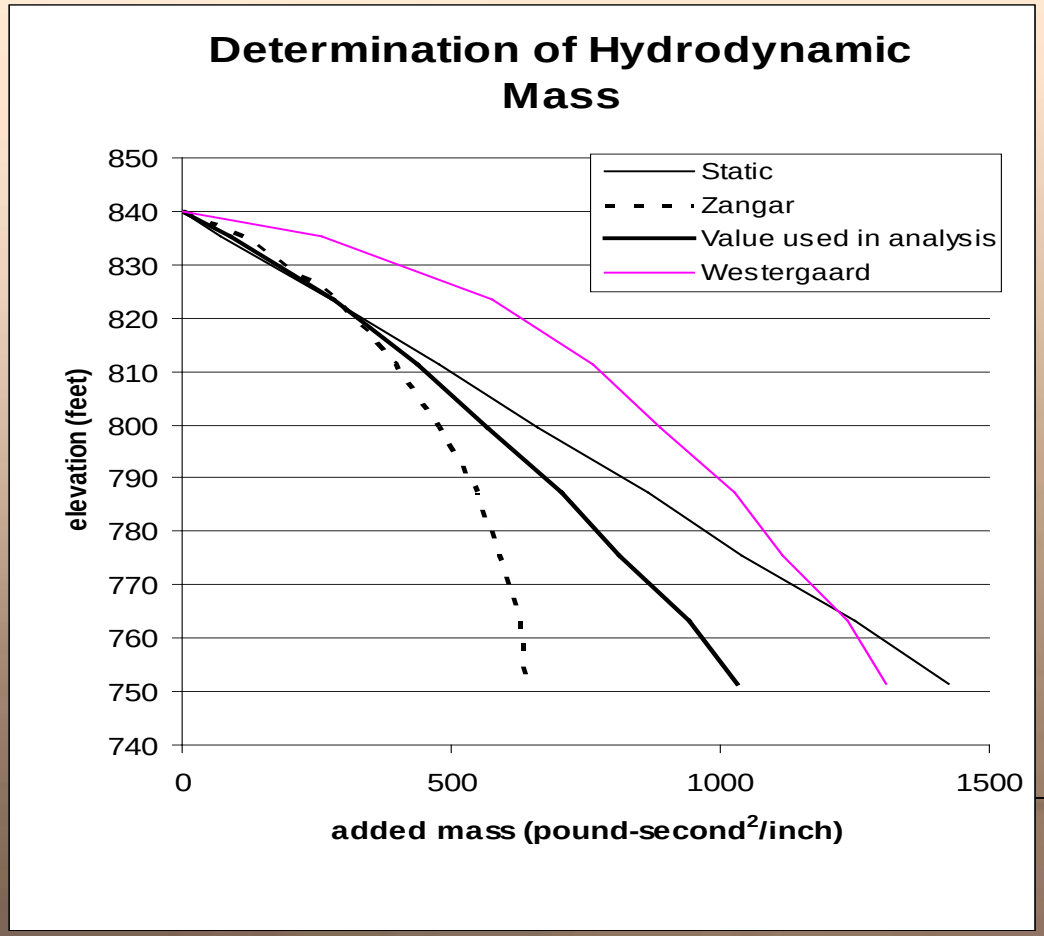
Hydrodynamic Interaction

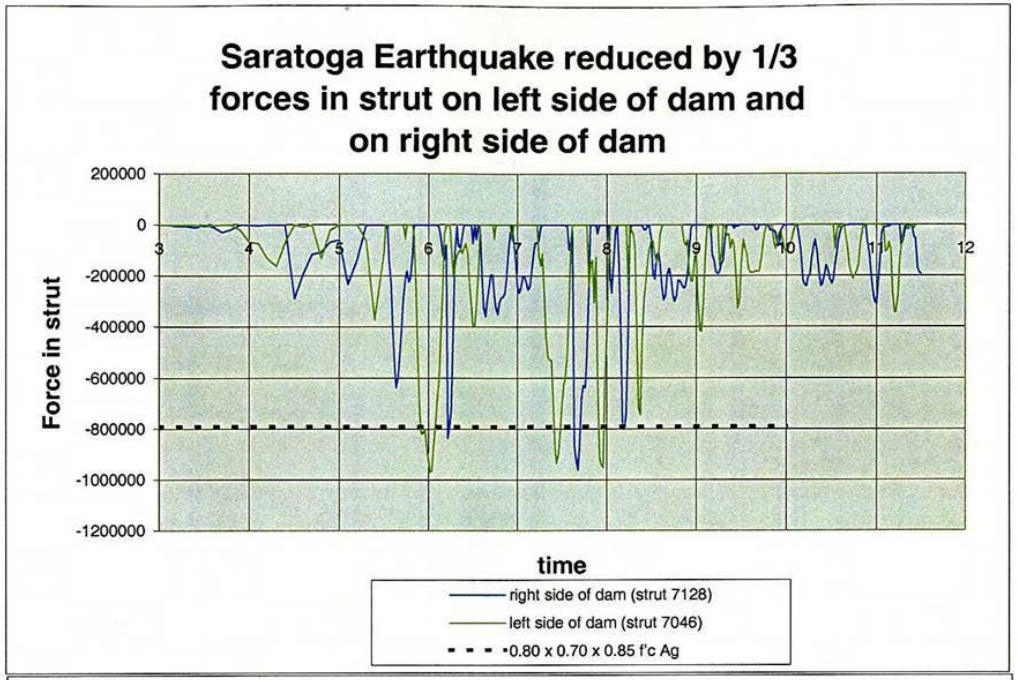
Different added mass in horizontal direction and vertical direction

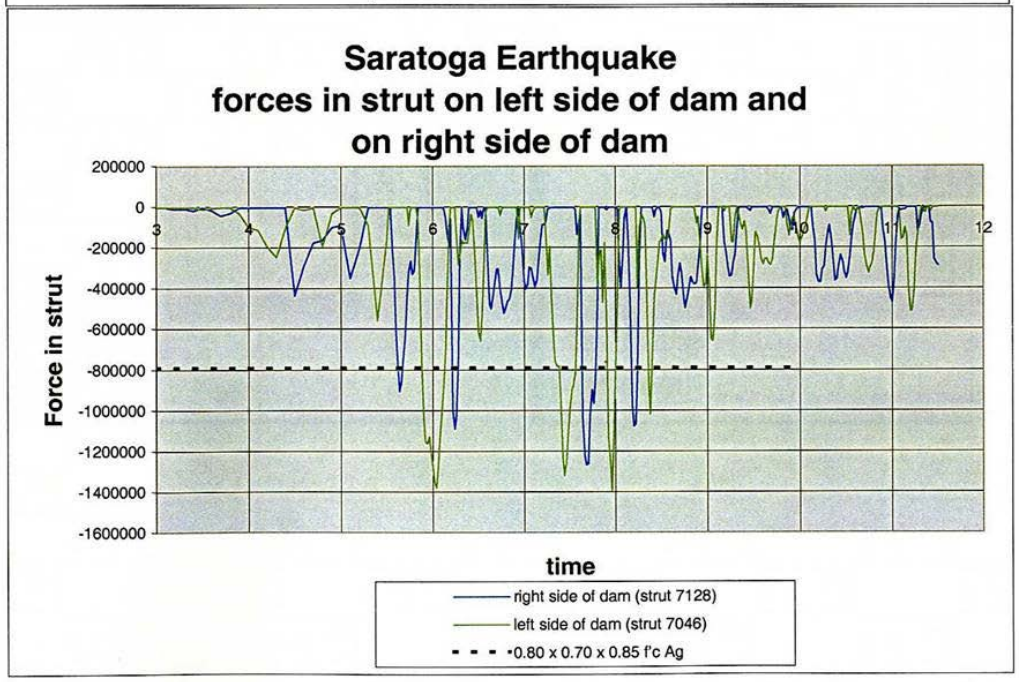
- Can account for directly when modeling fluids in LS-DYNA
- Can use directional lumped mass in implicit codes like SAP or NIKE
- Must approximate with added mass in explicit codes not using fluid elements

