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ANALYSIS OF CONCRETE AND MASONRY DAM INCIDENTS

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7. Abstract

This study set out to carry out as complete a study of concrete and masonry dam failures and accidents as was practicable, with a greater emphasis than in other studies on the geology, mode and cause of failure, and the warning signs that were observed. The study also sets out to assess the characteristics of the population of dams, and compares the characteristics of the failures and accidents with the population of dams, so that a probability of failure can be assigned. This data provides the basis for initial risk assessments of dams.

The source for the analysis was a database developed by the authors on failures and accidents in concrete and masonry dams known as *CONGDATA*.

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Table 29. Details of Dam Failures and Description of Warnings

Dam Name	Dam Type	Failure Type	Failure Mode	Failure Description	Warning Description	Warning Rating
Torrejon-Tajo	PG	Fa	SH	Failure of outlet gate.	No details available	?
Zerbino	PG	Faf	S/SC	Scour due to overtopping, followed by foundation failure (sliding or overturning)	No details available, but some warning issued - "Despite warnings, the flood drowned 100 people". Large scour occurred in power plant tunnel in 1928 (same rock).	M
Mohamed V	PG	Fb	?	No details available	No details available	?
Elwha River	PG	Ff	P	Piping through alluvial sand and gravel during construction of cutoff. Dam was completed and reservoir part filled before cutoff construction.	Leakage into caisson for cutoff. Failed in 1.5 hours.	M
Xuriguera	PG	Ff	S	No details available	No details available	?
Bayless (A)	PG	Ff	S	Left half of dam moved 450mm downstream at base, 790mm at top by sliding on foundation.	Landslide left abutment downstream, large leakage 4.5-15m downstream of dam 12 days before dam failed.	Y
Bayless (B)	PG	Ff	S	Rapid failure of most of dam by sliding and overturning.	Previous failure 8 months before. No remedial action taken.	Y
St Francis	PG	Ff	S	Sudden failure in foundation due to "softening of conglomerate" or sliding on existing landslide or foliation surface in schist.	Foundation seepage measured as reservoir rose to 1-2ft^3/sec (30-60l/sec) or 6-9hrs before failure water level recorder dropped 0.1m in ½ hour before failure. (There is a suggestion that this was due to the tilting of the dam, but in any case it would have acted as a warning.) Some evidence of cracking in foundation 2 months before failure (due to landslide in abutment).	Y/M
Hauser Lake II	PG	?	?	No details available.	No details available.	?
Kohodiar	PG/TE	?	?	No details available.	No details available.	?
Fergoug I	PG(M)	Fa	SC	50m spillway section scoured by flood and failed.	Flood caused by failure of Habra dam upstream.	DF
Fergoug II	PG(M)	Fa	SC?	125m section failed during flood.	Flood caused by failure of Habra dam upstream.	DF
Sig	PG(M)	Fa	SC?	Overtopped in flood. Founded on gravel.	Flood caused by failure of Cheurfas dam upstream 2 hours before.	DF
Santa Catalina	PG(M)	Fa	?	Overtopping. No details available.	No details available.	?
Cheurfas	PG(M)	Fb	?	No details available. ICOLD cite piping in foundation as cause, but failure in dam, which is inconsistent.	No details available.	?
Granadillar	PG(M)	Fb	?	Failure of dam due to inadequate cross section.	No data available.	?
Bouzey (B)	PG(M)	Fb	T	Sudden tensile/compressive and overturning failure. Failure surface slope gently 3.5m from upstream face, then steeply. Crush and shear marks near downstream face.	Dam had leaked badly in foundation and moved up to 0.34m downstream 11 years before failure. Repairs had been carried out 3 years before, and crest deflection 25mm observed. No warning immediately before failure.	Y
Khadakwasla	PG(M)	Fb	T/SH	Failure in masonry. Tensile/compression probably enhanced by stress concentration due to sudden change in foundation elevation.	Dam was overtopped for 4 hours prior to failure, and was vibrating. Flood due to failure of Panshet dam upstream 7 hours prior to breach.	DF
Habra (B)	PG(M)	Fba	T/SH	Sudden failure in masonry during flood.	No warning immediately before failure (flood).	F
Angels	PG(M)	Ff	P	Piping in (soil?) foundation.	No data available.	?
Puentes	PG(M)	Ffb	P	Piping failure through alluvium in foundation.	Leakage from fndn noted just over 0.5hr prior to failure. Just prior to failure there was a large explosion from the discharge wells and a large increase in leakage. It is said that the dam emptied in 1hr. A messenger was sent to warn the town of Lorca when the leakage was first noted (by bike) but was overtaken by the flood wave.	M

Dam Name	Dam Type	Failure Type	Failure Mode	Failure Description	Warning Description	Warning Rating
Tigra	PG(M)	Ff	S	Sliding on weak shale (?) seam in foundation under flood level. Dam overtopped by 0.15m only so overtopping itself unlikely to be critical re scour, but may have affected uplift inside dam.	Dam went overtopped ½ hour before failure.	F
Austin (A)	PG(M)	Ff	SC/P/S	Sliding on weak seam in foundation of two 80m long sections of the spillway, moved downstream 20m.	Whirlpools in storage 1 year before, 2m scour at toe of spillway section of dam. Failed in 3 minutes during flood of record.	Y
Kundli	PG(M)	Fm	?	Failure attributed to "green" uncured lime mortar masonry.	No data available.	?
Chickahole	PG(M)	Fm	T	Sudden tensile/overturning failure. Flood rise of 1.5m immediately prior to failure.	No warning immediately prior to failure. Cracking of dam occurred during consolidation grouting of foundation.	M
Gallinas	PG(M)	Fm/Fa	?	Overtopped and "washed out" (no details).	No data available. "Early warnings … credited with preventing loss of life".	M
Lynx Creek	PG(M)	Fm	?	Failure in masonry in flood.	No details available.	?
Pagara	PG(M)	Fmb	T?	Overtopping. No additional details.	No data available.	?
Habra (A)	PG(M)	Fmb	T/SH	Sudden failure in foundation or masonry during overtopping by flood.	No warning immediately before failure ("large leakage" in dam on first filling but had reduced).	Y
Habra (C)	PG(M)	Fmb	T/SH	Sudden failure in masonry during flood.	Flood no details about any warnings but, "reportedly did not result in a loss of human lives because of adequate advance warnings".	F
Elmali I	PG(M)/TE	Fa	?	Overtopped. No data available.	No data available.	?
Lower Idaho Falls	ER/PG(M)	Fa	?	Overtopped due to failure of Teton dam upstream.	Failure of Teton dam 96km upstream.	DF
Vaughn Creek	VA	Ff	P	Foundation piping and arch concrete failure. Considerable flow below west abutment, followed by settlement and sliding of abutment and in a short time, its overturning.	Some seepage in abutment on first filling. Very large and serious leakage just before failure through abutment.	Y
Malpasset	VA	Ff	S	Sudden shear failure in foundation controlled by geology and uplift.	Failure very rapid. Seepage in abutment on first filling 15 days, and more 2 days before failure. 17mm displacement of dam base compared to estimated 10mm.	M
Moyie River	VA	Ffa	SC	Spillway scoured and undermined left abutment dam left standing.	No details available, but scour should have been evident.	F
Meihua	VA(M)	Fb				?
Bacino di Rutte	VA(M)	Ff	D/P	Foundation seepage and movement causing crack to open upstream of dam on first filling. Crack sealed. Dam operated for 13 years, but failed when sediment removed from reservoir and dam refilled. Failure was piping initiated along crack, giving breach 12m by 2m into which dam collapsed.	Prior seepage, observation of cracks in foundation, and displacement.	Y
Ashley	CB	Ff	P	Piping failure in fine sand with a little clay and gravel, 6m deep below cutoff.	Seepage in foundation noted 1.5-2 hours before piping failure.	N
Stony Creek	CB	Ff	P	Piping in foundation followed by settling of dam, cracking and collapse of dam.	Large leakage through weep holes in floor of the dam 24 hours before flow developed rapidly in last 20 minutes before failure.	Y
Komoro	CB	Ff	S/P	Failure due to softening of volcanic ash in foundation. Unclear whether piping, sliding or both.	No details available.	?
Overholser	CB	Ffa	SC	Overtopping. Scour of abutment.	No details available.	?
Austin (B)	CB(M)	Fba	SH	Flood destroyed 20 gates of masonry dam, and filled tailrace and draft tubes with debris.	Flooding	F
Vega de Tera	CB(M)	Fm	T/C	Structural failure of masonry buttress.	No warning noted. "Heavy leakage" occurred through masonry but may have been unrelated.	M
Selsfors	CB/TE	Ff	P	Piping in foundations fluvioglacial sand, followed by collapse of dam into void.	Small seepage into abutment 4.25 hours prior to failure, increased slowly for 0.5 hour, then rapidly.	M/N
Gleno	MV	Fb	T/C	Rapid structural failure of multiple buttress arch dam attributed to weakness in poor quality supporting masonry.	Leakage through dam and on the cut off between dam and foundation during and after construction. Leakage increased markedly in the days before failure up to 50l/sec.	Y
Leguaseca	MV	Fb	T/C	Structural failure of an arch due to concrete deterioration in acidic reservoir water.	No details available (concrete deterioration).	M

Table 30. Details of Dam Significant Accidents and Description of Warnings

Dam Name	Dam Type	Failure Type	Failure Mode	H_d/W	Failure Description	Warning Description	Warning Rating
Bingham	PG	Fa	SC	?	Spillway failed by overturning due to piping and erosion of the weathered foundation rock.	No details available.	?
Wilbur	PG	Fa	ST	?	Overtopping of dam caused damage to power station downstream. Dam was not damaged.	Flood	F
Upper Glendevon	PG	Ff/Fb	P	1.32	Leakage of 25l/sec on first filling, giving high uplift.	Leakage through foundation of 25l/sec on first filling.	Y
Mequinenza	PG	Ff	S	0.6	Weak bedding surfaces in limestone, lignite and marl exposed during construction, led to strengthening works being built before the dam was completed.	Horizontal and vertical movements anticipated but did not occur because dam was strengthened before completion.	Y
Aguilar	PG	Ff	P	1.25	Piping of clay filled joint in limestone foundation giving leakage of 50l/sec.	Leakage in joint in foundation of 50l/sec.	Y
Villagarcia	PG	Ff	P	?	Leakage and piping through rock foundation of up to 100l/sec on first filling.	Leakage up to 100l/sec in foundations	Y
Hales Bar	PG	Ff	P	1.61	Leakage through karst limestone foundation, reaching 47600l/sec (47.6m^3/sec) 27 years after construction. Many attempts to stop leakage failed, dam abandoned 51 years after construction.	Leakage up to 47600l/sec, whirlpools in reservoir, boils downstream.	Y
Woodbridge (A)	PG	Ff	P	?	Piping of alluvial foundation.	No details available.	?
Zardezas	PG	Ff	S	?	Foundation slide during construction.	No details available.	?
Don Marco	PG	Ff	S	1.44	Scour of foundations due to spillway, and sliding of dam on weak zone in foundation rock.	Sliding of dam, erosion of downstream foundation.	Y
Castrelo	PG	Ff	S	?	Landslide from abutment onto power station outlet.	Landslide in abutment.	Y
Burrinjuck (C)	PG	Ffa	S	1.57	Rock slide in spillway channel partly damaged outlet works.	No details available.	?
Great Falls Generating Station (A)	PG	Ff	P	?	Leakage through a narrow ridge in reservoir which increased from 560l/sec on first filling, to 12600l/sec over 20 years. Leakage was through limestone interbedded with shale.	Leakage began at 560l/sec, increasing steadily each year at 640l/sec/year to 14 years after filling, and 840l/sec/year to 12600l/sec, 24 years after filling. Leakage was from 19 areas.	Y
Dworshak	PG	Fm	CR/L	1.25	Thermal cracking which developed to give up to 380l/sec leakage into the drainage gallery.	Cracking prior to initial filling, remained small for 9 years, then suddenly opened to give 380l/sec leakage.	M
Jandula	PG(M)	Fa	T/SH	?	Overtopped by flood to a depth of 0.15m.	Flood overtopping.	F
New Croton	PG(M)	Fa	CR	1.5	Cracking of spillway concrete due to vibration by floodwater over flashboards on top of the dam.	Flood, cracking in spillway, vibration and leakage up to 9l/sec.	F
Blackbrook II	PG(M)	Fb	CR	1.25	Earthquake caused cracking of parapit wall. Temporary increase in foundation seepage.	Cracking of dam, increased foundation seepage and earthquake itself.	N
Mulshi	PG(M)	Fb	L/SH	?	Leakage through dam increased to 42l/sec, analysis showed inadequate stability. Mortar quality was an issue.	Leakage through dam increased from 3.6l/sec 28 years after construction to 42l/sec 11 years later.	Y
Thokarwadi	PG(M)	Fb	L/SH	?	Fine cracks right through dam on abutments. 200l/sec leakage from weep holes drilled low down on downstream face.	Fine cracks through dam on abutments. 200l/sec flow from weep holes drilled in downstream face near foundation.	Y
Walman	PG(M)	Fb	L/SH	?	Leakage at many places, maximum 280l/sec.	Leakage at many places up to 280l/sec.	Y

Dam Name	Dam Type	Failure Type	Failure Mode	H_d/W	Failure Description	Warning Description	Warning Rating
Bhandardara	PG(M)	Fb	T/SH	1.15	Cracking of dam due to tensile failure of masonry under slightly higher flood level from previously. Also greatly increased leakage in dam. Dam must have gone very close to collapse.	Leakage through dam for 43 years less than 1.8l/sec. Suddenly increased to 870l/sec at dam/foundation interface and 150mm diameter hole in dam "as a powerful jet" (1 day after flood level reached). Cracking of dam located from upstream to downstream face.	N
Gela (A)	PG(M)	Fb	L/SH	?	"Considerable seepage" through dam into inspection gallery.	"Considerable seepage" through dam into inspection gallery.	Y
El Gasco (A)	PG(M)	Fba	?		Flood overtopped dam, saturated clay and rock filling between two outer masonry walls.	No data available.	?
Bouzey (A)	PG(M)	Ff	S	1.66	135m length of dam slid up to 0.34m downstream. Foundations disturbed up to 3m below dam.	Spring discharges in foundation 50-75l/sec 2 ¼ years before accident, increasing to 230l/sec after accident.	Y
Shirawata	PG(M)	Fmb	L/SH	?	Leakage through dam increased to 600l/sec 10 years after construction. Mortar quality was an issue.	Leakage through dam increased from first filling to 600l/sec 10 years after construction.	Y
Olef	CB	Fbm	CR		Tensile cracking of buttress dam during curing of concrete in construction.	Cracking of concrete.	Y
Estremera	CB	Ff	P		"High leakage" through alluvial foundation with solution of gypsum.	"High leakage" through foundation.	Y
Ayers Islands	CB	Fm	CR/L		Concrete deterioration by freeze-thaw until a hole formed in buttress slab concrete.	Concrete deterioration, hole formed, leakage of dam.	M
Austin (C)	CB(M)/PG(M)	Fa	ST		Spillway piers destroyed during flood and hollow concrete dam section partly destroyed.	Flood. Dam previously damaged and foundations scoured.	F
Austin (D)	CB(M)/PG(M)	Faf	SC/P		Scour and piping of foundation of hollow concrete dam caused collapse of 60m of dam.	Flood. Dam previously damaged and foundations scoured.	Y
Umberumba	VA	Fa	SC/L		Overtopped by flood, scour of downstream toe, leakage under dam.	No details available. (Flood)	F
Idbar	VA	Ff	P		High seepage and piping of limestone foundation which had not been grouted. Dam was abandoned.	Leakage, piping of foundation.	Y
Vajont	VA	Fa	S		Massive landslide in reservoir caused overtopping of dam by many metres (>100m). Dam remained intact.	Movements in landslide accelerating with time.	M

3.7 Remedial Measures

'Abandonment of the dam' and 'reconstruction with a new design' were the most common remedial measures for failures. For accidents, reconstruction of deteriorated zones in appurtenant works and water tightening treatment in the foundations were the most common. Repairing concrete/masonry facing or reconstructing the deteriorated concrete/masonry was the most frequent remedial method for major repairs. Figure 30 shows the most common remedial measures vs incident type. Table 31 shows the number of dams within each remedial measure category.