At Stony Gorge (slab and buttress): No cross-canyon hydrodynamic interaction on flat slab

At Bartlett (multiple arch): Highest hydrodynamic pressures on outer arches







Struts

Some buttresses have struts between buttresses for lateral support

As buttresses move in earthquake, load accumulates across dam and can overload end struts (push over analysis)

Crushing stress in struts normally controls over buckling

Condition of Struts During Initial Pulses of Saratoga Ground Motions

Struts for which output was requested:

Buttress	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
Elevation 822	7002	7003	7004	7005	7006	7007	7008	7009	7010	7011	7012	7013							7020	7021	7022	7023	7024	7025	7026	7027	7028	7029	7030	7031	7032	7033	7034	7035	7036	7037	7038	7039	7040
Elevation 798 ds						7045	7046	7047	7048	7049	7050	7051	7052	7053	7054	7055	7056	7057	7058	7059	7060	7061	7062	7063	7064	7065	7066	7067	7068	7069	7070	7071	7072	7073	7074	7075	7259	7261		
Elevation 798 us								7076	7077	7078	7079	7080	7081	7082	7083	7084	7085	7086	7087	7088	7089	7090	7091	7092	7093	7094	7095	7096	7097	7098	7099	7100	7101	7102	7103	7104	7260			
Elevation 774 ds								7253	7105	7106	7107	7108	7109	7110	7111	7112	7113	7114	7115	7116	7117	7118	7119	7120	7121	7122	7123	7124	7125	7126	7127	7128	7256						
Elevation 774								7254	7129	7130	7131	7132	7133	7134	7135	7136	7137	7138	7139	7140	7141	7142	7143	7144	7145	7146	7147	7148	7149	7150	7151	7152	7257						
Elevation 774 us								7255	7153	7154	7155	7156	7157	7158	7159	7160	7161	7162	7163	7164	7165	7166	7167	7168	7169	7170	7171	7172	7173	7174	7175	7176	7258						
Elevation 750 ds										7249	7177	7178	7179	7180	7181	7182	7183	7184	7185	7186	7187	7188	7189	7190	7191	7192	7193	7194											
Elevation 750										7250	7195	7196	7197	7198	7199	7200	7201	7202	7203	7204	7205	7206	7207	7208	7209	7210	7211	7212											
Elevation 750										7252	7213	7214	7215	7216	7217	7218	7219	7220	7221	7222	7223	7224	7225	7226	7227	7228	7229	7230											
Elevation 750 us										7251	7231	7232	7233	7234	7235	7236	7237	7238	7239	7240	7241	7242	7243	7244	7245	7246	7247	7248											

Struts selected for time history output

First struts removed (Saratoga EQ)
(due to exceedance of capacity at first pulse)