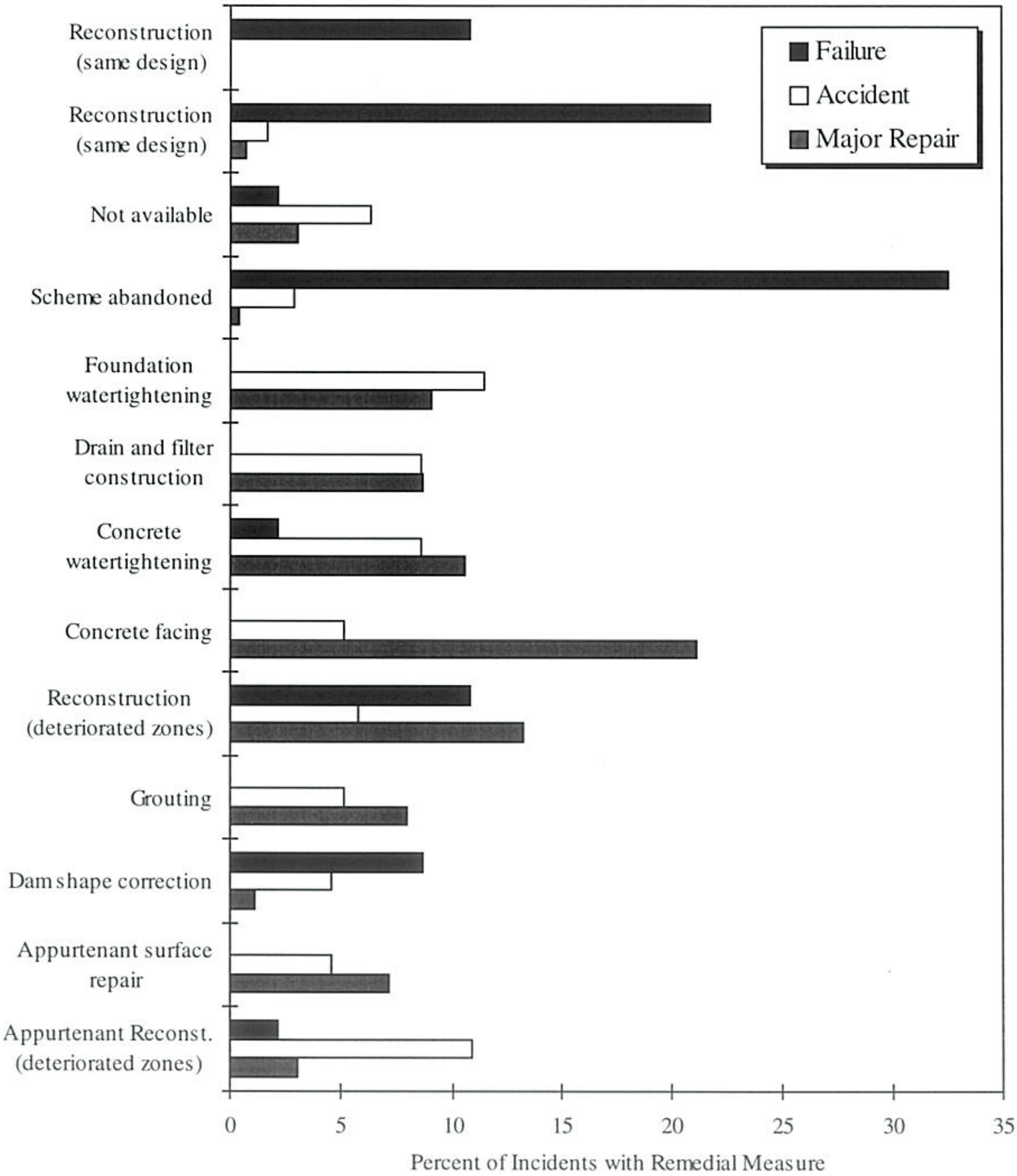


Figure 30. Most Common Remedial Measures - All Dam Incidents

Table 31. Remedial Measures - All Dam Incidents

Remedial Measure	Failures		Accidents		Major Repairs		All Incidents	
	Number	%*	Number	%*	Number	%*	Number	%*
Of a general nature:								
Investigation	1	*2*	8	*5*	19	*7*	28	*6*
Monitoring	0	*0*	9	*5*	14	*5*	23	*5*
Lowering of reservoir level	1	*2*	10	*6*	11	*4*	22	*5*
Overall reconstruction (same design)_	5	*11*	0	*0*	0	*0*	5	*1*
Reconstruction with new design	10	*22*	3	*2*	2	*1*	15	*3*
None	1	*2*	8	*5*	7	*3*	16	*3*
Not available	1	*2*	11	*6*	8	*3*	20	*4*
Scheme abandoned	15	*33*	5	*3*	1	*0*	21	*4*
In foundations:								
Water tightening treatment	0	*0*	20	*11*	24	*9*	44	*9*
Drain & filter construction or repair	0	*0*	15	*9*	23	*9*	38	*8*
Strengthening by grouting or other methods	0	*0*	10	*6*	6	*2*	16	*3*
Filling in of fractures & cavities	1	*2*	2	*1*	1	*0*	4	*1*
Anchoring	1	*2*	0	*0*	2	*1*	3	*1*
In concrete and masonry dams:								
Water tightening treatment	1	*2*	15	*9*	28	*11*	44	*9*
Drain construction or repair	1	*2*	1	*1*	14	*5*	16	*3*
Thermal protection (exc. facing)	0	*0*	0	*0*	7	*3*	7	*1*
Facing	0	*0*	9	*5*	56	*21*	65	*13*
Reconstruction of deteriorated zones	5	*11*	10	*6*	35	*13*	50	*10*
Execution of joints	0	*0*	3	*2*	5	*2*	8	*2*
Strengthening by grouting	0	*0*	9	*5*	21	*8*	30	*6*
Strengthening by anchoring	2	*4*	7	*4*	11	*4*	20	*4*
Strengthening by shape correction	4	*9*	8	*5*	3	*1*	15	*3*
In appurtenant works:								
Discharge increase	1	*2*	8	*5*	7	*3*	16	*3*
Construction of additional appurtenant work	1	*2*	2	*1*	1	*0*	4	*1*
Overall reconstruction of appurtenant works_	0	*0*	2	*1*	6	*2*	8	*2*
Partial reconstruction with strengthening	0	*0*	5	*3*	6	*2*	11	*2*
Shape correction of surfaces contacting flow	0	*0*	3	*2*	5	*2*	8	*2*
Aeration devices: construction or capacity inc.	0	*0*	0	*0*	2	*1*	2	*0*
Repair of surfaces contacting flow	0	*0*	8	*5*	19	*7*	27	*6*
Slope protection & stabilisation	0	*0*	2	*1*	1	*0*	3	*1*
Const., modification & repair of valves & gates	0	*0*	10	*6*	4	*2*	14	*3*
Establish. & update rules for gate & valve ops	0	*0*	0	*0*	2	*1*	2	*0*
Reconstruction of deteriorated zones	1	*2*	19	*11*	8	*3*	28	*6*
Abandonment of appurtenant work	0	*0*	0	*0*	1	*0*	1	*0*
In reservoir:								
Reforestation	0	*0*	2	*1*	0	*0*	2	*0*
Torrent training	0	*0*	5	*3*	0	*0*	5	*1*
Sediment discharge diversion	0	*0*	1	*1*	0	*0*	1	*0*
Slope regularisation, protection & strengthening	0	*0*	2	*1*	0	*0*	2	*0*
Water tightening	0	*0*	4	*2*	1	*0*	5	*1*
Dredging	0	*0*	2	*1*	2	*1*	4	*1*
Downstream of Dam:								
Draining	0	*0*	2	*1*	0	*0*	2	*0*
Slope regularisation, protection & strengthening	0	*0*	2	*1*	2	*1*	4	*1*
TOTAL	52		242		365		659	

Note: (*) Percent of dams (of particular incident type) with particular remedial measure

3.8 Geology

3.8.1 Geology of Dam Foundations Experiencing Incidents

In previous databases and analyses the dam foundation geology has been simply described using categories of soil and/or rock. Since a large proportion of failures have occurred due to deficiencies in the foundation, an improved analysis would be to classify what type of soil or rock the dam was founded on, and then assess whether certain foundation types are more susceptible to failure.

The aim of this section is to assess the geology of the foundations of dams that have failed with particular reference to those that have undergone failure due to sliding or piping in the foundation. There are 65 dams in the database that have experienced foundation incidents, of which there are 19 failures 25 accidents and 25 (16 of which were 'significant') major repairs. Table 32 lists the dams that have had failures or accidents due to deficiencies in the foundation.

Figure 31 shows the age to failure for dams with failure in the foundation. Times to failure and accidents in the foundation tend to be confined to less than five years. Major repairs have occurred up to 45 years after commissioning. Failures due to the foundation have occurred mainly in dams constructed prior to 1940.

Figure 32 shows the foundation geology types for incidents occurring in the foundation. Limestone, shale, granite and alluvium are the most common foundation geology types for dam foundations that have had accidents. Shale, limestone, sandstone and alluvium are the most common for major repairs. However, there are a large number of foundation major repairs (27%) with unknown foundation geologies.

The two main foundation failure modes are:

(a) Sliding on/in the Foundation

Table 32 shows that sliding is most prevalent in interbedded sedimentary sequences particularly with shale, and in schistose metamorphic where weaknesses could be expected. The tuff and conglomerate (and shale for Bayless Dam) were noted to have softened when wet. In the case of Malpasset the rock type played some role in the failure but it was predominately due to uplift pressure and a fault zone. In the case of Zerbino Dam the failure occurred along the foliations of the schist. There are no cases of dam sliding associated with igneous rocks. Overtopping preceded four of the foundation sliding cases.

Table 32. Geology for Dams with Failure and Accidents in the Foundation

Dam Name	Dam Type	Year Failed	Failure Mode[*]	Fndn Material[**]	Geology		
FAILURES							
Bayless (A)	PG	1910	Slide	R	Shale	Sandstone	
Bayless (B)	PG	1911	Slide	R	Shale	Sandstone	
St Francis	PG	1928	Slide	R	Conglomerate	Schist	
Xuriguera	PG	1944	Slide	R	Unknown		
Austin (A)	PG(M)	1900	Slide	R	Shale	Limestone	Dolomite
Tigra	PG(M)	1917	Slide	R	Shale	Sandstone	
Malpasset	VA	1959	Slide/Uplift	R	Gneiss		
Komoro	CB(M)	1928	Slide/Piping	R	Tuff		
Elwha River	PG	1912	Piping	S/R	Fluvioglacial	Conglomerate	
Angels	PG(M)	1895	Piping	S	Unknown		
Puentes	PG(M)	1802	Piping	S	Alluvium	Sandstone	
Vaughn Creek	VA	1926	Piping (abt)	S/R	Residual	Conglomerate	
Ashley	CB	1909	Piping	S	Fluvioglacial		
Selsfors	CB	1943	Piping	S/R	Fluvioglacial		
Stony River	CB	1914	Piping	S	Alluvial	Shale	
Bacino di Rutte	VA(M)	1965	Deformation/Piping	R	Dolomite		
Zerbino	PG	1935	Scour/Slide	R	Schist	Hornfeld	
Moyie River	VA	1926	Scour	R	Unknown		
Overholser	CB	1923	Scour	R	Unknown		
ACCIDENTS							
Castrelo	PG	-	Slide	R	Granite		
Don Marco	PG	1975	Slide	R	Unknown		
Mequinenza	PG	1966	Slide	R	Limestone	Lignite	
Zardezas	PG	1932	Slide	R	Sandstone	Limestone	Conglomerate
Bouzey (A)	PG(M)	1884	Slide	R	Sandstone		
Dobra	VA	1954	Slide	R	Unknown		
Aguilar	PG	1963	Piping	R	Limestone		
Great Falls (A)	PG	1945	Piping	R	Shale	Limestone	
Hales Bar	PG	1964	Piping	R	Limestone	Shale	
Kawamata	PG	1966	Piping	?	Unknown		
Upper Glendevon	PG	1956	Piping	R	Andesite	Agglomerate	Siltstone
Villagarcia	PG	1961	Piping	R	Granite		
Woodbridge (A)	PG	-	Piping	S	Alluvial		
Idbar	VA	1959	Piping	R	Limestone	Schist	
Estremera	CB	1955	Piping	S	Alluvial		
Logan Martin	PG/TE	1964	Piping	R	Dolomite	Limestone	
Koshibu	PG	1969	Piping/Leakage	R	Granite		
Bingham	PG	-	Piping/Scour	R	Unknown		
Austin (D)	CB(M)	1937	Scour/Piping	R	Limestone	Shale	Dolomite
Saulspoort	PG	1988	Scour	R	Sandstone	Siltstone	Dolerite
Albigna	PG	-	Deformation	R	Granite		
Santa Maria	VA	1968	Deformation	R	Granite		
Gerlos	VA	1964	Deformation	R	Unknown		
Kariba	VA	1958	Leakage	R	Unknown		
Kolnbrein	VA	1978	Uplift/Tension/Leakage	R	Gneiss		

[*] Piping failure through abutment denoted by (abt).

[**] Note: S= Soil; R= Rock

(b) Piping through the Foundation

Piping has tended to occur in soils namely alluvium, fluvioglacial and residual. Although large concrete dams are generally not built on soil foundations, smaller structures such as weirs are. Where foundations were rock, piping failure was through the abutment of the dam. The abutment is defined by ICOLD(1978) as 'that part of the valley side against which the dam is constructed' (i.e. zones L2 and L4 of Figure 2 in Section 2.4.7). A disproportionately high number of piping failures occurred in buttress and arch dams. This is likely to be due to the high hydraulic gradients in the foundations/abutments of these types of dams. Note, the scouring associated with Overholser Dam was also through the abutment. When accidents are included limestone becomes notably more prevalent.

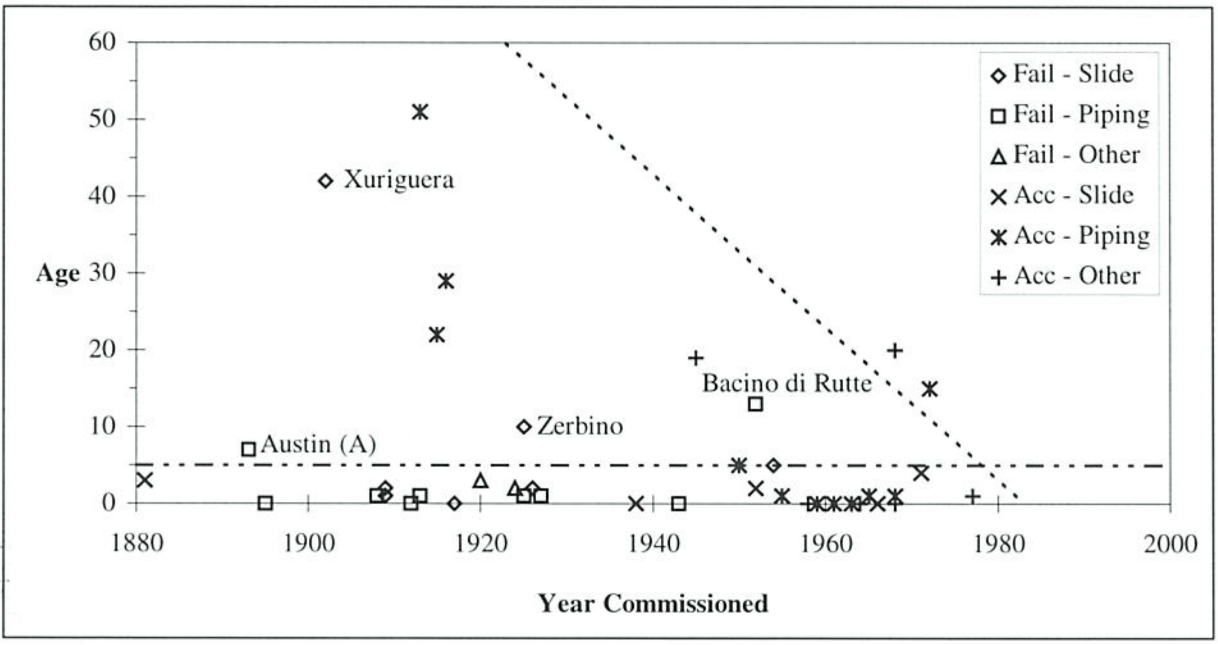
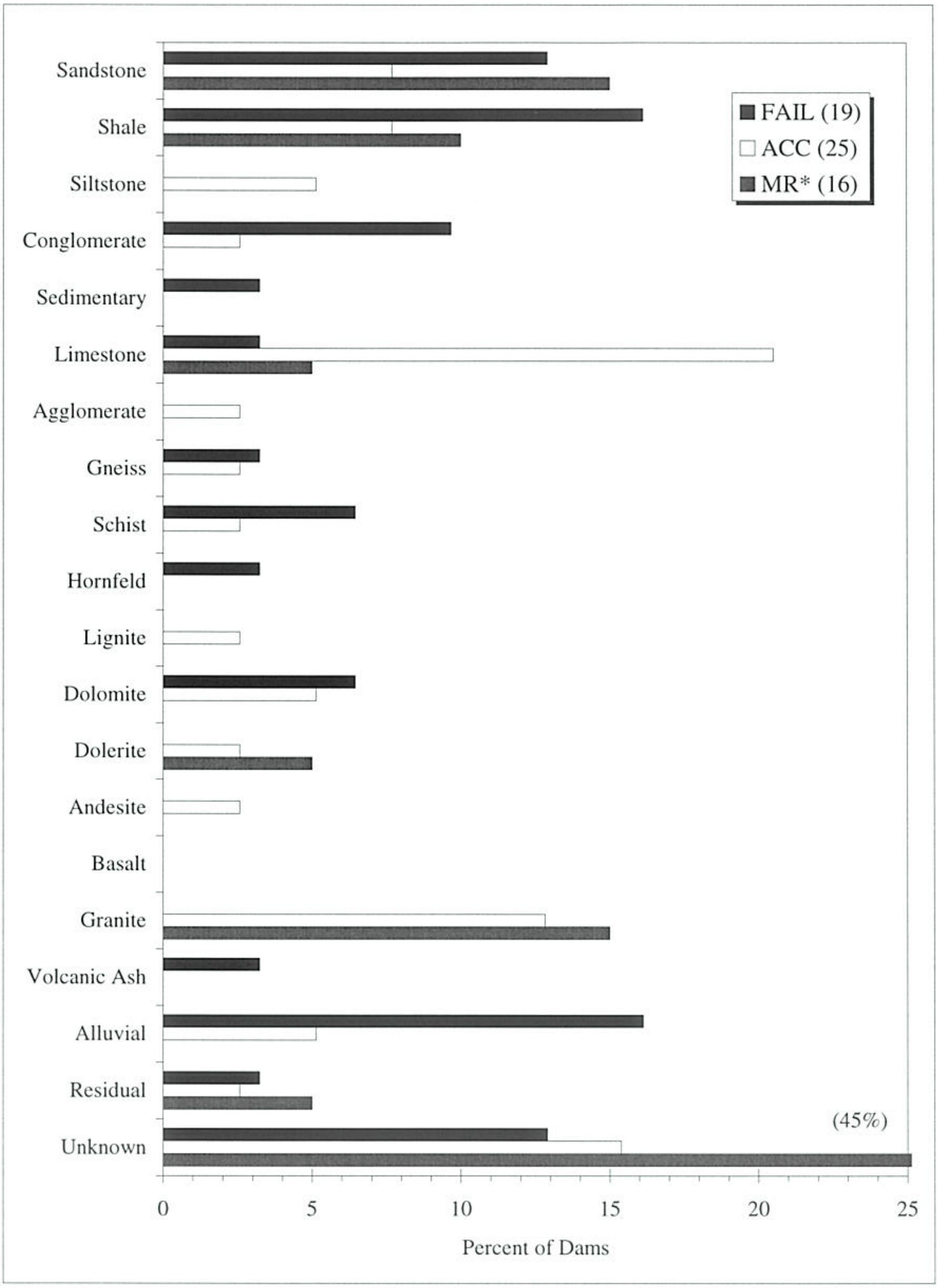


Figure 31. Foundation Incidents Age, Type and Year Commissioned - All Dams



Note (*) Significant incidents only

Figure 32: Foundation Incidents Geology - All Incidents

3.8.2 Geology of the Population of Dams

As discussed above a large proportion of concrete dam failures have occurred in the foundation. ICOLD (1974, 1983 and 1995) and USCOLD (1975 and 1988) have only assessed the foundation of dams as soil or rock. Little work has been done in attempting to compare foundation geology to likelihood of failure. This would allow comparison of the geology of those dams experiencing incidents to the geology of the population of dams allowing identification of those with disproportionately high or low number of incidents.

To gain a better understanding of which foundation geology is likely to cause problems a population of dams was required. The difficulty in doing this was finding populations of concrete and masonry dams where the geology of dams could reasonably be attained. The following populations were chosen:

- USBR;
- Australia/New Zealand; and
- Portugal.

Descriptions of the populations are given below. The results of the analysis are shown in Tables 33 and 34. It should be noted that where a dam has two foundation geology types both are included in the tables. This results in the total number of dams being less than the total number of foundation geology types in Tables 33 and 34. The percentage figures are calculated as the number of occurrences of a particular geology type divided by the number of dams (and not the total number of geology types). The figures therefore represent the percentage of dams with a particular geology type.

(a) USBR Large Concrete Dams

The USBR large concrete dam population was chosen for its good information on geologies. The main sources being:

- USBR (1996) Large Concrete Dams Online Database;
- USBR SEED Reports;
- USBR database Dam Safety Information System; and
- personal communication with USBR personnel.

The results of the analysis on the dams are shown in Table 33. The results are in percent per dam type. The number of dams is given in italics. The predominant foundation types were granite (25%) and sandstone (22%). The total number of unknowns was six.

(b) Australian and New Zealand Dams

The Australia/New Zealand population of dams was taken primarily from the ANCOLD dam register with more detailed information provided by the sponsors of the research project. Other information was taken from ICOLD Congresses, the ANCOLD Bulletin and other journals. The major New Zealand dam owners (besides ECNZ who were a sponsor) were contacted and the following companies provided information:

- Contact Energy Ltd
- Central Electric Ltd
- Egmont Electricity Ltd
- Marlborough Electric Ltd

Table 33 gives the breakdown of foundation geology types. The most common foundation geology types were sandstone (26%) and granite (14%).

(c) Portuguese Dams

The Portuguese population was taken from LNEC (1996). The results are given in Table 33 in a similar method to above. There were 52 dams on rock foundations; 1 on a soil/rock foundation and 1 unknown. The most common geology types were granite (50%), schist (30%) and sandstone (19%).

The populations from Australia, New Zealand, the USBR and the Portuguese population have been added into one population, which is presented in Table 34. Sandstone (24%) and granite (24%) were the most common foundation geology types. 2% of the dam population had soil, namely alluvium, foundations.

Table 33. Foundation Geology for Australia, New Zealand, Portugal and USBR (Percent and *Number* for Each Group)

	AUSTRALIA/NEW ZEALAND					PORTUGAL					USBR			
	Grav	Arch	Butt	MA	ALL	Grav	Arch	Butt	MA	ALL	Grav	Arch	Butt	ALL
Total Dams	*97*	*42*	*10*	*3*	*152*	*28*	*20*	*4*	*2*	*54*	*21*	*7*	*31*	*59*
Sandstones	24 *23*	36 *15*	20 *2*		26 *40*	21 *6*	15 *3*	25 *1*		19 *10*	24 *5*	43 *3*	16 *5*	22 *13*
Shale	8 *8*	5 *2*			7 *10*					*0*	10 *2*	14 *1*	3 *1*	7 *4*
Siltstone	5 *5*	14 *6*	20 *2*		9 *13*					*0*				*0*
Conglomerate		10 *4*			3 *4*					*0*	5 *1*	14 *1*	10 *3*	8 *5*
Limestone		5 *2*			1 *2*				50 *1*	2 *1*	5 *1*		13 *4*	8 *5*
Claystone	3 *3*	7 *3*			4 *6*					*0*				*0*
Mudstone	4 *4*		10 *1*		3 *5*					*0*				*0*
Chert	2 *2*	2 *1*			2 *3*					*0*				*0*
Breccia	2 *2*				1 *2*					*0*				*0*
Dolomite											5 *1*		3 *1*	3 *2*
Tillite		2 *1*			1 *1*					*0*				*0*
Marl											5 *1*			2 *1*
Schist	7 *7*	7 *3*			7 *10*	21 *6*	30 *6*	75 *3*	50 *1*	30 *16*	14 *3*		6 *2*	8 *5*
Quartzite	7 *7*	12 *5*	10 *1*	33 *1*	9 *14*	4 *1*	5 *1*			4 *2*		14 *1*	6 *2*	5 *3*
Gneiss	7 *7*				5 *7*		5 *1*			2 *1*			3 *1*	2 *1*
Phylitte	2 *2*	2 *1*			2 *3*	7 *2*	5 *1*	25 *1*		7 *4*				*0*
Slate	3 *3*	7 *3*			4 *6*					*0*				*0*
Hornfels					*0*		5 *1*			2 *1*	5 *1*			2 *1*
Argillite	1 *1*				1 *1*					*0*				*0*
Granite	21 *20*	5 *2*			14 *22*	43 *12*	65 *13*	50 *2*		50 *27*	24 *5*	14 *1*	29 *9*	25 *15*
Basalt	4 *4*	5 *2*	10 *1*		5 *7*				50 *1*	2 *1*	14 *3*	29 *2*	10 *3*	14 *8*
Tuff	9 *9*	5 *2*	20 *2*		9 *13*					*0*	5 *1*		3 *1*	3 *2*
Dolerite	8 *8*	5 *2*			7 *10*					*0*				*0*
Rhyolite	4 *4*	5 *2*			4 *6*					*0*	5 *1*		10 *3*	7 *4*
Andesite	3 *3*	5 *2*	10 *1*		4 *6*					*0*				*0*
Porphyry	2 *2*				1 *2*					*0*			6 *2*	3 *2*
Diorite	1 *1*	2 *1*			1 *2*					*0*	5 *1*		3 *1*	3 *2*

	AUSTRALIA/NEW ZEALAND					PORTUGAL					USBR			
	Grav	Arch	Butt	MA	ALL	Grav	Arch	Butt	MA	ALL	Grav	Arch	Butt	ALL
Granodiorite	2 *2*				1 *2*	4 *1*				2 *1*				*0*
Greenstone	1 *1*				1 *1*					*0*	5 *1*		3 *1*	3 *2*
Agglomerate	1 *1*				1 *1*					*0*			3 *1*	2 *1*
Pumice	1 *1*				1 *1*					*0*				*0*
Volcanic Ash					*0*					*0*				*0*
Alluvium	2 *2*				1 *2*					*0*	5 *1*	14 *1*		3 *2*
Glacial											5 *1*			2 *1*
Residual	1 *1*				1 *1*					*0*				*0*
Unknown	20 *19*	14 *6*	50 *5*	67 *2*	21 *14*	18 *5*				9 *5*				*0*

Grav - Gravity; Butt - Buttress; MA - Multi-Arch

Table 34. Foundation Geology for Australia, New Zealand, Portugal & USBR dams - Totalled Figures

	Gravity		Arch		Buttress		Multi-Arch		ALL	
Total Dams		*125*		*93*		*21*		*5*		*265*
Sandstone	27	*34*	25	*23*	29	*6*			24	*63*
Shale	8	*10*	3	*3*	5	*1*			5	*14*
Siltstone	4	*5*	6	*6*	10	*2*			5	*13*
Conglomerate	1	*1*	8	*7*	5	*1*			3	*9*
Limestone	1	*1*	6	*6*			20	*1*	3	*8*
Claystone	2	*3*	3	*3*					2	*6*
Mudstone	3	*4*			5	*1*			2	*5*
Chert	2	*2*	1	*1*					1	*3*
Breccia	2	*2*							1	*2*
Dolomite	1	*1*	1	*1*					1	*2*
Tillite			1	*1*					0	*1*
Marl	1	*1*							0	*1*
Schist	13	*16*	12	*11*	14	*3*	20	*1*	12	*31*
Quartzite	6	*8*	9	*8*	10	*2*	20	*1*	7	*19*
Gneiss	6	*7*	2	*2*					3	*9*
Phylitte	3	*4*	2	*2*	5	*1*			3	*7*
Slate	2	*3*	3	*3*					2	*6*
Hornfels	1	*1*	1	*1*					1	*2*
Argillite	1	*1*							0	*1*
Granite	30	*37*	26	*24*	14	*3*			24	*64*
Basalt	6	*7*	5	*5*	14	*3*	20	*1*	6	*16*
Tuff	8	*10*	3	*3*	10	*2*			6	*15*
Dolerite	6	*8*	2	*2*					4	*10*
Rhyolite	4	*5*	5	*5*					4	*10*
Andesite	2	*3*	2	*2*	5	*1*			2	*6*
Porphyry	2	*2*	2	*2*					2	*4*
Diorite	2	*2*	2	*2*					2	*4*
Granodiorite	2	*3*							1	*3*
Greenstone	2	*2*	1	*1*					1	*3*
Agglomerate	1	*1*	1	*1*					1	*2*
Pumice	1	*1*							0	*1*
Alluvium	2	*3*			5	*1*			2	*4*
Glacial	1	*1*							0	*1*
Residual	1	*1*							0	*1*
Unknown	19	*24*	6	*6*	24	*5*	40	*2*	14	*37*

3.9.3 Geology - Comparison Between Incidents and Population

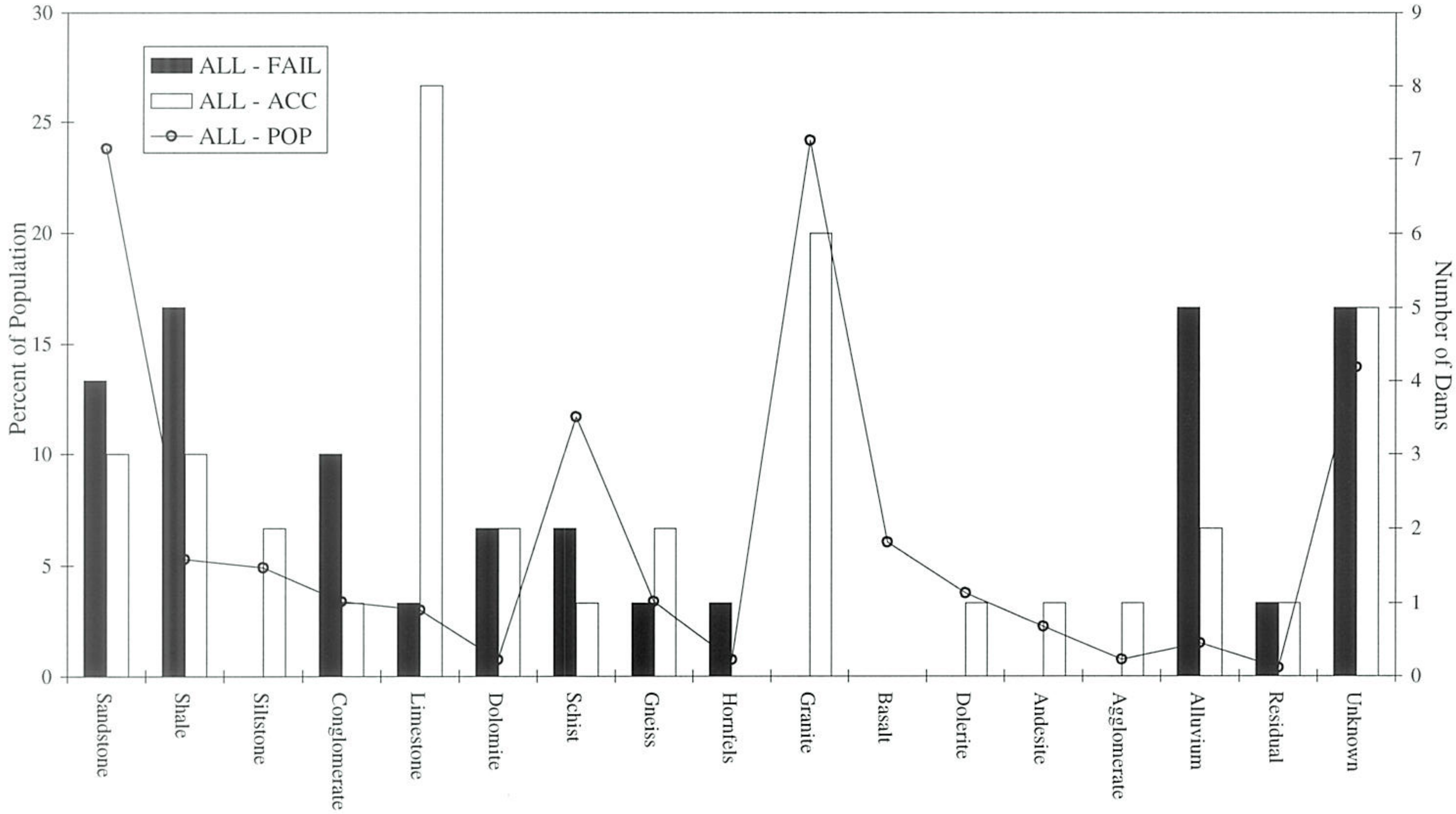
The following assesses the foundation geology more likely to cause foundation piping and stability problems. This has been based on the statistics of failures and accidents and the "population" assumed in Table 34. Due to the limited number of foundation failures that have occurred and the potential inaccuracies introduced by adopting Table 34 as a world population, care should be exercised here and the information taken as qualitative only.

Figures 33 to 35 give the number of incidents in each geology type for: all dams; concrete gravity dams; and masonry gravity dams respectively. From these figures it becomes evident that soil foundations - most particularly alluvial soils are over represented in the foundation incidents. The alluvial soils have a tendency to pipe under the high gradients imposed. No dam has been reported to have failed by sliding on alluvial soils. Normally a large concrete or masonry dam would not be built on a soil foundation. It is interesting that sandstone does not appear to be over represented when the population is taken into account. Failures tend not to occur in sandstone alone but only when the sandstone is interbedded with shales. Shale and limestone (often interbedded) have a high incidence for failing. The limestone has a high proportion of accidents generally due to excessive leakage through dissolution. Another point of note is that no incidents have occurred in basalt foundations.

Figures 36 to 39 give the number of incidents in each geology type over the population of dams in the same geology. The population was estimated using the figures from Table 34 and the estimated world population of dams at 1983 (the available ICOLD world population data cutoff). For gravity dams conglomerate, limestone, dolomite and alluvium foundations stand out. Dams with limestone foundations appear to be very susceptible to accidents. The figures for arch and buttress dams are based on small failure populations and should therefore be looked at with caution. Dolomite and gneiss stands out for arch dams whilst alluvium and shale are notable in buttress dams.

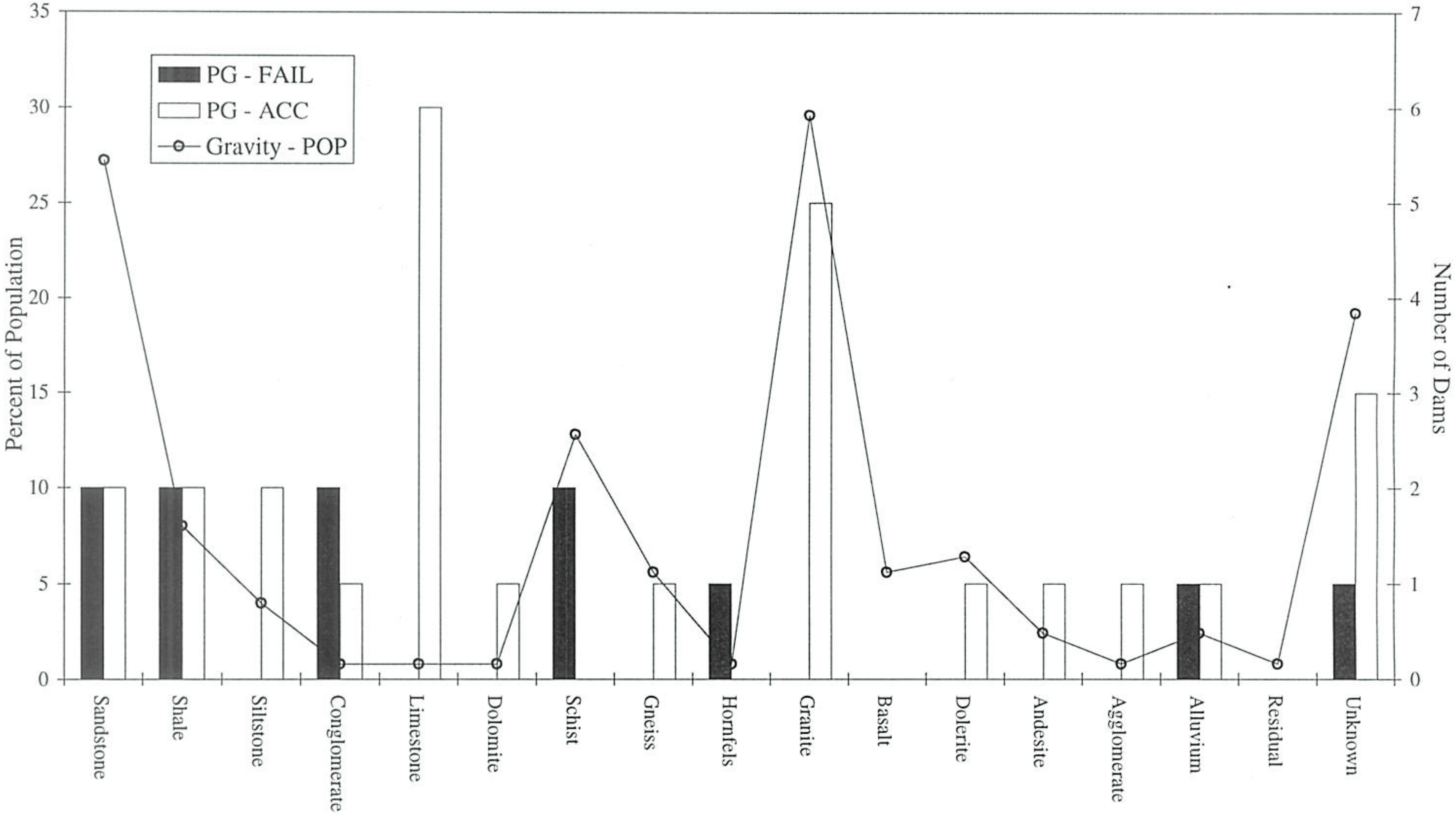
Figure 40 gives a clear indication of which foundation geology types have a tendency to slide or pipe fail. Soils (particularly alluvial and fluvioglacial) and limestones are more likely to have piping problems. Shale (interbedded with other sedimentary units) has a greater tendency to be involved with sliding failure because of the likely presence of weaknesses in the bedding such as bedding surface shears. These conclusions agree with the general knowledge regarding the geology types (e.g. as described in Fell *et al*, 1992).

Figure 33. Geology for Incidents in the Foundation and Dam Population - All Dams



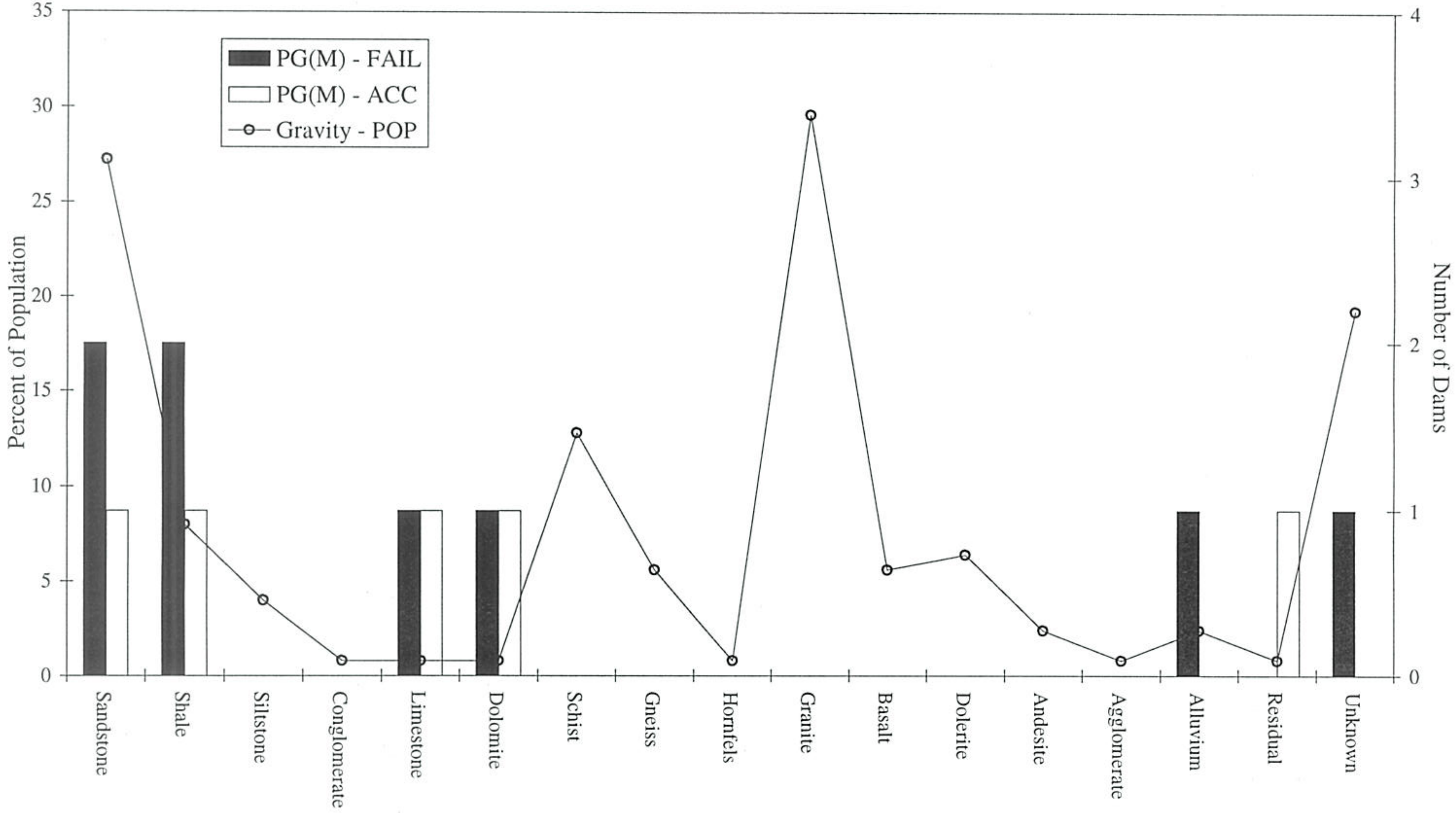
Note: Population based on Australia, New Zealand, Portugal and USBR

Figure 34. Geology for Incidents in the Foundation and Dam Population - Concrete Gravity Dams