Buttress	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
Elevation 822	7002	7003	7004	7005	7006	7007	7008	7009	7010	7011	7012	7013							7020	7021	7022	7023	7024	7025	7026	7027	7028	7029	7030	7031	7032	7033	7034	7035	7036	7037	7038	7039	7040
Elevation 798 ds						7045	7046	7047	7048	7049	7050	7051	7052	7053	7054	7055	7056	7057	7058	7059	7060	7061	7062	7063	7064	7065	7066	7067	7068	7069	7070	7071	7072	7073	7074	7075	7259	7261		
Elevation 798 us								7076	7077	7078	7079	7080	7081	7082	7083	7084	7085	7086	7087	7088	7089	7090	7091	7092	7093	7094	7095	7096	7097	7098	7099	7100	7101	7102	7103	7104	7260			
Elevation 774 ds								7253	7105	7106	7107	7108	7109	7110	7111	7112	7113	7114	7115	7116	7117	7118	7119	7120	7121	7122	7123	7124	7125	7126	7127	7128	7256						
Elevation 774								7254	7129	7130	7131	7132	7133	7134	7135	7136	7137	7138	7139	7140	7141	7142	7143	7144	7145	7146	7147	7148	7149	7150	7151	7152	7257						
Elevation 774 us								7255	7153	7154	7155	7156	7157	7158	7159	7160	7161	7162	7163	7164	7165	7166	7167	7168	7169	7170	7171	7172	7173	7174	7175	7176	7258						
Elevation 750 ds										7249	7177	7178	7179	7180	7181	7182	7183	7184	7185	7186	7187	7188	7189	7190	7191	7192	7193	7194											
Elevation 750										7250	7195	7196	7197	7198	7199	7200	7201	7202	7203	7204	7205	7206	7207	7208	7209	7210	7211	7212											
Elevation 750										7252	7213	7214	7215	7216	7217	7218	7219	7220	7221	7222	7223	7224	7225	7226	7227	7228	7229	7230											
Elevation 750 us										7251	7231	7232	7233	7234	7235	7236	7237	7238	7239	7240	7241	7242	7243	7244	7245	7246	7247	7248											

Struts removed due to exceedance of capacity at first pulse of Saratoga Record

From analysis with above struts removed,
the following additional struts reached loads exceeding capacity

Buttress	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
Elevation 822	7002	7003	7004	7005	7006	7007	7008	7009	7010	7011	7012	7013							7020	7021	7022	7023	7024	7025	7026	7027	7028	7029	7030	7031	7032	7033	7034	7035	7036	7037	7038	7039	7040
Elevation 798 ds						7045	7046	7047	7048	7049	7050	7051	7052	7053	7054	7055	7056	7057	7058	7059	7060	7061	7062	7063	7064	7065	7066	7067	7068	7069	7070	7071	7072	7073	7074	7075	7259	7261		
Elevation 798 us								7076	7077	7078	7079	7080	7081	7082	7083	7084	7085	7086	7087	7088	7089	7090	7091	7092	7093	7094	7095	7096	7097	7098	7099	7100	7101	7102	7103	7104	7260			
Elevation 774 ds								7253	7105	7106	7107	7108	7109	7110	7111	7112	7113	7114	7115	7116	7117	7118	7119	7120	7121	7122	7123	7124	7125	7126	7127	7128	7256						
Elevation 774								7254	7129	7130	7131	7132	7133	7134	7135	7136	7137	7138	7139	7140	7141	7142	7143	7144	7145	7146	7147	7148	7149	7150	7151	7152	7257						
Elevation 774 us								7255	7153	7154	7155	7156	7157	7158	7159	7160	7161	7162	7163	7164	7165	7166	7167	7168	7169	7170	7171	7172	7173	7174	7175	7176	7258						
Elevation 750 ds										7249	7177	7178	7179	7180	7181	7182	7183	7184	7185	7186	7187	7188	7189	7190	7191	7192	7193	7194											
Elevation 750										7250	7195	7196	7197	7198	7199	7200	7201	7202	7203	7204	7205	7206	7207	7208	7209	7210	7211	7212											
Elevation 750										7251	7213	7214	7215	7216	7217	7218	7219	7220	7221	7222	7223	7224	7225	7226	7227	7228	7229	7230											
Elevation 750 us										7252	7239	7240	7241	7242	7243	7244	7245	7246	7247	7248																			

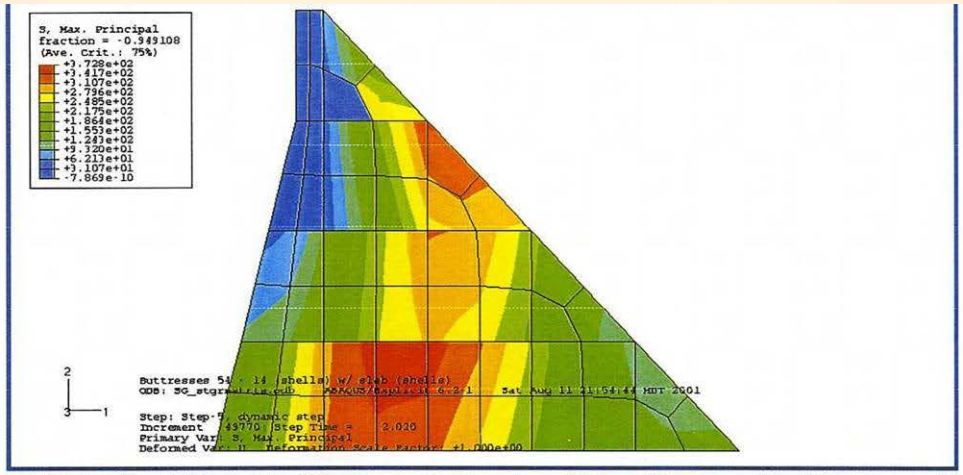
Struts removed due to exceedance of capacity at first pulse (red) of Saratoga Record

Additional struts exceeding capacity (blue) Struts for which forces were reduced (purple)

Results by Barbara Mills-Bria using ABAQUS

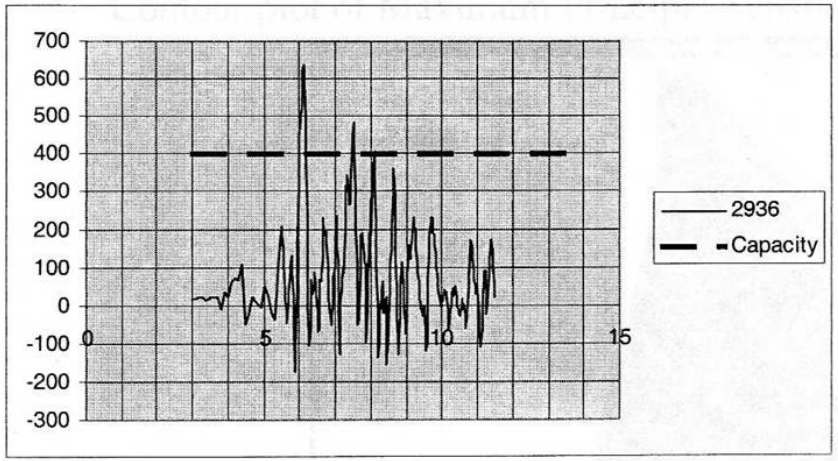
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

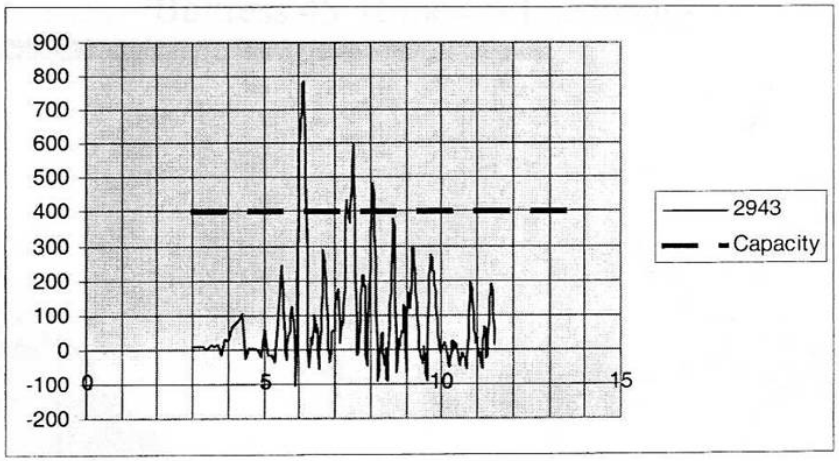
As Struts Crush, Lateral Support of Buttresses is Lost and Instability may Result