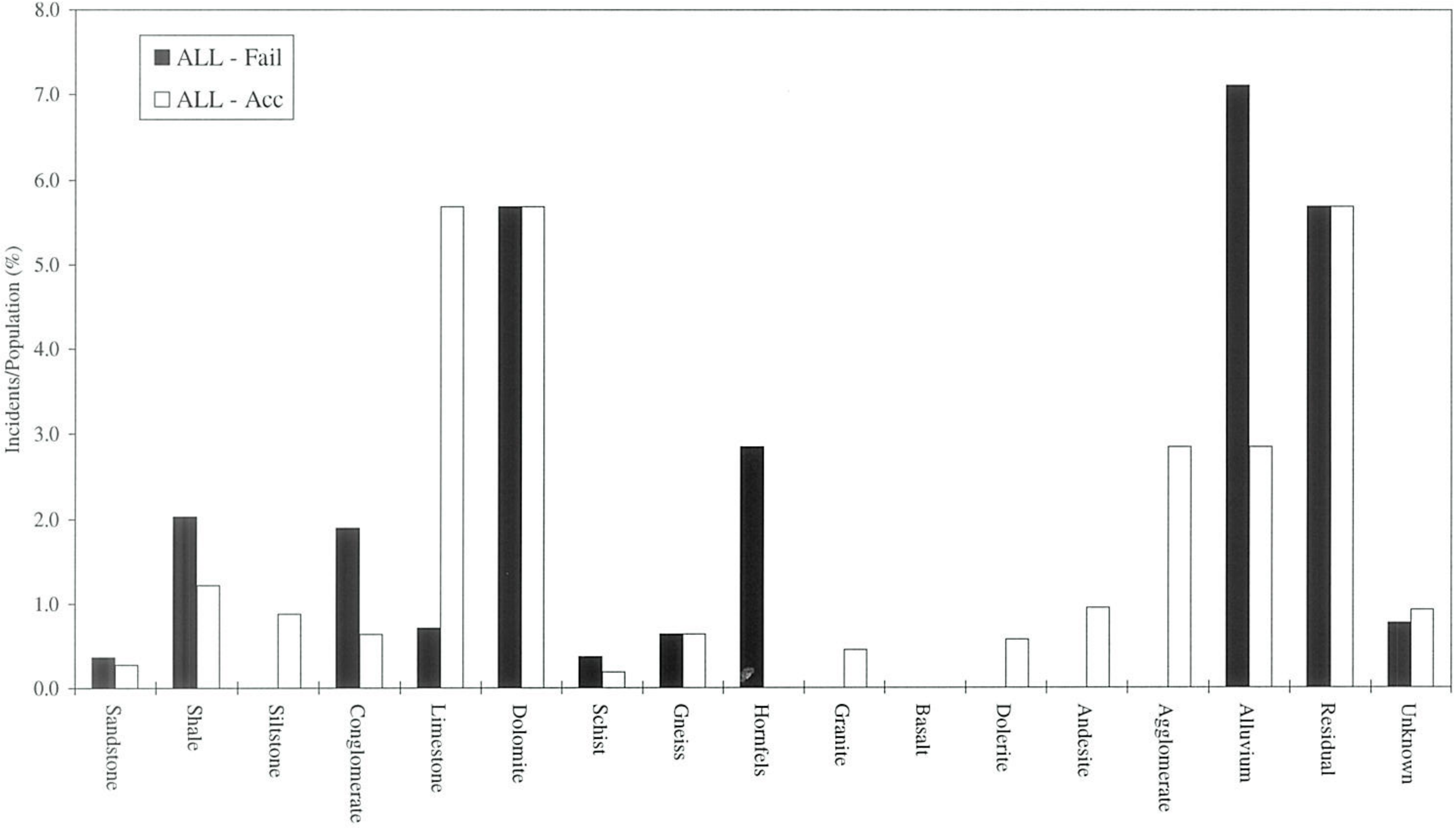
Note: Population based on Australia, New Zealand, Portugal and USBR

Figure 35. Geology for Incidents in the Foundation and Dam Population - Masonry Gravity Dams



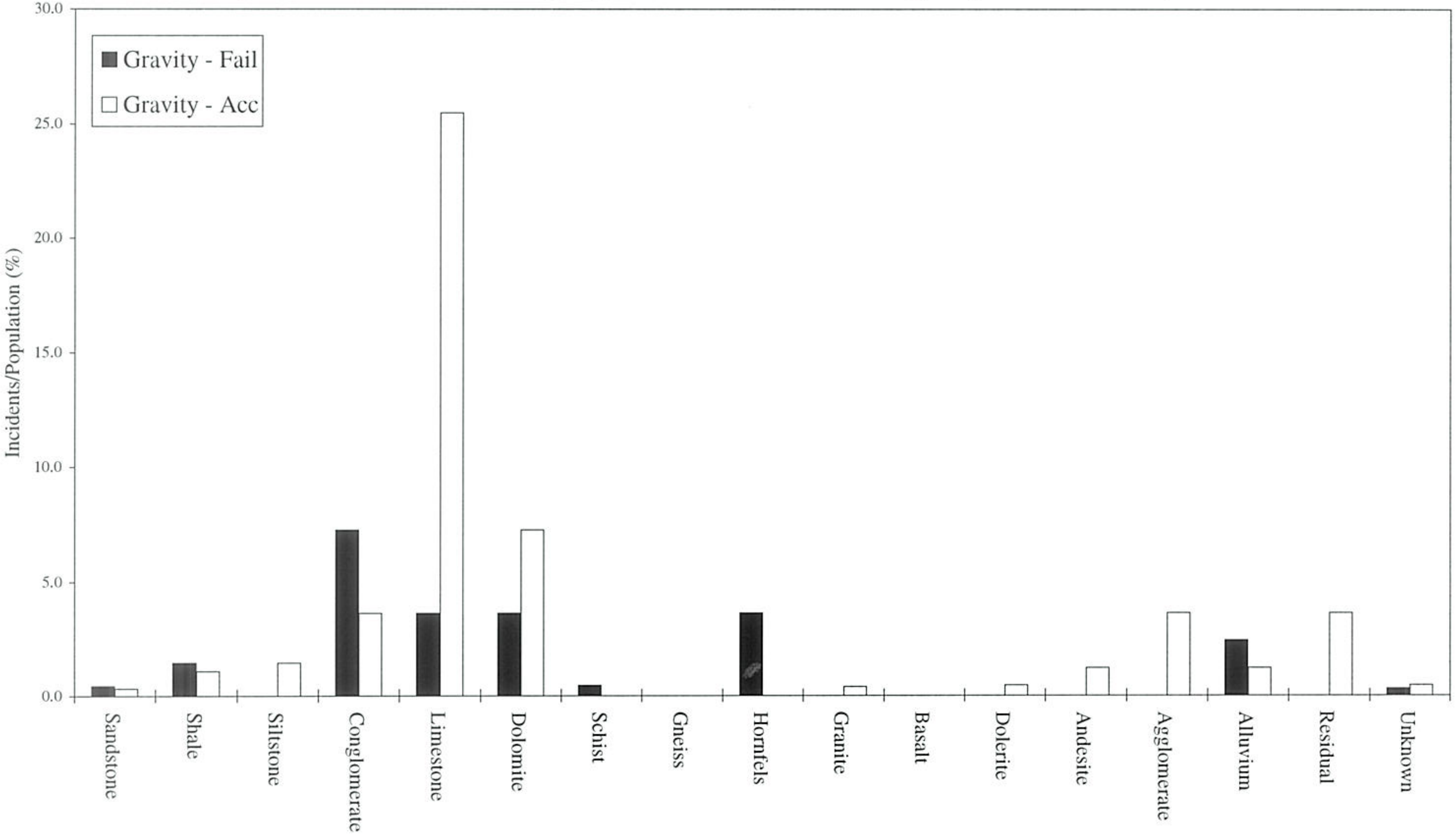
Note: Population based on Australia, New Zealand, Portugal and USBR

Figure 36. Foundation Geology Type as Percentage of Geology Population - All Dams



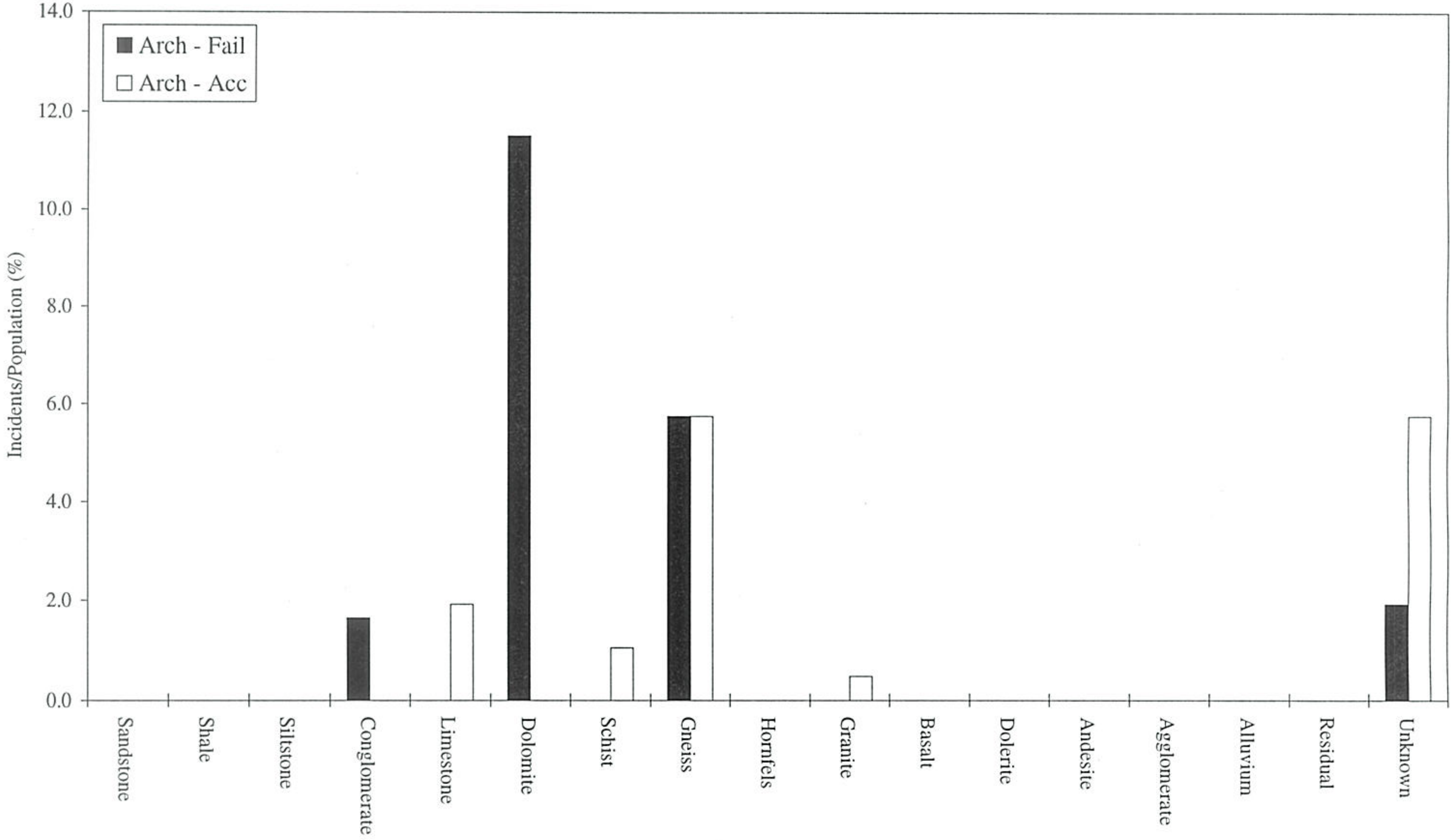
Note: Population based on Australia, New Zealand, Portugal and USBR

Figure 37. Foundation Geology Type as Percentage of Geology Population - Gravity Dams



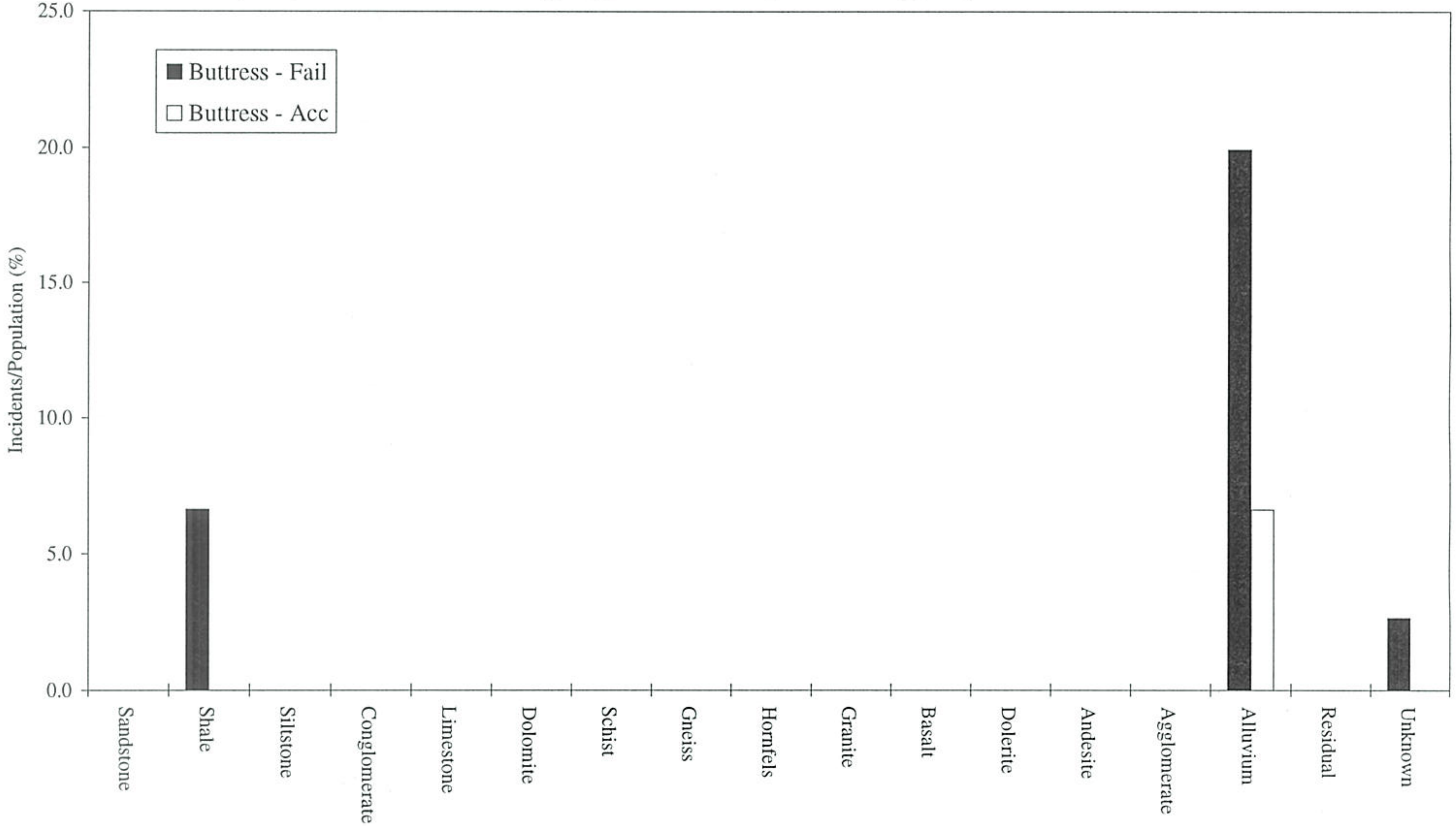
Note: Population based on Australia, New Zealand, Portugal and USBR

Figure 38. Foundation Geology Type as Percentage of Geology Population - Arch Dams



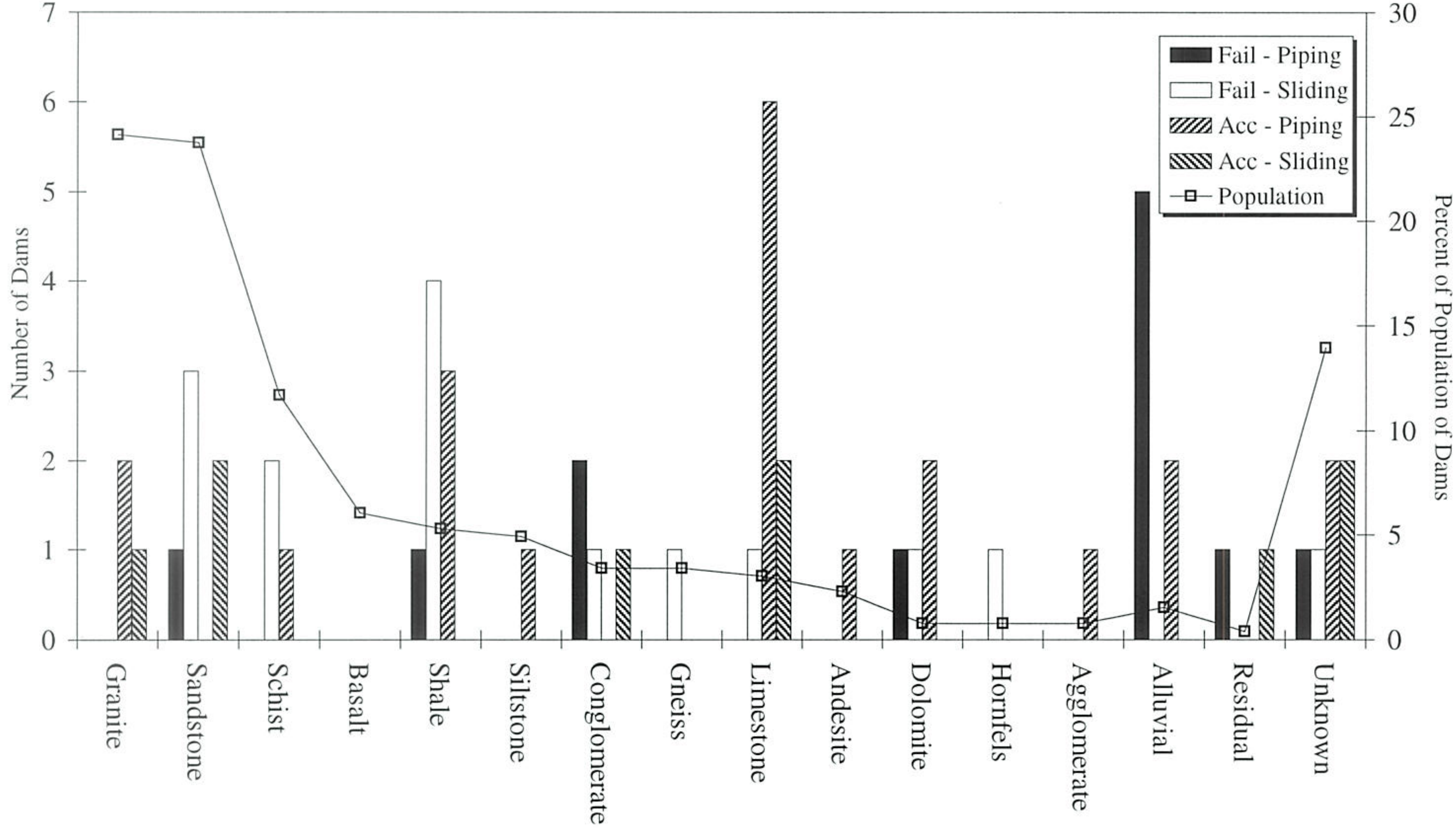
Note: Population based on Australia, New Zealand, Portugal and USBR

Figure 39. Foundation Geology Type as Percentage of Geology Population - Buttress Dams



Note: Population based on Australia, New Zealand, Portugal and USBR

Figure 40. Foundation Incident Geology and Population - Mode of Failure/Accident



Note: Population based on Australia, New Zealand, Portugal and USBR

3.9 Other Design Factors in Failed Dams

Due to the limited information no conclusions could be drawn for the following factors.

(a) Post-Tensioning

No dam that failed was found to have been post-tensioned. The dams where there is no information tend to be older dams (generally masonry) where post-tensioning is unlikely.

(b) Gallery and Drains

Of the 46 dam failures, information could be found on the gallery and drains for 21 dams. Of these, only Zerbino Dam had drains present. The gallery was 4m above the base of the dam with drains to the concrete-rock interface. Zerbino overtopped by 3m causing erosion of the weak foundation rock at the toe, which resulted in foundation sliding. It is not known what effect, if any, the drains had on the failure.

(c) Foundation Grouting

Of the 46 dam failures, information could be found on the foundation grouting for 20 dams. Of these, 2 dams had curtain grouting; three dams had consolidation grouting; and one (Vega de Tera) had both. These dams are shown in Table 35. The foundations of the other 14 failed dams were not grouted.

Table 35. Failed Dams with Grouted Foundation

Dam Name	Dam Type	Grout Type	Foundation Geology	Failure Comments
Cheurfas	PG(M)	curtain	limestone	failed in dam body
Austin (B)	PG(M)	curtain	limestone/shale/ dolomite	seepage softened fndn prior to sliding - grouting inadequate
Zerbino	PG	consolidation	hornfeld/schist	overtopped by 3m with toe erosion then sliding
Chickahole	PG(M)	consolidation	gneiss	failed in dam body
Bacino di Rutte	VA(M)	consolidation	dolerite	concrete failure due to fndn movement
Vega de Tera	CB(M)	both	gneiss/schist	failed in dam body

(d) Shear Key

Bouzey Dam was the only failed dam found to have a shear key. The failure occurred within the body of the dam.

(e) Radius of Curvature

Where information on the radius of curvature for failed gravity dams was available (15), all but two dams had straight sections. Tigra Dam and St Francis Dam had radii of curvature of 1000m and 152m respectively.

(f) Valley Shape

18 failed dams were found with information on the valley shape. The gradient of the valley sides ranged from 0.06 to 2.0 (H/L) for gravity dams and 0.6 to 1.3 for arch dams. The averages were 0.72 and 0.84 respectively.