Contour plot of Maximum Principal Tensile Stresses following Strut Removal – Buttress 45 (time= 7.52 sec)

Saratoga Ground Motions





Time history plot of Maximum Principal Tensile Stresses following Strut Removal – Buttress 25

Buttress Dams Vary in Thickness and Reinforcement from Base to Crest

Elevations	Thickness	d	Vertical Mv allowable	Horizontal Mh allowable
834 - 846	18	16	1.3×10^5	0.7×10^5
822 - 834	20	18	1.4×10^5	0.8×10^5
810 - 822	22	20	1.6×10^5	0.9×10^5
798 - 810	24	22	1.7×10^5	3.7×10^5
786 - 798	26	24	1.9×10^5	4.1×10^5
774 - 786	28	26	2.1×10^5	1.2×10^5
762 - 774	32	30	2.4×10^5	1.4×10^5
750 - 762	36	34	2.7×10^5	1.6×10^5
738 - 750	41	39	3.1×10^5	1.8×10^5
722 - 738	45	43	3.4×10^5	2.0×10^5

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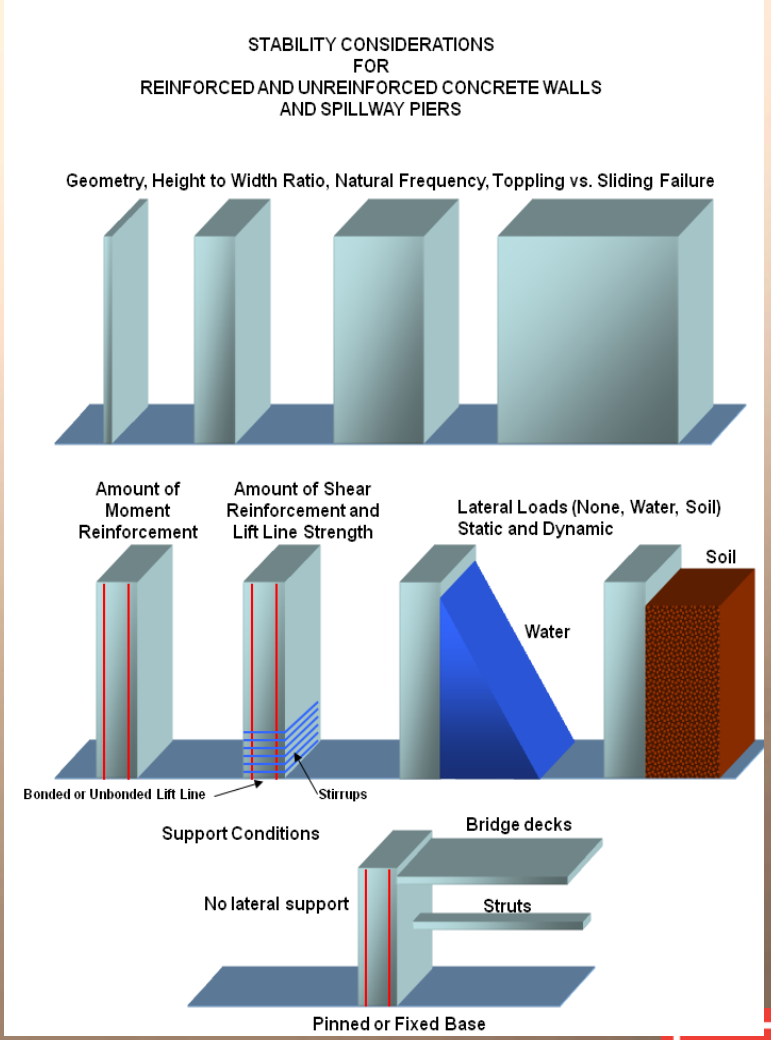
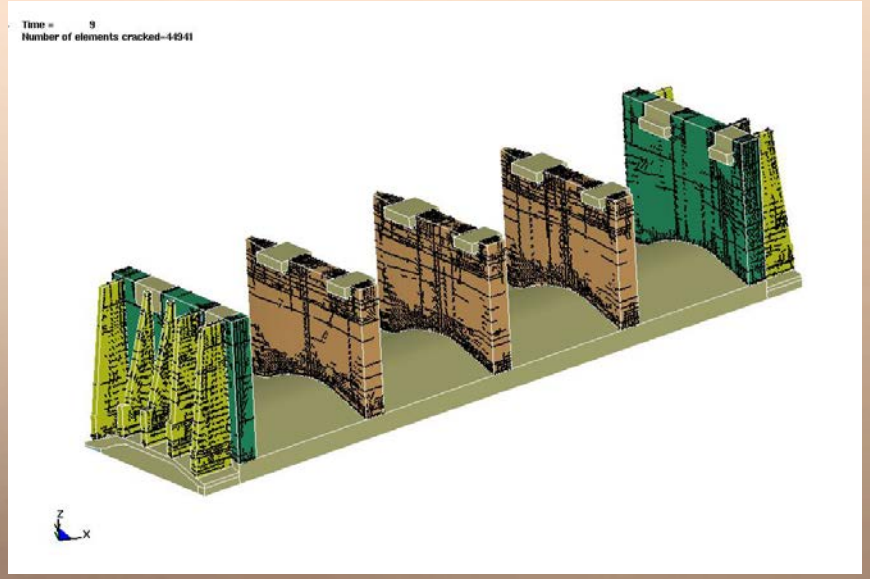
Risk Analysis of Buttress Dams