Table 36 shows the ratio of crest length to dam height for both failed dams (where information was available) and the population of dams. The structural height, H_d, was used for the failed dams. The population from ICOLD as described in Section 2.6 was used for the comparison. Dams with composite embankment sections were omitted from both the failure and population analyses. The data shows that the failures were in relatively wide valleys ($L_l/H_d \geq 3.1$ for gravity dams) where three-dimensional effects are unlikely to make a significant impact to the strength of the dams.

Elwha River Dam, a gravity dam which pipe failed, had a very narrow valley (11m) with reasonably steep sides. However the failure was likely to be mainly due to the alluvial foundation. No conclusive results were attained from this analysis.

Table 36. Crest Length/Height for Failed Dams and Population

DAM	FAILURES			POPULATION		
TYPE	Number	Range	Mean	Number	Range	Mean
Gravity	27	3.1-53	13.2	2887	0.3-182$^{(1)}$	10.1
Arch	5	2.9-4.3	3.6	663	0.2-29	3.8
Buttress	6	6.0-26	13.2	232	1.0-131	10.1
Multi-Arch	2	3.5-6.8	5.1	82	2.0-47	9.2

Note (1) 80% of the population of gravity dams has a crest length/height greater than 3.1.

(g) Upstream/Downstream Slopes

Table 37 shows the upstream and downstream slopes for the failed dams where the information was available. Of the 15 gravity dams in the table, 13 had vertical or near vertical upstream slopes. On the downstream face the concrete gravity dams ranged from 0.55:1 (H:V) to 1:1. The masonry gravity dams ranged from 0.38:1 to 3:1. The arch dams ranged from near vertical to 0.32:1.

Table 37. Upstream and Downstream Slopes for Failed Dams

Dam Name	Dam Type	Upstream (xH:1V)	Downstream (yH:1V)	Failure Mode	
				Foundation	Dam
Bayless (A)	PG	0	1	S	
Bayless (B)	PG	0	1	S	
Elwha River	PG	0	0.75	P	
St. Francis	PG	0	1	S	
Zerbino	PG	0.05	0.55	S/SC	
Angels	PG(M)	0	0.6	P	
Austin (A)	PG(M)	0	0.38	SC/P/S	
Bouzey	PG(M)	0	1		T
Chickahole	PG(M)	0.1	0.7		T
Habra (A)	PG(M)	0.3	0.8		T/SH
Habra (B)	PG(M)	3	1		T/SH
Habra (C)	PG(M)	3	1		T/SH
Khadakwasla	PG(M)	0.05	0.4		T/SH
Puentes	PG(M)	0	0.6	P	
Tigra	PG(M)	0	0.67	S	
Malpasset	VA	0	0	S	
Moyie River	VA	0	0.06	SC	
Vaughn Creek	VA	0	0.2	P	
Bacino di Rutte	VA(M)	0.12	0.12	D/P	
Gallinas	VA(M)	0	0.32		?
Meihua	VA(M)	0	0		SH
Ashley	CB	1	0.5	P	
Stony Creek	CB	1	0.15	P	
Vega de Tera	CB(M)	0.05	0.75		T/C
Austin (B)	CB(M)	0	1		SH
Gleno	MV	0.85	0.1		T/C

(h) Dam Height/Base Width (H_d/W)

Table 38 shows the dam structural height and height of water at failure over base width (H_d/W and h_{wf}/W respectively) for the failed dams where the information was available. Figure 1 in Section 2.4.7 shows the definition of these terms. The H_d/W and/or h_{wf}/W ratios give an indication of the stability and hydraulic gradient of the dams. A high H_d/W or h_{wf}/W indicates a slender dam with potentially a high hydraulic gradient. These are common for arch dams. The definitions for the failure modes are given in Sections 2.4.2 and 2.4.3.

Dams that failed by piping generally had soil foundations. Those with alluvial foundations had h_{wf}/W ratios of 0.6 to 1.1. Vaughn Creek, an arch dam which pipe failed through its extremely to highly weathered conglomerate abutment, had a ratio of 3.0. Austin (A), the only dam to have pipe failure through rock (weathered) had a h_{wf}/W of 1.2. Gravity dams that failed by sliding had h_{wf}/W ratios of 1.2 to 2.1. Of these, Zerbino Dam (h_{wf}/W=2.1) was the only dam known to have drainage. Malpasset Dam, an arch dam, had a h_{wf}/W of 5.8.

Table 38. H_d/W for Failed Dams

Dam Name	Dam Type	H_d/W	h_{wf}/W	Failure Mode	
				Foundation	Dam
Bayless (A)	PG	1.6	1.6	S	
Bayless (B)	PG	1.6	1.6	S	
Elwha River	PG	1.4	0.6	P	
St. Francis	PG	1.2	1.2	S	
Zerbino	PG	1.7	2.1	S/SC	
Austin (A)	PG(M)	1.0	1.2	SC/P/S	
Bouzey	PG(M)	1.7	1.7		T
Cheurfas	PG(M)	1.0			?
Chickahole	PG(M)	1.3	1.0		?
Fergoug I	PG(M)	1.3			?
Fergoug II	PG(M)	1.3			
Habra (A)	PG(M)	1.3			T/SH
Habra (B)	PG(M)	1.3	1.2		T/SH
Habra (C)	PG(M)	1.3	1.4		T/SH
Khadakwasla	PG(M)	1.8	2.0		T/SH
Puentes	PG(M)	1.1	1.1	P	
Tigra	PG(M)	1.5	1.5	S	
Malpasset	VA	6.0	5.8	S	
Moyie River	VA	7.0		SC	
Vaughn Creek	VA	4.3	3.0	P/D	
Gallinas	VA(M)	3.1	3.2		?
Meihua	VA(M)	18.3	17.5		SH
Ashley	CB	1.2	1.1	P	
Stony River	CB	1.0	0.9	P	
Vega de Tera	CB(M)	2.0	1.8		T/C
Austin (B)	CB(M)	0.7	1.2		SH
Gleno	MV	1.1	1.1		T/C

(i) Stability Analyses

Gulan (1995) and Rich (1995) collated information for 13 concrete gravity dams that had failed by either sliding or overturning through their foundations or the concrete mass. Of the 13 cases, nine failures were back analysed to determine the shear strength properties of either the foundation or concrete. Table 39 shows the results from the analyses, which have been checked and some adjustments to the cohesion results made. The results are quoted as c=0, ϕ or c, ϕ=0. Actual strengths are between these limits. The results for Khadakwasla Dam have been omitted as the analysis technique was not valid for the failure mode. The failure plane for Khadakwasla Dam was 6m below the base of the dam.

An additional analysis was carried out for Bhandardara Dam, an 82m high gravity dam in India. The dam suffered extensive cracking, from an elevation of 39m at the upstream face to the toe, and came close to failure. The dam has been extensively investigated and several papers describe the accident including: Murthy *et. al.* (1976 & 1979); and Kulkarni & Kulkarni (1994). Two simple analyses were carried out: the first assuming a horizontal failure at the elevation where the cracking initiated; and the second assuming an angled crack from the location of crack initiation to the toe. The results from the analyses have been included in the tables and figures below.

Table 40 shows the reanalysed stresses along the failure planes. As can be seen seven of the dams had tensile stresses, up to -280KPa at the heel of the dam. Bhandardara Dam, a concrete gravity structure, experienced up to -440kPa tension.

Table 39. Back Analysed Shear Strengths for Failed Dams (modified from Rich, 1995)

Name	Dam Type	Failure	φ′ (°)	C′ (KPa)	Foundation	Concrete
Austin (A)	PG(M)	foundation sliding	49 0	0 120	limestone	rubble limestone in portland cement-mortar
Bouzey (1st)	PG(M)	foundation sliding	40 0	0 110	sandstone & schist	masonry in lime-mortar
Bouzey (2nd)	PG(M)	through concrete	34 0	0 75	sandstone & schist	masonry in lime-mortar
El Habra (3rd)	PG(M)	foundation sliding	46 0	0 605	int. sandstone & clay	rubble masonry in lime-mortar
Tigra	PG(M)	foundation sliding	48 0	0 195	stratified sandstone	rubble masonry in lime-mortar
Bayless	PG	foundation sliding	43 0	0 300	int. sandstone & shale	cyclopean concrete
St. Francis	PG	foundation sliding	41 0	0 155	mica schist & conglomerate	portland cement
Bhandardara (horizontal)	PG	severe cracking - tension & shear	>46 0	0 >1015	basalt	rubble masonry
Bhandardara (angled)	PG	severe cracking - tension & shear	>71 0	0 >480	basalt	rubble masonry

Table 40. Calculated Normal Stresses Along the Failure Plane of Back Analysed Gravity Dams

Name	Dam Type	σ_n Upstream (KPa)	σ_n Downstream (KPa)
Austin	PG(M)	-20	+210
Bouzey (1st)	PG(M)	-20	+265
Bouzey (2nd)	PG(M)	-10	+220
El Habra (3rd)	PG(M)	-280	+735
Tigra	PG(M)	+25	+355
Bayless	PG	-155	+425
St. Francis	PG	+35	+355
Bhandardara (horizontal)	PG	-440	+1085
Bhandardara (angled)	PG	-50	+320

The average stresses acting along the failure planes have been calculated using the forces on each dam provided by Rich (1995). Figures 41 and 42 compare the ANCOLD guidelines (ANCOLD, 1991) to the failure stresses of the nine failure cases. It was assumed that shear strength only acted in the region of compression along the failure plane. The figures show that the failure stresses were much lower than those recommended by ANCOLD for initial assessments. The likely reason for this is the existence of continuous defects through or below the dam. The friction angle and cohesion suggested by ANCOLD assumes no continuous defects. The results show the importance of having a good geotechnical model for the dam and a good bond at the dam/foundation interface.

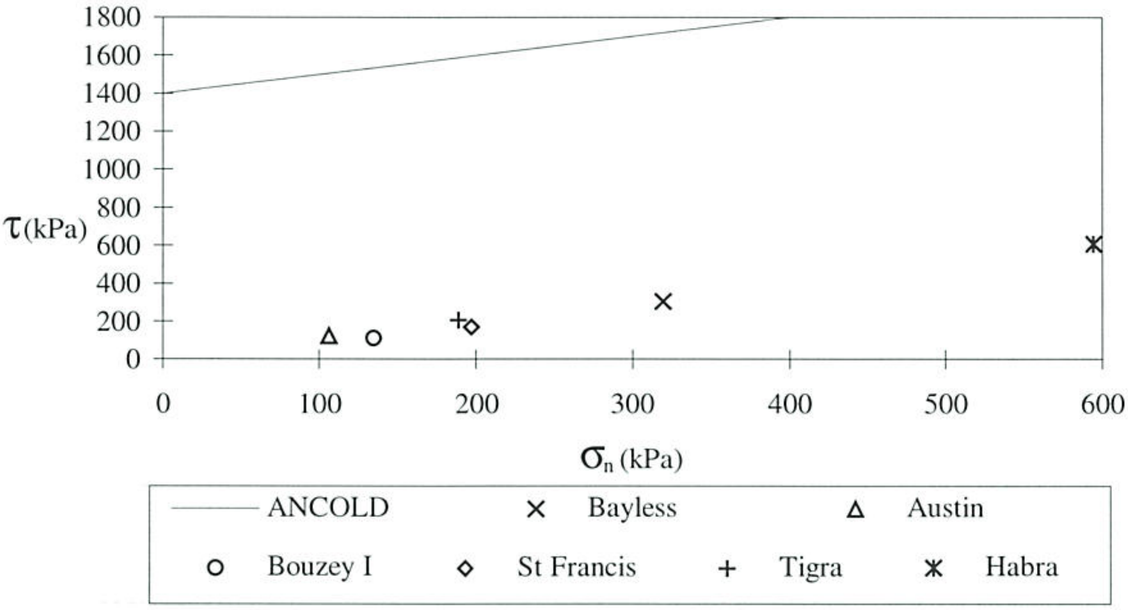


Figure 41. Average Failure Stresses for Dams with Failure through the Foundation

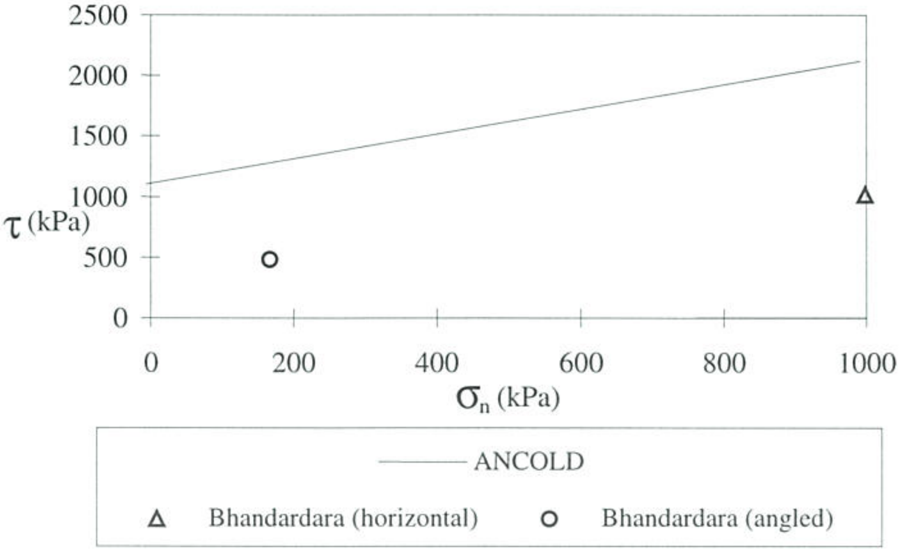


Figure 42. Average Failure Stresses for Bhandardara Dam

4 METHOD OF FIRST ORDER PROBABILITY ASSESSMENT

4.1 Probability of Failure

4.1.1 Introduction

This section describes an attempt to develop a 'first' estimate of the annual probability of failure of concrete and masonry dams based on the history of dam failures. 'Average' annual probabilities of failure have been assessed for all concrete and masonry dam types. These probabilities have been further refined for concrete and masonry gravity dams.

The initial or 'average' annual probability of failure was calculated as the number of dam failures, using the history of failures, over an estimate of the population of dams. The cut off year for the population of dams was taken as 1992 as the latest ICOLD statistics on failures (ICOLD, 1995) go up to this time. Dams were separated using the following categories:

(a) Dam type: gravity, arch, buttress, multi-arch;
(b) year commissioned;
(c) age at failure (0-5 years and >5 years); and
(d) Concrete or masonry (gravity dams).

4.1.2 Population of Dams

The total number of concrete and masonry dams as at 1992 (excluding China) is shown in Table 41. Since the ICOLD world population data for post 1983 was not available, the population for the period 1983-1992 was estimated as shown in the table below.

Table 41. Number of Dams as at 1992

Year Commissioned	Number of Dams	Reference
1700-1799	37	ICOLD (1983)
1800-1899	167	ICOLD (1983)
up to 1977	4446	ICOLD (1984)
1978-1982	217	ICOLD (1984)
1983-1992	434	estimated as 2 x 1978-82
Total	5097	

Dams were divided into gravity, arch, buttress and multi-arch dams. Where a dam was described as a composite section an assessment of the category best describing the dam was made. The population was also split according to age (year commissioned) to account for progress in the methods used for dam construction. The breakdown of the population of dams into dam types and year commissioned was performed using a computer database created by the authors using ICOLD (1979). The database comprised the concrete and masonry dams from the 26 countries with the largest dam populations. These countries included all those that had experienced failures (excluding China). Table 42 shows the percentage split for population of dams according to dam type and year commissioned.

Table 42. Population of Dams by Dam Type and Year Commissioned

Year Commissioned	Gravity (%)	Arch (%)	Buttress (%)	Multi-Arch (%)
<1900	2.7	0.2	0.0	0.1
1900-1909	2.5	0.4	0.1	0.1
1910-1919	4.7	0.7	0.5	0.2
1920-1929	8.3	2.2	0.6	0.4
1930-1939	7.5	1.7	0.5	0.2
1940-1949	7.4	1.4	0.6	0.3
1950-1959	16.9	3.8	1.9	0.4
1960-1969	17.3	4.8	1.6	0.3
1970-1977	7.8	1.5	0.4	0.2
1977-1983(1)	81.1	12.0	6.0	0.9

Note (1) Data from ICOLD (1983)

For dams commissioned during the period 1978 to 1982 the distribution of concrete and masonry dam types was taken from ICOLD (1983). Dams commissioned between 1983 and 1992 were assumed to have a similar distribution of dam types.

Table 43 shows the number of dams as at 1992 calculated from Tables 41 and 42.

Table 43. Number of Dams (excluding China) in the Population

Year Commissioned	Gravity	Arch	Buttress	Multi-Arch	Total
1700-1799	34	2	0	1	37
1800-1899	152	10	1	4	167
1900-1909	109	17	4	3	133
1910-1919	205	31	21	11	267
1920-1929	362	94	27	18	501
1930-1939	327	75	20	11	433
1940-1949	321	62	28	12	422
1950-1959	738	164	85	17	1004
1960-1969	757	208	71	13	1049
1970-1977	339	67	18	8	433
1978-1982	176	26	13	2	217
1983-1992*	352	52	26	4	434
Total	3872	808	314	103	5097

Note (1) Estimated as 2 x 1977-1982

4.1.3 Dam Year

As most failures occur prior to five years after commissioning (Douglas *et al*, 1998) the failure probabilities were broken into: less than or equal to five years of age; and greater than five years of age. Equations 1 and 2 were used to calculate the number of dam years for dams less than or equal to five years, and for dams greater than five years of age respectively.

$$Y_{\leq 5} = n \times 5 \tag{1}$$

$$Y_{>5} = \sum \left(y_i - 5 \right) \tag{2}$$

where,

n = total number of dams
y_i = age of individual dam in years

4.1.4 Probabilities of Failure

Annual probabilities (number of failures/number of dam years) and straight probabilities of failure (number of failures/number of dams) were calculated from the database of failures and the population of dams.

A distinction was made between dams commissioned prior to, and those commissioned after 1930. This represents the historical change to a better understanding of uplift pressures and materials properties for dams. Categories without failures have been denoted as 'NF'.

The probabilities were recalculated for the various failure modes. The following failure modes were used:

- All modes (Tables 44 and 45)
- Sliding (Tables 46 and 47)
- Piping (Tables 48 and 49)
- Through the dam body (Tables 50 and 51)

Tables 52 and 53 show the number of failures with unknown failure modes. Table 52 shows those unknowns where failure during overtopping was known to have occurred.