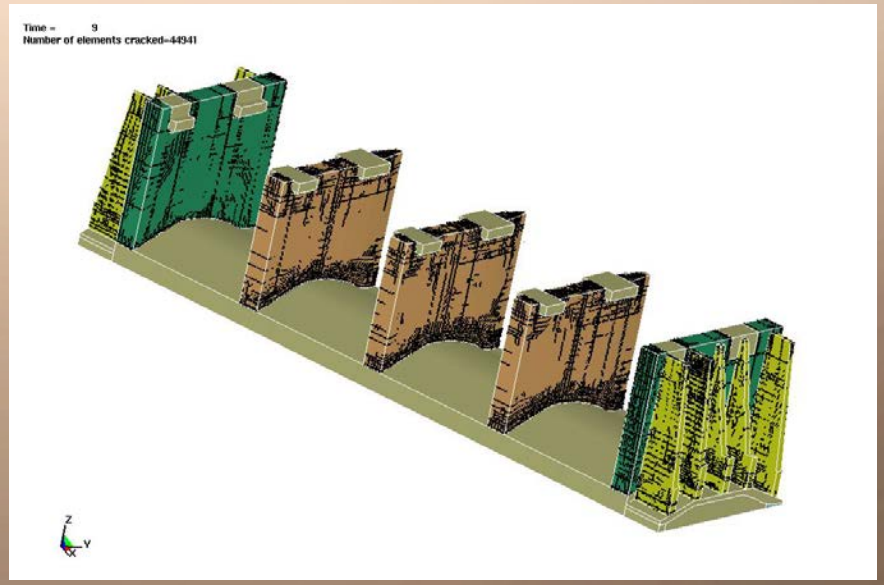
- Refer to Reinforced Concrete Section of Best Practices
- Depending on level of study, various methods can be used for evaluating the effectiveness of reinforcement in the buttresses.
  - D/C Ratios and hand calculations
  - Nonlinear finite element analysis



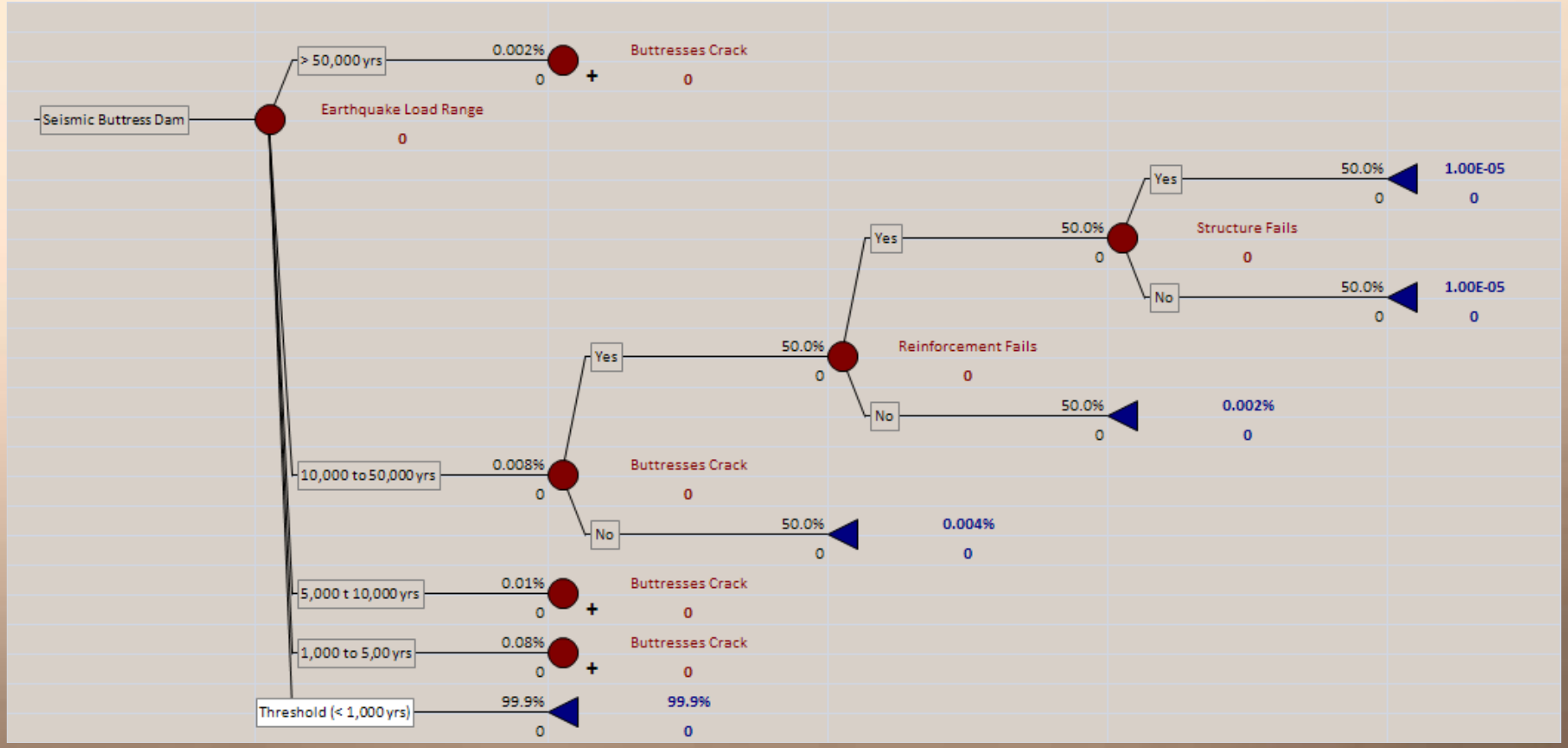
Nonlinear Structural Analysis

- The best way to estimate this type of behavior is using a nonlinear finite element analysis that can model cracking of the concrete and transfer of load to the reinforcement
- Reclamation uses LS-DYNA for these analyses
- See Reinforced Concrete Section





Nonlinear Analysis Event Tree



See pg. V-4-18