Table 44. Annual Probability of Failure (as at 1992, excluding China) - All Failure Types

Year	Gravity			Arch			Buttress			Multi-Arch			All Concrete & Masonry		
Comm.	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total
1700-1799	5.9E-03	NF	1.2E-04	NF	NF	NF	NF	NF	NF	NF	NF	NF	5.4E-03	NF	1.1E-04
1800-1899	6.6E-03	3.8E-04	6.0E-04	NF	NF	NF	NF	NF	NF	NF	NF	NF	6.0E-03	3.5E-04	5.5E-04
1900-1909	3.7E-03	2.2E-04	4.2E-04	NF	NF	NF	4.7E-02	NF	2.7E-03	NF	NF	NF	4.5E-03	1.8E-04	4.3E-04
1910-1919	2.0E-03	1.4E-04	2.5E-04	NF	4.5E-04	4.2E-04	1.9E-02	NF	1.2E-03	NF	NF	NF	3.0E-03	1.6E-04	3.4E-04
1920-1929	1.1E-03	8.9E-05	1.7E-04	4.2E-03	NF	3.2E-04	1.5E-02	NF	1.1E-03	1.1E-02	NF	8.3E-04	2.8E-03	6.4E-05	2.7E-04
1930-1939	6.1E-04	NF	5.4E-05	NF	NF	NF	NF	NF	NF	NF	NF	NF	4.6E-04	NF	4.1E-05
1940-1949	NF	NF	NF	NF	NF	NF	7.3E-03	NF	7.7E-04	NF	NF	NF	4.7E-04	NF	5.0E-05
1950-1959	NF	NF	NF	1.2E-03	1.9E-04	3.3E-04	2.4E-03	NF	3.2E-04	NF	1.8E-03	1.6E-03	4.0E-04	6.2E-05	1.1E-04
1960-1969	5.3E-04	1.2E-04	2.0E-04	NF	NF	NF	NF	NF	NF	NF	NF	NF	3.8E-04	8.7E-05	1.4E-04
1970-1977	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	7.7E-03	NF	3.2E-03	NF	NF	NF	NF	NF	NF	9.2E-04	NF	3.8E-04
1983-1992(3)	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1700-1929	2.8E-03	1.9E-04	3.3E-04	2.6E-03	8.9E-05	2.5E-04	1.9E-02	NF	1.2E-03	5.4E-03	NF	3.2E-04	3.6E-03	1.6E-04	3.6E-04
1930-1992(3)	2.0E-04	2.6E-05	5.5E-05	6.2E-04	5.8E-05	1.5E-04	1.6E-03	NF	2.5E-04	NF	5.1E-04	4.3E-04	3.6E-04	3.9E-05	9.0E-05
Total(3)	7.9E-04	1.1E-04	1.8E-04	1.0E-03	7.0E-05	1.8E-04	4.5E-03	NF	5.8E-04	2.0E-03	2.0E-04	3.7E-04	1.1E-03	9.7E-05	2.1E-04

Note *(1) Assumes dam years = number of dams * five years life*

(2) NF - No Failure

*(3) Assumes number of dams constructed in 1983-1992 = 2 * number of dams in 1978-1982*

Table 45. Probability of Failure (as at 1992, excluding China, non-annualised) - All Failure Types

Year	Gravity			Arch			Buttress			Multi-Arch			All Concrete & Masonry		
Comm.	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total
1700-1799	3.0E-02	NF	3.0E-02	NF	NF	NF	NF	NF	NF	NF	NF	NF	2.7E-02	NF	2.7E-02
1800-1899	3.3E-02	5.3E-02	8.5E-02	NF	NF	NF	NF	NF	NF	NF	NF	NF	3.0E-02	4.8E-02	7.8E-02
1900-1909	1.8E-02	1.8E-02	3.7E-02	NF	NF	NF	2.4E-01	NF	2.4E-01	NF	NF	NF	2.2E-02	1.5E-02	3.7E-02
1910-1919	9.8E-03	9.8E-03	2.0E-02	NF	3.3E-02	3.3E-02	9.4E-02	NF	9.4E-02	NF	NF	NF	1.5E-02	1.1E-02	2.6E-02
1920-1929	5.5E-03	5.5E-03	1.1E-02	2.1E-02	NF	2.1E-02	7.5E-02	NF	7.5E-02	5.5E-02	NF	5.5E-02	1.4E-02	4.0E-03	1.8E-02
1930-1939	3.1E-03	NF	3.1E-03	NF	NF	NF	NF	NF	NF	NF	NF	NF	2.3E-03	NF	2.3E-03
1940-1949	NF	NF	NF	NF	NF	NF	3.6E-02	NF	3.6E-02	NF	NF	NF	2.4E-03	NF	2.4E-03
1950-1959	NF	NF	NF	6.1E-03	6.1E-03	1.2E-02	1.2E-02	NF	1.2E-02	NF	5.9E-02	5.9E-02	2.0E-03	2.0E-03	4.0E-03
1960-1969	2.6E-03	2.6E-03	5.3E-03	NF	NF	NF	NF	NF	NF	NF	NF	NF	1.9E-03	1.9E-03	3.8E-03
1970-1977	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	3.8E-02	NF	3.8E-02	NF	NF	NF	NF	NF	NF	4.6E-03	NF	4.6E-03
1983-1992	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1700-1929	1.4E-02	1.6E-02	3.0E-02	1.3E-02	6.5E-03	2.0E-02	9.3E-02	NF	9.3E-02	2.7E-02	NF	2.7E-02	1.8E-02	1.4E-02	3.2E-02
1930-1992	1.0E-03	6.6E-04	1.7E-03	3.1E-03	1.5E-03	4.6E-03	7.7E-03	NF	7.7E-03	NF	1.5E-02	1.5E-02	1.8E-03	1.0E-03	2.8E-03
Total	3.9E-03	4.1E-03	8.0E-03	5.0E-03	2.3E-03	7.3E-03	2.2E-02	NF	2.2E-02	9.7E-03	9.7E-03	1.9E-02	5.3E-03	3.7E-03	9.0E-03

Table 46. Annual Probability of Failure (as at 1992, excluding China) - Sliding Failures

Year	Gravity			Arch			Buttress			Multi-Arch			All Concrete & Masonry		
Comm.	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total
1700-1799	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1800-1899	1.3E-03	NF	4.6E-05	NF	NF	NF	NF	NF	NF	NF	NF	NF	1.2E-03	NF	4.2E-05
1900-1909	3.7E-03	1.1E-04	3.2E-04	NF	NF	NF	NF	NF	NF	NF	NF	NF	3.0E-03	9.1E-05	2.6E-04
1910-1919	9.8E-04	NF	6.3E-05	NF	NF	NF	NF	NF	NF	NF	NF	NF	7.5E-04	NF	4.9E-05
1920-1929	5.5E-04	4.5E-05	8.3E-05	NF	NF	NF	7.5E-03	NF	5.6E-04	NF	NF	NF	8.0E-04	3.2E-05	8.9E-05
1930-1939	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1940-1949	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1950-1959	NF	NF	NF	1.2E-03	NF	1.6E-04	NF	NF	NF	NF	NF	NF	2.0E-04	NF	2.7E-05
1960-1969	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1970-1977	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1983-1992(3)	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1700-1929	1.2E-03	2.7E-05	8.8E-05	NF	NF	NF	3.7E-03	NF	2.5E-04	NF	NF	NF	1.1E-03	2.2E-05	8.1E-05
1930-1992(3)	NF	NF	NF	3.1E-04	NF	4.9E-05	NF	NF	NF	NF	NF	NF	5.1E-05	NF	8.2E-06
Total(3)	2.6E-04	1.3E-05	4.1E-05	2.5E-04	NF	3.1E-05	6.5E-04	NF	8.3E-05	NF	NF	NF	2.8E-04	1.0E-05	4.1E-05

*Note (1) Assumes dam years = number of dams * five years life*

(2) NF - No Failure

*(3) Assumes number of dams constructed in 1983-1992 = 2 * number of dams in 1978-1982*

Table 47. Probability of Failure (as at 1992, excluding China, non-annualised) - Sliding Failures

Year	Gravity			Arch			Buttress			Multi-Arch			All Concrete & Masonry		
Comm.	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total
1700-1799	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1800-1899	6.6E-03	NF	6.6E-03	NF	NF	NF	NF	NF	NF	NF	NF	NF	6.0E-03	NF	6.0E-03
1900-1909	1.8E-02	9.2E-03	2.7E-02	NF	NF	NF	NF	NF	NF	NF	NF	NF	1.5E-02	7.5E-03	2.2E-02
1910-1919	4.9E-03	NF	4.9E-03	NF	NF	NF	NF	NF	NF	NF	NF	NF	3.7E-03	NF	3.7E-03
1920-1929	2.8E-03	2.8E-03	5.5E-03	NF	NF	NF	3.8E-02	NF	3.8E-02	NF	NF	NF	4.0E-03	2.0E-03	6.0E-03
1930-1939	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1940-1949	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1950-1959	NF	NF	NF	6.1E-03	NF	6.1E-03	NF	NF	NF	NF	NF	NF	1.0E-03	NF	1.0E-03
1960-1969	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1970-1977	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1983-1992	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1700-1929	5.8E-03	2.3E-03	8.1E-03	NF	NF	NF	1.9E-02	NF	1.9E-02	NF	NF	NF	5.4E-03	1.8E-03	7.2E-03
1930-1992	NF	NF	NF	1.5E-03	NF	1.5E-03	NF	NF	NF	NF	NF	NF	2.5E-04	NF	2.5E-04
Total	1.3E-03	5.2E-04	1.8E-03	1.2E-03	NF	1.2E-03	3.2E-03	NF	3.2E-03	NF	NF	NF	1.4E-03	3.9E-04	1.8E-03

Table 48. Annual Probability of Failure (as at 1992, excluding China) - Piping Failures

Year	Gravity			Arch			Buttress			Multi-Arch			All Concrete & Masonry		
Comm.	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total
1700-1799	5.9E-03	NF	1.2E-04	NF	NF	NF	NF	NF	NF	NF	NF	NF	5.4E-03	NF	1.1E-04
1800-1899	1.3E-03	NF	4.6E-05	NF	NF	NF	NF	NF	NF	NF	NF	NF	1.2E-03	NF	4.2E-05
1900-1909	NF	NF	NF	NF	NF	NF	4.7E-02	NF	2.7E-03	NF	NF	NF	1.5E-03	NF	8.6E-05
1910-1919	9.8E-04	NF	6.3E-05	NF	NF	NF	9.4E-03	NF	6.1E-04	NF	NF	NF	1.5E-03	NF	9.7E-05
1920-1929	NF	NF	NF	2.1E-03	NF	1.6E-04	NF	NF	NF	NF	NF	NF	4.0E-04	NF	3.0E-05
1930-1939	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1940-1949	NF	NF	NF	NF	NF	NF	7.3E-03	NF	7.7E-04	NF	NF	NF	4.7E-04	NF	5.0E-05
1950-1959	NF	NF	NF	NF	1.9E-04	1.6E-04	NF	NF	NF	NF	NF	NF	NF	3.1E-05	2.7E-05
1960-1969	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1970-1977	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1983-1992(3)	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1700-1929	7.0E-04	NF	3.8E-05	1.3E-03	NF	8.3E-05	7.5E-03	NF	4.9E-04	NF	NF	NF	1.1E-03	NF	6.1E-05
1930-1992(3)	NF	NF	NF	NF	5.8E-05	4.9E-05	7.8E-04	NF	1.2E-04	NF	NF	NF	5.1E-05	9.8E-06	1.6E-05
Total(3)	1.6E-04	NF	1.8E-05	2.5E-04	3.5E-05	6.1E-05	1.9E-03	NF	2.5E-04	NF	NF	NF	2.8E-04	5.1E-06	3.6E-05

*Note (1) Assumes dam years = number of dams * five years life*
(2) NF - No Failure
*(3) Assumes number of dams constructed in 1983-1992 = 2 * number of dams in 1978-1982*

Table 49. Probability of Failure (as at 1992, excluding China, non-annualised) - Piping Failures

Year	Gravity			Arch			Buttress			Multi-Arch			All Concrete & Masonry		
Comm.	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years(1)	>5 years	Total
1700-1799	3.0E-02	NF	3.0E-02	NF	NF	NF	NF	NF	NF	NF	NF	NF	2.7E-02	NF	2.7E-02
1800-1899	6.6E-03	NF	6.6E-03	NF	NF	NF	NF	NF	NF	NF	NF	NF	6.0E-03	NF	6.0E-03
1900-1909	NF	NF	NF	NF	NF	NF	2.4E-01	NF	2.4E-01	NF	NF	NF	7.5E-03	NF	7.5E-03
1910-1919	4.9E-03	NF	4.9E-03	NF	NF	NF	4.7E-02	NF	4.7E-02	NF	NF	NF	7.5E-03	NF	7.5E-03
1920-1929	NF	NF	NF	1.1E-02	NF	1.1E-02	NF	NF	NF	NF	NF	NF	2.0E-03	NF	2.0E-03
1930-1939	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1940-1949	NF	NF	NF	NF	NF	NF	3.6E-02	NF	3.6E-02	NF	NF	NF	2.4E-03	NF	2.4E-03
1950-1959	NF	NF	NF	NF	6.1E-03	6.1E-03	NF	NF	NF	NF	NF	NF	NF	1.0E-03	1.0E-03
1960-1969	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1970-1977	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1983-1992	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1700-1929	3.5E-03	NF	3.5E-03	6.5E-03	NF	6.5E-03	3.7E-02	NF	3.7E-02	NF	NF	NF	5.4E-03	NF	5.4E-03
1930-1992	NF	NF	NF	NF	1.5E-03	1.5E-03	3.8E-03	NF	3.8E-03	NF	NF	NF	2.5E-04	2.5E-04	5.0E-04
Total	7.7E-04	NF	7.7E-04	1.2E-03	1.2E-03	2.5E-03	9.5E-03	NF	9.5E-03	NF	NF	NF	1.4E-03	2.0E-04	1.6E-03

Table 50. Annual Probability of Failure (as at 1992, excluding China) - Tension/Shear Failures Through Dam Body

Year	Gravity			Arch			Buttress			Multi-Arch			All Concrete & Masonry		
Comm.	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total	0-5 years(1)	>5 years	Total
1700-1799	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1800-1899	2.6E-03	2.4E-04	3.2E-04	NF	NF	NF	NF	NF	NF	NF	NF	NF	2.4E-03	2.2E-04	3.0E-04
1900-1909	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1910-1919	NF	NF	NF	NF	NF	NF	9.4E-03	NF	6.1E-04	NF	NF	NF	7.5E-04	NF	4.9E-05
1920-1929	NF	4.5E-05	4.1E-05	NF	NF	NF	NF	NF	NF	1.1E-02	NF	8.3E-04	4.0E-04	3.2E-05	6.0E-05
1930-1939	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1940-1949	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1950-1959	NF	NF	NF	NF	NF	NF	2.4E-03	NF	3.2E-04	NF	1.8E-03	1.6E-03	2.0E-04	3.1E-05	5.4E-05
1960-1969	2.6E-04	6.0E-05	9.8E-05	NF	NF	NF	NF	NF	NF	NF	NF	NF	1.9E-04	4.3E-05	7.1E-05
1970-1977	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	7.7E-03	NF	3.2E-03	NF	NF	NF	NF	NF	NF	9.2E-04	NF	3.8E-04
1983-1992(3)	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1700-1929	4.6E-04	8.0E-05	1.0E-04	NF	NF	NF	3.7E-03	NF	2.5E-04	5.4E-03	NF	3.2E-04	7.2E-04	6.5E-05	1.0E-04
1930-1992(3)	6.8E-05	1.3E-05	2.2E-05	3.1E-04	NF	4.9E-05	7.8E-04	NF	1.2E-04	NF	5.1E-04	4.3E-04	1.5E-04	2.0E-05	4.1E-05
Total(3)	1.6E-04	4.6E-05	5.9E-05	2.5E-04	NF	3.1E-05	1.3E-03	NF	1.7E-04	2.0E-03	2.0E-04	3.7E-04	2.9E-04	4.0E-05	6.8E-05

*Note (1) Assumes dam years = number of dams * five years life*
(2) NF - No Failure
*(3) Assumes number of dams constructed in 1983-1992 = 2 * number of dams in 1978-1982*

Table 51. Probability of Failure (as at 1992, excluding China, non-annualised) - Tension/Shear Failures Through Dam Body

Year	Gravity			Arch			Buttress			Multi-Arch			All Concrete & Masonry		
Comm.	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years(1)	>5 years	Total
1700-1799	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1800-1899	1.3E-02	3.3E-02	4.6E-02	NF	NF	NF	NF	NF	NF	NF	NF	NF	1.2E-02	3.0E-02	4.2E-02
1900-1909	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1910-1919	NF	NF	NF	NF	NF	NF	4.7E-02	NF	4.7E-02	NF	NF	NF	3.7E-03	NF	3.7E-03
1920-1929	NF	2.8E-03	2.8E-03	NF	NF	NF	NF	NF	NF	5.5E-02	NF	5.5E-02	2.0E-03	2.0E-03	4.0E-03
1930-1939	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1940-1949	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1950-1959	NF	NF	NF	NF	NF	NF	1.2E-02	NF	1.2E-02	NF	5.9E-02	5.9E-02	1.0E-03	1.0E-04	2.0E-03
1960-1969	1.3E-03	1.3E-03	2.6E-03	NF	NF	NF	NF	NF	NF	NF	NF	NF	9.5E-04	9.5E-04	1.9E-03
1970-1977	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	3.8E-02	NF	3.8E-02	NF	NF	NF	NF	NF	NF	4.6E-03	NF	4.6E-03
1983-1992	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1700-1929	2.3E-03	7.0E-03	9.3E-03	NF	NF	NF	1.9E-02	NF	1.9E-02	2.7E-02	NF	2.7E-02	3.6E-03	5.4E-03	9.0E-03
1930-1992	3.3E-04	3.3E-04	6.6E-04	1.5E-03	NF	1.5E-03	3.8E-03	NF	3.8E-03	NF	1.5E-02	1.5E-02	7.5E-04	5.0E-04	1.3E-03
Total	7.7E-04	1.8E-03	2.6E-03	1.2E-03	NF	1.2E-03	6.4E-03	NF	6.4E-03	9.7E-03	9.7E-03	1.9E-02	1.4E-03	1.6E-03	2.9E-03

1 INTRODUCTION

This report comprises a component of the research project on the risk assessment of dams. 17 sponsors comprising major dam owners and consultants from Australia and New Zealand support the project. The United States Bureau of Reclamation (USBR) and BC Hydro from Canada are also assisting with the project.

The aim of this component of the research was to provide a guide as to which dams were more likely to experience incidents based purely on a statistical analysis of historical incidents. The report describes the analysis of historical concrete and masonry dam incidents. For comparative purposes a compilation of data from a sample of existing concrete and masonry dams from Australia, New Zealand, Portugal and the USA is also presented for comparison with the incident database. A large portion (4168 dams from 22 countries) of the ICOLD (1973 and 1979) World Register was entered into a computer for further comparative purposes. The source for the analysis was a database developed by the authors on failures and accidents in concrete and masonry dams known as *CONGDATA*.

Many attempts have been made at compiling and assessing statistics of dam failures. The main attempts at assessing dam incidents on a worldwide scale have been by ICOLD (1974, 1983 and 1995). ICOLD (1974) analysed previous dam failures and accidents based on questionnaires provided by the National Committees on Large Dams. ICOLD (1983) attempted to improve the completeness of the information with further questionnaires. The presentation of the data and analyses was improved with the use of tables. An existing dam population was also developed for comparison with failures. The population comprised a sample of dams from the ICOLD World Register of Dams (ICOLD 1973, 1976 and 1979). ICOLD (1995) was an attempt to update the statistics on failures of dams with particular emphasis on comparisons with dam types, heights and years commissioned of existing dams. Although an extensive analysis, the ICOLD attempt lacks depth in some key areas. Most notably in information on the foundation conditions and the geometry of the dams where failures have occurred. The accuracy and consistency of the ICOLD data has also come into question during this current research (see Section 2.5).

Vogel (1980, with updates to 1994) and Babb and Mermel (1968) have compiled lists of dam incidents with some limited comments and dimensions. Their main value is in providing a large source of references. USCOLD (1976 and 1988) collated a large amount of information on incidents in the USA. Other attempts at collecting data on historical incidents have been made by Jorgensen (1920), Jansen (1980), Varshney and Raheem (1971), USCOLD (1996) and Rao (1960). All of these either suffer from a lack of detail or from a limited data set.

Smaller country scale data collections have been made for:

- Spanish accidents and failures (Gomez Laa *et al*, 1979);
- the deterioration of Italian Dams (Paolina *et al*, 1991);
- South African dam incidents (Olwage & Oosthuizen, 1984);
- Swedish accidents (Graham & Bartsch, 1995);
- failures and accidents in the United Kingdom (Charles, 1985);
- incidents in Australia (Ingles, 1984); and
- failures and accidents in the USA (Hatem, 1985).

Von Thun (1985) made an assessment of USA dams and their probability of failure based on a calculation of dam years. The parameters assessed were generally similar to those of ICOLD. Others who have attempted to analyse probabilities of failure include: da Silveira (1984, 1990); Fell (1996); Blind (1983); and Schnitter (1993) who generally based their analysis on ICOLD data and experience. Serafim (1981a, 1981b); Tavares and Serafim (1983); Smith (1972); Biswas and Chatterjee (1971); Gruner (1963, 1967); Kaloustian (1984) analysed incidents using ICOLD data and their own selected databases. These analyses tend not to go into much detail, generally assessing only height, year commissioned and type of dam structure. Most of the emphasis in the analysis of dam incidents has been on embankment dams.

This study set out to carry out as complete a study of concrete and masonry dam failures and accidents as was practicable, with a greater emphasis than in other studies on the geology, mode of failure, and the warning signs that were observed. The study also sets out to assess the characteristics of the population of dams, and compares the characteristics of the failures and accidents with the population of dams, so a probability of failure or accident can be assigned. This data provides the basis for initial risk assessments of dams.

The basic definitions used in *CONGDATA* and the subsequent analyses have been taken from ICOLD and are given in Section 2.3.1. The term incident has been used for both accidents and failures.

Section 2 of this report describes the methods used in compiling and assessing the incident statistics. The results have been presented in Section 3. A method of first order probability assessment for gravity dams is provided in Section 4.

2 STRUCTURE AND ASSEMBLY OF CONGDATA DATABASE

2.1 Sources of Data

CONGDATA began with the information from the three ICOLD compilations of failures and accidents:

- ICOLD (1995) *Dam Failures Statistical Analyses.*
- ICOLD (1983) *Deterioration of Dams and Reservoirs.*
- ICOLD (1974) *Lessons From Dam Incidents.*

Where practicable ICOLD (1995) definitions were used. ICOLD (1995) was the main reference for the failures whilst accidents were principally from ICOLD (1983). ICOLD (1974) was used for further details when adding information into *CONGDATA*.

The information in *CONGDATA* was then checked and updated using other existing databases including:

- USCOLD (1976) *Lessons from dam incidents, USA.*
- USCOLD (1988) *Lessons from dam incidents. USA-II.*
- Vogel (1980) *Bibliography of the History of Dam Failures.*
- Babb and Mermel (1968) *Catalogue of Dam Disasters, Failures and Accidents.*

A large literature review was then conducted to gather as much information on dam failures and accidents as possible. References cited in the databases above were sought and then further references were obtained from journals; conference proceedings; reports; theses; and Internet pages. Published and unpublished reports were also accessed through sponsors and dam organisations. All references were followed to their origins as far as practically possible. The literature review was far more extensive than those previously reported for the development of other databases.

Data from several additional dams was added to the database during the data gathering process. The additions are described in detail in Section 2.4.

The sponsors of the research project, who are listed below, also provided access to information on their dams.

- Australian Water Technologies, Sydney Water Corporation;
- Department of Land and Water Conservation;
- NSW Department of Public Works and Services;
- SA Water Corporation;
- ACT Electricity and Water;
- Hydro-Electric Commission;
- Dams Safety Committee of NSW;
- Department of Land and Water Conservation - Dams Safety;
- Snowy Mountains Engineering Corporation (SMEC);
- Queensland Department of Natural Resources;
- Goulburn-Murray Water;

- Gutteridge Haskins and Davey;
- Melbourne Water;
- Pacific Power;
- Sydney Water Corporation;
- Water Authority of Western Australia;
- Electric Corporation of New Zealand;
- Snowy Mountains Hydro-Electricity Authority.

The United States Bureau of Reclamation (USBR) in Denver allowed access to the information on their dams. This information was collected over two, three-week periods by the first and third authors and M. Foster. Other organisations that allowed access to data included:

- BC Hydro; and the
- Alberta Dam Safety Association.

The data collected from the sponsors and other assisting organisations was used as a source of information on failures and more notably to assist in a collation of information on dam populations.

2.2 *CONGDATA* Layout

The database was created using *Microsoft Access for Windows 95 Version 9.0 (Access).* The information was grouped under the following categories:

- General description;
- incident Details;
- dimensions;
- geology;
- hydrology; and
- references.

An example of the forms used for entering dam information is provided in Appendix B. A list of the parameters entered is given in Appendix C.

Queries were developed in *Access* to analyse the data. Tables were then linked to *Microsoft Excel for Windows 95 (Excel)* spreadsheets for further analysis and interpretation. *Excel* was used to graph the various parameters.

2.3 Data Entered into *CONGDATA*

Details of dam incidents are given in *CONGDATA*. The following sections describe the coding used for input into *Access*.

2.3.1 Definitions of Failures/Accidents

ICOLD(1995) define failure as 'collapse or movement of part of a dam or part of its foundation, so that the dam cannot retain water. In general, a failure results in the release of large quantities of water, imposing risks on the people or property downstream'. ICOLD(1974) give the following definitions for failures and accidents.

F1 - A major failure involving the complete abandonment of the dam
F2 - A failure which at the time may have been severe, but yet has permitted the extent of damage to be successfully repaired and the dam again brought into use

A1 - An accident to a dam which has been in use for some time but which has been prevented from becoming a failure by immediate remedial measures, including possibly drawing down the water
A2 - An accident to a dam which has been observed during the initial filling of the reservoir and which has been prevented from becoming a failure by immediate remedial measures, including possibly drawing down the water
A3 - An accident to a dam during construction, i.e. by settlement of foundations, slumping of side slopes etc., which have been noted before any water was impounded and where the essential remedial measures have been carried out, and the reservoir safely filled thereafter.

The term *incident* is used to describe failures, accidents and major repairs. USCOLD(1988) give the following definitions for other accidents and deteriorations. These have been adopted for the database.

AR - Accidents or unusual problems encountered in the reservoir upstream of the dam, which have occurred during operation of the project, but which have not caused failure or major accident to the dam structure.
MR - Extensive or important repairs to a dam that were required because of deterioration or to update certain features. Refacing of deteriorated concrete, repair of deteriorated riprap, or replacement of gates are examples under this definition.
DDC - Damage to partially constructed dam or to temporary structure required for construction prior to the dam being essentially completed. Failure of cofferdam or unplanned overtopping of partially completed dam are examples under this definition.

Where the exact definition of the failure or accident is uncertain an 'F' or an 'A' has been used respectively.

The term *significant incident* has been introduced to describe failures, accidents and major repairs where the incident has directly affected the dam stability. Cases where the dam has been repaired due to a 'theoretical danger', such as the updating of design standards, or due to minor damage to the dam or spillways have not been included under this term.

2.3.2 Types of Dams

Coding for the types of dams in *CONGDATA* are:

PG - Concrete gravity
CB - Concrete buttress
VA - Concrete arch
MV - Concrete multi-arch
PG(M) - Masonry gravity
CB(M) - Masonry buttress
VA(M) - Masonry arch
MV(M) - Masonry multi-arch

2.3.3 Failure Types

Codes for the failure types were obtained from ICOLD(1983) and are:

Ff - Failure due to the dam foundation
Fm - Failure due to the dam materials
Fb - Failure due to the structural behaviour of the dam body
Fa - Failure due to the appurtenant works
Ffb - Failure due to the foundation and to the structural behaviour of the dam body
Ffa - Failure due to the foundation of the dam and to the appurtenant works
Fba - Failure due to the structural behaviour of the dam body and to the appurtenant works
Fbm - Failure due to the structural behaviour of the dam body and to the dam materials

2.3.4 Incident Time

The times at which the incident took place (or was detected) are indicated by the codes below. These codes were obtained from ICOLD(1983). In Section 2.4.1 the incident time is further discussed and T4 and T5 are redefined.

T1 - During construction
T2 - During the first filling
T3 - During the first five years
T4 - After five years
T5 - Not available

2.3.5 Type of Foundation

The foundation type was split into two categories as shown below.

R - Rock mass
S - Soil mass

This was further differentiated as discussed in Section 2.4.6.

2.3.6 Dam Height

Where the height of the dam (from lowest foundation) is uncertain the following definitions from ICOLD(1983) have been used. In other cases the actual height has been added.

H1 5m ≤ H1 < 15m
H2 15m ≤ H2 < 30m
H3 30m ≤ H3 < 50m
H4 50m ≤ H4 < 100m
H5 100m ≤ H5
H6 Not available

2.3.7 Detection Methods

The methods for detecting incidents and the need for major repairs were obtained from ICOLD(1983) and are:

D01 - Direct observation
D02 - Sampling and laboratory test
D03 - Water flow measurements
D04 - Phreatic level measurements
D05 - Uplift measurements
D06 - Pore pressure measurements
D07 - Turbidity measurements
D08 - Chemical analysis of water
D09 - Seepage path investigations
D10 - Joint and crack measurements
D11 - Horizontal displacement measurements
D12 - Vertical displacement measurements
D13 - Angular displacement measurements
D14 - Strain measurements
D15 - Stress measurements
D16 - Water level measurements
D17 - Temperature measurements
D18 - Hydrometric measurements
D19 - Rainfall measurements
D20 - Seismicity control
D21 - Sounding investigation
D22 - Water pressure measurements
D23 - Silting measurements
D24 - Design revision (new criteria)
D25 - Not available

2.3.8 Classification of Causes of Incidents of Dams And Reservoirs

The following tables show the codes defining the types and causes of incidents and the need for major repairs that occurred at the dams. The table was obtained from ICOLD(1983) with some additions from ICOLD(1995). The codes used are followed in the database by a letter that determines their origin.

- x - ICOLD(1983)
- y - Not from ICOLD
- - ICOLD(1995)

It will be noted that the causes are an unfortunate mixture of physical and human factors. They have been adopted for consistency with ICOLD data.

Table 1. Causes of Incidents of Concrete Dams

1.1 - Due to foundation

1.1.1 - Inadequacy of site investigation
1.1.2 - Deformation and land subsidence
1.1.3 - Shear strength
1.1.4 - Seepage
1.1.5 - Internal erosion
1.1.5.1 - in foundation
1.1.5.2 - in abutment
1.1.6 - Degradation (including swelling)
1.1.7 - Initial state of stress
1.1.8 - Tensile stresses at the upstream toe
1.1.9 - Preparation of the foundation surface
1.1.10 - Strengthening treatment
1.1.11 - Grout curtains and other watertight systems
1.1.12 - Drainage systems
1.1.13 - Sealing of galleries, shafts and boreholes used for investigation
1.1.14 - Leak of drainage system

1.2 - Due to concrete

1.2.1 - Reactions of concrete constituents (including alkali-aggregate reaction)
1.2.2 - Reaction between concrete constituents and the environment (including dissolution of calcium hydroxide)
1.2.3 - Resistance to freezing and thawing
1.2.4 - Attack by bacteria
1.2.5 - Compressive strength
1.2.6 - Shear strength
1.2.7 - Tensile strength
1.2.8 - Permeability
1.2.9 - Concreting (including order of casting of monoliths)
1.2.10 - Cooling
1.2.11 - Structural joints (including watertight systems)
1.2.12 - Arrangement of reinforcements and anchorages
1.2.13 - Ageing of concrete

1.3 - Due to unforeseen actions or to actions of exceptional magnitude (as a principle, when the case does not fall under other headings)

1.3.1 - Hydrostatic pressure and from accumulated silt (including pressure and impact of ice in the reservoir)
1.3.2 - Uplift
1.3.3 - Earthquakes (natural or man-made)
1.3.4 - External temperature variation
1.3.5 - Temperature variation due to the heat of hydration
1.3.6 - Moisture variation
1.3.7 - Overtopping
1.3.7.2 - of abutment
1.3.7.3 - of main section
1.3.8 - Deterioration of concrete-rock interface

1.4 - Due to structural behaviour of the arch and multiple arch dams (including the construction period)

1.4.1 - Shape of the dam and its position in the valley
1.4.2 - Tensile stresses
1.4.3 - Stress concentration due to shape discontinuities in the foundation surface
1.4.4 - Stress concentration at openings and shape discontinuities
1.4.5 - Artificial abutments and foundation
1.4.6 - Distribution and types of joints
1.4.7 - Facings

1.5 - Due to structural behaviour of gravity and buttress dams

1.5.1 - shape of the dam and its position in the valley
1.5.2 - Tensile stresses
1.5.3 - Stress concentration due to shape discontinuities in the foundation surface
1.5.4 - stress concentration at openings and shape discontinuities
1.5.5 - Distribution and types of joints
1.5.6 - Facings

1.6 - Due to monitoring

1.6.1 - Inadequacy of instrumentation

1.7 - Due to maintenance

1.7.1 - Periodic inspections
1.7.2 - Cleaning of drains
1.7.3 - Control of seepage
1.7.4 - Pumping of seepage water
1.7.5 - Deterioration of instrumentation

2.3.9 - Failure due to an upstream dam collapse

Table 2. Causes of Incidents of Masonry Dams

3.1	*- Due to foundation*
3.1.1	- Inadequacy of site investigation
3.1.2	- Deformation and land subsidence
3.1.3	- Shear strength
3.1.4	- Seepage
3.1.5	- Internal erosion
3.1.6	- Degradation (including swelling)
3.1.7	- Initial state of stress
3.1.8	- Tensile stresses at the upstream toe
3.1.9	- Preparation of the foundation surface
3.1.10	- Strengthening treatment
3.1.11	- Grout curtains and other watertight systems
3.1.12	- Drainage systems
3.1.13	- Sealing of galleries, shafts and boreholes used for investigation
3.2	*- Due to mortar*
3.2.1	- Reactions of masonry constituents (including alkali-aggregate reaction)
3.2.2	- Reaction between masonry constituents and the environment (including dissolution of calcium hydroxide)
3.2.3	- Resistance to freezing and thawing
3.2.4	- Attack by bacteria
3.2.5	- Compressive strength
3.2.6	- Shear strength
3.2.7	- Tensile strength
3.2.8	- Permeability
3.2.9	- Masonry construction (including order of placement)
3.2.10	- Structural joints (including watertight systems)
3.3	*- Due to stone*
3.3.1	- Weathering
3.3.2	- Joints between stones
3.4	*- Due to unforeseen actions or to actions of exceptional magnitude (as a principle, when the case does not fall under other headings)*
3.4.1	- Hydrostatic pressure and from accumulated silt (including pressure and impact of ice in the reservoir
3.4.2	- Uplift
3.4.3	- Earthquakes (natural or triggered)
3.4.4	- External temperature variation
3.4.5	- Variations due to changes of moisture content
3.4.6	- Overtopping
3.5	*- Due to structural behaviour of masonry dams (including the construction period)*
3.5.1	- Shape of the dam and its position in the valley
3.5.2	- Tensile stresses
3.5.3	- Stress concentration due to shape discontinuities in the foundation surface
3.5.4	- Distribution and types of joints
3.5.5	- Facings
3.6	*- Due to monitoring*
3.6.1	- Inadequacy of instrumentation
3.7	*- Due to maintenance*
3.7.1	- Periodic inspections
3.7.2	- Cleaning of drains
3.7.3	- Control of seepage
3.7.4	- Pumping of seepage water
3.7.5	- Deterioration of instrumentation

Table 3. Causes of Incidents to Appurtenant Works

4.0 - Inadequate design

4.0.1 - Tunnels and canals

4.1 - Due to foundations (when these ones do not have the same characteristics as dam foundations)

4.1.1 - Inadequacy of site investigations
4.1.2 - Deformation and land subsidence
4.1.3 - Shear strength
4.1.4 - Percolation
4.1.5 - Internal erosion
4.1.6 - Degradation (including swelling)
4.1.7 - Initial state of stress
4.1.8 - Preparation of foundation surface
4.1.9 - Strengthening treatment
4.1.10 - Grout curtains and other watertight systems
4.1.11 - Drainage systems
4.1.12 - Sealing of galleries, shafts and boreholes used for investigation

4.2 - Due to concrete (when the structures do not have dam characteristics or, in the opposite case, they concern flow of water)

4.2.1 - Reactions of concrete constituents (including alkali-aggregate reaction)
4.2.2 - Reactions between concrete constituents and the environment (including dissolution of calcium hydroxide)
4.2.3 - Resistance to freezing and thawing
4.2.4 - Attack by bacteria
4.2.5 - Mechanical strength (including tensile strength)
4.2.6 - Permeability
4.2.7 - Concreting (cooling included)
4.2.8 - Cracking
4.2.9 - Surface finishing (facing included)
4.2.10 - Structural joints (including watertight systems)
4.2.11 - Arrangement of reinforcements and anchorages
4.2.12 - Erosion by abrasion
4.2.13 - Erosion by cavitation

4.3 - Due to riprap

4.3.1 - Disintegration of blocks
4.3.2 - Removal of blocks

4.4 - Due to steel and other materials

4.4.1 - Chemical and biological agents
4.4.2 - Erosion by abrasion
4.4.3 - Erosion by cavitation
4.4.4 - Mechanical strength

4.5 - Due to unforeseen actions or to actions of exceptional magnitude (as a principle, when the case does not fall under other headings)

4.5.1 - Hydrostatic pressure and pressure due to silt accumulation
4.5.2 - Pressure and impact of ice
4.5.3 - Uplift
4.5.4 - Earthquakes (natural or triggered)
4.5.5 - Temperature and moisture variations
4.5.6 - Delay in construction at the time of flood

4.6 - Due to structural behaviour

4.6.1 - Structural behaviour of spillways
4.6.2 - Insufficient capacity of spillway
4.6.3 - Erosion of spillway basement
4.6.4 - Inadequate design of spillway
4.6.4.2 - of canal or tunnel

4.7 - Due to water flow, water level and water-borne debris (including construction periods)

4.7.1 - Excessive rates of flow
4.7.2 - Turbulence
4.7.3 - Vortices
4.7.4 - Waves
4.7.5 - Abnormal pressures
4.7.6 - Entrapped air
4.7.7 - Inaccurate discharge curves
4.7.8 - Solid materials carried by water flow
4.7.9 - Discharge of floating materials
4.7.10 - Piping outside inserted conduit

4.8 - Due to local scour

4.9 - Due to operation

4.9.1 - Sudden opening of the discharge equipment
4.9.2 - Inadequate instructions for operating the discharge equipment

4.10 - Due to monitoring

4.10.1 - Inadequacy of instrumentation

4.11 - Due to maintenance

4.11.1 - Periodic inspections
4.11.2 - Cleaning of drains
4.11.3 - Control of seepage
4.11.4 - Pumping of seepage water
4.11.5 - Deterioration of measurement instrumentation
4.11.6 - Malfunction of discharge equipment
4.11.7 - Debris in stilling basins

Table 4. Causes of Incidents of Reservoirs

5.1 - *Slope sliding*

5.2 - *Overturning of rock blocks*

5.3 - *Permeability*

5.4 - *Silting*

5.5 - *Ecological balance*

Table 5. Causes of Incidents Downstream of Dam

6.1 - *Equilibrium of river bed*

6.2 - *Slope stability*

6.3 - *Ecological balance*

2.3.9 Classification of Remedial Measures

Table 6 shows the coding used for remedial measures. The codes used were obtained from ICOLD(1983).The codes used are followed by a letter which determines their origin.

- x - ICOLD(1983)
- y - Not from ICOLD
- - ICOLD(1995)

Table 6. Classification of Remedial Measures

- Of a general nature

R101 - Investigation
R102 - Monitoring
R103 - Lowering of reservoir level
R104 - Raising of dam crest
R105 - Overall reconstruction (same design
R106 - Reconstruction with new design
R107 - None
R108 - Not available
R109 - Scheme abandoned

- In foundations

R201 - Water tightening treatment
R202 - Drain & filter construction or repair
R203 - Strengthening by grouting or other methods (excluding anchoring)
R204 - Filling in of fractures and cavities
R205 - Anchoring

- In concrete and masonry dams

R301 - Water tightening treatment
R302 - Drain construction or repair
R303 - Thermal protection (excluding facing)
R304 - Facing
R305 - Reconstruction of deteriorated zones
R306 - Execution of joints
R307 - Strengthening by grouting
R308 - Strengthening by anchoring
R309 - Strengthening by shape correction

- In earth and rockfill dams

R401 - Impervious core repair
R402 - Construction or repair of other watertight systems
R403 - Drain & filter construction or repair
R404 - Slope protection construction or repair
R405 - Filling in of cracks and cavities
R406 - Reconstruction of deteriorated zones
R407 - Upstream slope flattening, construction of upstream berm or other stabilisation methods
R408 - Downstream slope flattening, construction of downstream berm or other stabilisation methods

- In appurture works

R501 - Discharge increase
R502 - Construction of additional appurtenant work
R503 - Overall reconstruction of appurtenant works
R504 - Partial reconstruction with strengthening or structural changes
R505 - Shape correction of surfaces contacting flow
R506 - Aeration devices: construction or increase of capacity
R507 - Repair of surfaces contacting flow (including facings and special treatments)
R508 - Joint water tightening treatment
R509 - Construction & repair of drains
R510 - Slope protection & stabilisation
R511 - Sediment discharge removal from surfaces contacting flow
R512 - Construction, modification and repair of valves and gates
R513 - Establishment and updating of rules for gate and valve operations
R514 - Reconstruction of deteriorated zones and other correcting measures
R515 - Abandon of appurtenant work

- In reservoir

R601 - Reforestation
R602 - Torrent training
R603 - Sediment discharge diversion
R604 - Slope regularisation, protection and strengthening
R605 - Draining
R606 - Water tightening
R607 - Dredging

- Downstream of dam

R701 - Draining
R702 - Slope regularisation, protection and strengthening

2.4 Selection of Additional Variables

As the ICOLD (1974, 1983 and 1996) databases were limited in their scope it was decided to add additional variables to CONGDATA. The additional variables were generally proposed by the authors and reviewed by the sponsors. Further variables were added where requested by the sponsors. Some potential variables were rejected due to limited information in the literature, reports etc. Following is a description of the additional data variables including a discussion of why each was chosen.

2.4.1 Time of Incidents

It is important to understand at what age dams are more likely to fail or experience accidents. This can give dam owners a guide as to what intensity of monitoring they need to have throughout the life of a dam. ICOLD (1983) have analysed the time to failure and grouped their data into categories T1 to T5 as shown in Section 2.3.4. The oldest group is T4, which indicates an incident occurred after five years. It is clear that this is a large category that cannot adequately indicate potential deterioration effects in dams. The following grouping was used to allow for a better distribution, and hence understanding, of times to failure.

T1 - During construction
T2 - During first fill
T3 - 0-5 years
T4 - 5-10 years
T5 - 10-20 years
T6 - 20-30 years
T7 - 30-40 years
T8 - 40-50 years
T9 - >50 years
T10 - >5 years (else unknown)
T11 - Unknown

2.4.2 Foundation Incident Mode

Where the foundation has played a part in the incident of the dam further codes have been added. This allows for a better understanding of the foundation parameters affecting different incident modes. The codes are:

S - Sliding - where failure has occurred by the dam sliding on the foundation. Sliding can be along the dam-foundation interface or along a foundation discontinuity.
P - Piping - of materials within soil foundations or rock discontinuities (generally joints).
SC - Scour - of the foundation or the abutment.
U - Uplift - in the foundation.
D - Deformation - settlement or other movements of the foundation not including sliding.
L - Leakage - beneath the dam or through the abutments.

2.4.3 Dam Incident Mode

Where the incident occurred in the dam the following codes have been used to define the incident mode.

SH - Shear (sliding) within the dam.
T - Tensile (overturning) within the dam.
C - Compressive failure within the dam.
CR - Cracking (due to concrete hydration etc.)
ST - Structural damage to appurtenant structure such as spillway gates.
LD - Leakage - through dam.
EQ - Earthquake damage.

2.4.4 Comments on Incidents

The causes of incidents as given in Section 2.3.8 are often too general to explain the type of incident. A brief description of the incident has been included in the database to allow for a better understanding of the causes of the incident.

2.4.5 Description of the Failure or Accident

Brief descriptions of the failure or accident and warning are included in the database.

2.4.6 Additional Geological Information

Previous dam failure databases have only listed the foundation as soil, rock or both. The dam geology has been included in the database in an attempt to determine whether certain foundation geology types are more susceptible to incidents and vice-versa. The geology of each dam was categorised into the following categories:

Foundation Geology Categories - Rock

Sedimentary	**Metamorphic**	**Igneous**
Conglomerate	Gneiss	Granite
Sandstone	Schist	Gabbro
Mudstone	Phyllite	Rhyolite
Shale	Slate	Andesite
Siltstone	Marble	Basalt
Claystone	Quartzite	
Limestone	Hornfels	
Dolomite		
Chalk		
Agglomerate		
Volcanic Breccia		
Tuff		
Saline Rocks		
Coal		
Lignite		

Foundation Geology Categories - Soil

Alluvial	Aeolian	Marine
Lacustrine	Colluvial	Volcanic (ash)
Glacial	Residual	

Unfortunately this detail is often not available, so the database is incomplete.

2.4.7 Dam Dimensions

The databases that have been developed previously included the height of the dam (taken as above the lowest foundation for ICOLD) and crest length. These are insufficient to fully describe the dam. To allow for the determination of gradients and performing simple analyses of some of the dam incidents, further dimensions were included in the database. The height to full supply level (FSL), tailwater height and the water height at failure were included. These are shown in Figure 1 and listed below. All heights, excluding H_{lf}, have the general foundation level of the dam as their reference level.

H_{lf} - Height of dam above lowest foundation
h_d - Structural height
h_{wu} - Reservoir height at full supply level (FSL)
h_{wt} - Height of the tail water
W - Base width of dam section
h_f - Height to failure plane (=0 if in foundation)
h_{wf} - Reservoir height at failure
W_f - Width of failure plane
$xH:1V$ - Upstream slope
$yH:1V$ - Downstream slope

The drain depth, gallery height and length of spillway were also included in the database. The extent of each failure was also seen as important and so the length of the failed section and where the dam failed (spillway section/non-overflow section/both) were also included in the database.

2.4.8 Valley Shape

Stress concentrations and differential movements can occur at changes of section. This is particularly important with sharp section changes in the foundation. For this reason a method was developed to assess the valley shape. The parameters given below are shown in Figure 2.

$L1$ - Crest length
$L2$ - Left abutment length
$L3$ - Length of valley section
$L4$ - Right abutment length

2.4.9 Radius of Curvature

A dam will have increased stability where there is some curvature in the dam and load is transferred to the dam abutments. The database includes the radius of curvature of the dam. For dams with straight axes the radius is shown as *straight*.

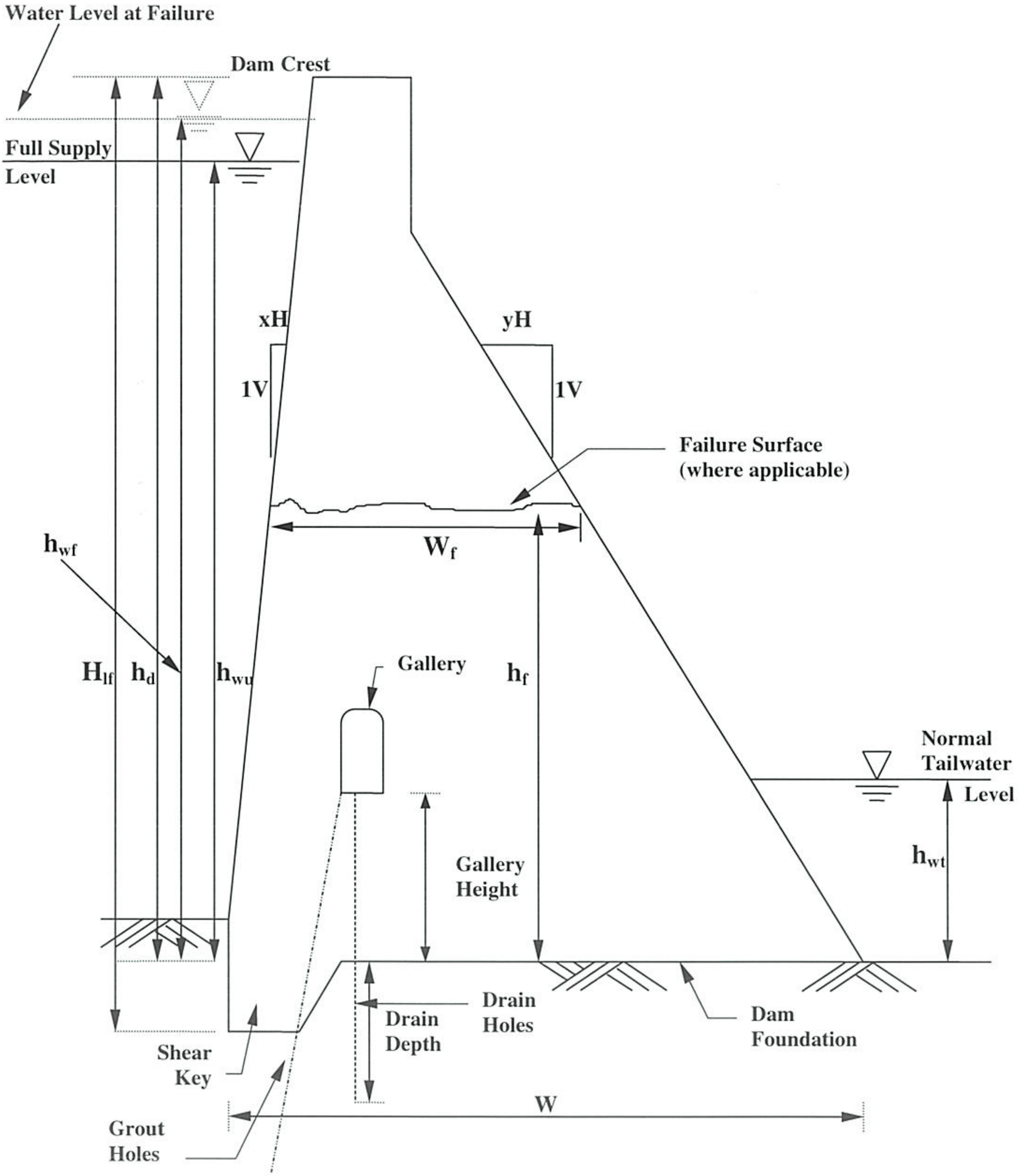


Figure 1. Definition of Dimensions in *CONGDATA*

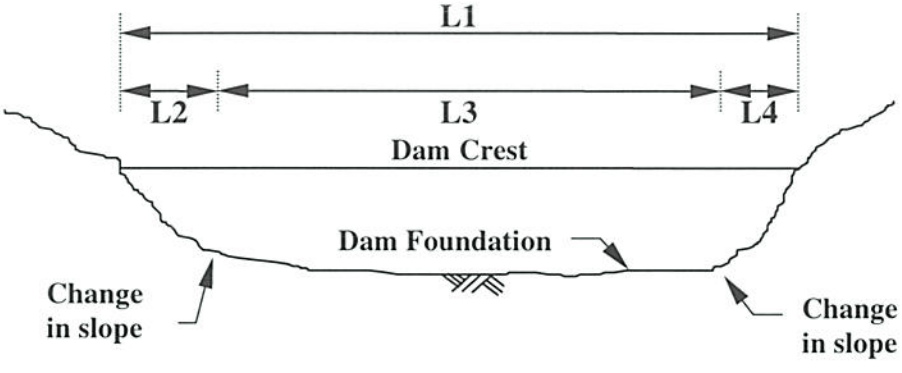


Figure 2. Definition of Dimensions in *CONGDATA* - Section across River

2.4.10 Monitoring and Surveillance Data

In some cases there have been signs of displacement, cracking, seepage and other factors prior to the incident, giving some warning. These have been included in the database as:

0 - None observed
1 - Foundation piping
2 - Foundation leakage
3 - Dam leakage
4 - Horizontal displacements
5 - Vertical displacements
6 - Cracking
7 - Expansion & cracking
8 - Concrete deterioration
9 - Scour of the foundation
11 - Overtopping
12 - Slide downstream of dam
13 - Abnormal uplift development
14 - Unknown

A brief description of the warning is also included. This allows some quantification of the warning e.g. the amount of leakage, and time before failure.

2.4.11 Warning Rating

The following qualitative codes were used to show whether there was sufficient warning prior to the failure to allow for preventative measures and/or warning of people downstream.

Y - Yes
M - Maybe
N - No
F - Flood
DF - Dam failure upstream
? - No data

2.4.12 Warning Time

The time from when a warning was given to when the dam failed or when an accident occurred and the dam was remediated was recorded as the warning time.

2.4.13 Other Design Factors

(a) Post-Tensioning

Whether the dam was post-tensioned was included to assess the effects of post-tensioning dams.

(b) Gallery

The presence of a gallery allows for better maintenance and uplift pressure relief and the provision or otherwise of a gallery is included in the database.

(c) Drain Depth and Spacing

Drain depths and spacing were included in the database to assess the effects of reducing uplift pressure on dam stability.

(d) Shear Key

A shear key may increase the resistance of a dam to sliding and the presence of the key is included.

(e) Grouting Type and Depth

Consolidation and/or grout curtains can be used to improve the stability of dam foundations and to reduce uplift pressures. The presence of, depth and spacing are included in the database.

(f) Number of Victims of Dam Failures

This was included to crudely assess the hazard of the dam. It is possible that high hazard dams may have a lower chance of failure as they have better maintenance and higher factors of safety in design.

2.5 Assumptions Made in Assembling the Database

The majority of the information in *CONGDATA* has been derived from ICOLD (1974,1983 and 1995). The ICOLD data was collated by sending questionnaires to the various National Committees. This method of data collection caused several problems (ICOLD, 1995).

- Some failures were not reported due to a lack of response from some National Committees.
- Replies from National Committees were not consistent with each other - some committees calling incidents failures where others would call them accidents.
- Gate failure was included by some committees whilst others did not include them. It was ICOLD (1995) policy not to include gate failures.
- The data from China was inconsistent with the rest of the world. China has the same amount of dams as the rest of the world put together yet has only reported 3 dam failures as opposed to 180 for the world. When comparing similar construction periods (post-1955) this becomes 3 failures as opposed to 50. It was ICOLD (1995) policy to ignore China when performing their statistical analyses. This policy has also been adopted here.

When assessing the ICOLD data more specific inconsistencies were found in the following:

- *Dam type* - Where failures occurred in composite structures (e.g. embankment/concrete gravity) some National Committees listed the dam as a composite structure (TE/PG) whereas others listed only the section of the dam that failed (e.g. TE). It is important when analysing dam failures that the section that failed be identified so that misleading conclusions are not made. Dams where failure occurred only through the embankment section were discarded in the preparation of CONGDATA.
- *Height* - When comparing ICOLD data to that of other reports/papers/drawings etc. inconsistencies became apparent in the assigning of heights to each dam. Where possible the data was changed to what was understood to be the accurate height. Where corroborating information was not available the ICOLD heights were assumed.
- *Length* - Similar inconsistencies to the height category were found here. Attempts were also made to determine the crest length of the failed section.
- *Year* - generally the years of construction and incident were found to be accurate. Some small inconsistencies (1-2 years) were found in old dams. There were some errors found in the accidents.
- *Foundation* - In ICOLD some dams are noted as having soil/rock foundations. Where possible it was determined where the failure occurred and which foundation type played a part. Where there was no other information the ICOLD foundation was assumed.
- *Failure type and cause* - It appears that most of the ICOLD causes were chosen by the individual National Committees (and potentially smaller dam owners that the questionnaires were passed on to). There appears to be a bias as to which failure categories each country chooses. This has resulted in marked inconsistencies in the ICOLD causes. It is also often difficult to assess how a dam failed by the failure category alone. An attempt has been made to assess all the dams in CONGDATA independently. However, often the ICOLD data is the only available. Failure types were found to be misleading in several dams and have been corrected.
- *Remediation measures* - Similar problems arise here as for failure type. However, many of the failed dams have been abandoned and so the effects are minimal.

Many of the causes of incidents in CONGDATA are subjective but they have been chosen with as much care as possible from the references available.

Where several sources have been found with conflicting information an attempt has been made to select the most 'credible' source. Most of the dams with most uncertainty are the older dams (prior-1950s).

It should be remembered that many of the failures occurred a long time ago and hence information is scarce.

2.6 Data on the Population of Dams

The assessment of dam incident statistics is of value to the dam engineering community. With these statistics engineers can see which dams have had more dam incidents than other types. This method of analysis however can lead to incorrect conclusions. For example, from a cursory assessment of the failure statistics for concrete and masonry and embankment dams it is shown that there is many more embankment failures compared with concrete and masonry dams. This could lead to the assumption that an embankment dam is much more likely to fail than a concrete dam. If the analysis is continued by comparing the failure statistics to the total population of existing dams then it is shown that the percentage of failures for each dam type is roughly the same (ICOLD, 1995).

ICOLD (1995) was the first to attempt to produce statistics on failures taking into account the number and type of existing dams. The population data was taken from the ICOLD World Register of Dams (1984 edition and 1988 updating). ICOLD (1995) compared statistics on existing and failed dams for their type, height and year commissioned. The results of the analyses assisted in qualifying many assumptions that were made on the basis of incident statistics alone.

The assessment of the incidents in *CONGDATA* needed to be qualified with dam population data. ICOLD (1995) used a computerised version of the World Register of Dams that was unavailable to the authors. To overcome this, the populations of dams in countries where either a failure had occurred or there was a large number of concrete/masonry dams were entered into a database to use for basic comparisons with the incident data. The table below shows the breakdown of the 4168 dams from 22 countries that were used.

Population of Dams from World Register of Dams used for Analysis

Country	Gravity	Arch	Buttress	Multi-Arch	Total
Algeria	5	1		4	10
Australia	69	39	10	3	121
Austria	23	15			38
Brazil	86	3	9	4	102
Canada	190	6	19	2	217
France	130	85	11	12	238
Great Britain	95	11	14	1	121
India	146				146
Italy	208	65	24	8	305
Japan	536	44	17	3	600
Mexico	101	6	3	1	111
Morocco	11	4			15
Norway	26	38	42	3	109
New Zealand	13	19	2		34
Portugal	27	19	4	1	51
South Africa	95	59	7	15	176
Spain	546	30	23	4	603
Sweden	12	5	27		44
Switzerland	51	48	3		102
Turkey	12	1	1		14
USA	717	169	46	25	957
Yugoslavia	30	19	1	4	54

CONGDATA included many more variables for each dam incident than is included in the World Register. A major component of this report is an assessment of the foundation geology type that ICOLD does not assess. It was therefore assessed that the population of dams needed to come from sources other than the World Register.

The ideal statistical analysis would be made on the total population of dams however this would be impossible to collect. A compromise was made where large subsets of the world population were chosen. The populations chosen and the reasons why are given below.

- Australia/New Zealand - This population was chosen for a number of reasons. The dam population is large and covers numerous geology and topography types. The sponsors of the project comprised the major dam owners in the two countries and hence access to data was made easier. It was also important to make sure the project produced results that could be used by the sponsors in Australia and New Zealand. Appendix E provides a listing of the dams used.
- USBR - The USBR has been involved with a large number of dams that cover the western half of the USA. This population covers a wide area and hence a wide range of geology and topography. It was also seen as important to include a population from the country with the highest number of reported incidents. Another major factor was the free access to data that the USBR gave the authors. Information on the dams was also available from USBR(1996). The list of dams used for the population is given in Appendix E.
- US National Inventory of Dams - This computerised database comprised 1049 large concrete and masonry dams. Such statistics as foundation geology were not included. The inventory instead allowed assessment of the basic variables of dam type, age and height in the country with the greatest number of reported failures.
- Portugal - Due to the easy access to the LNEC(1992) report on the Internet this population was also assessed. An attractive feature of this population was the inclusion of foundation geology types in a country with a much different geological environment (generally igneous and metamorphic). This population is shown in Appendix E.

The populations of dams from the US National Inventory of Dams and Portugal were collated directly from the CD-ROM and the Internet respectively. The authors collected the information from the USBR offices in Denver. Further information was taken from the Internet, personal communication with USBR staff, journal papers and various dam compilation reports published by the USBR and the United States Committee on Large Dams (USCOLD). The information on the Australia/New Zealand population was collected in person by the authors and by using questionnaires sent to the sponsors and several other dam owners. Where required additional information was collected from journal papers and conference proceedings.

The populations' chosen above have several limitations including:

- Limited extent - Using subsets of the world population can limit the extent to which the information is used. The information can be expected to be as accurate as possible in the areas surveyed but may not be typical of other areas. Countries where geological environments and dam design and construction methods are different to those assessed are likely to have led to different results. It is believed that the use of populations that cover a wide area of land and are located in the areas of most failures has reduced potential inaccuracies.

- Errors/omissions - Where data has been collected second hand there is always a chance of inconsistencies. Attempts to limit these were made by providing extensive information with the questionnaires and checking data against other references. This problem was also limited by personal collection of a large amount of the population data.

3 RESULTS OF ANALYSIS OF THE DATABASE

3.1 Summary of Incidents

This chapter describes the main results obtained from the analysis of the database *CONGDATA*. A total of 485 dams comprising: 46 failures; 174 accidents; and 265 major repairs were entered into *CONGDATA* for 29 countries. Table 7 shows the number of incidents by dam type in the database. Table 8 shows the number of significant incidents as defined in Section 2.3.1. Figure 3 and Table 9 show the distribution of reported incidents by country.

Table 7. Number of Dam Incidents in Database by Type

Type	Failures	Accidents	Major Repairs	Total	Population(1)
PG	10	44	165	219	3434
PG(M)	21	17	39	77	
VA	3	85	22	110	808
VA(M)	3	0	0	3	
CB	4	8	30	42	316
CB(M)	3	1	2	6	
MV	2	17	6	25	105
MV(M)	0	2	1	3	
Total	46	174	265	485	4663

Note (1) ICOLD (1984) world population excluding China.

Table 8. Number of Significant Dam Incidents in Database by Type

Type	Failures	Accidents	Major Repairs	Total	Population(1)
PG	10	38	52	100	3434
PG(M)	21	15	19	55	
VA	3	85	1	89	808
VA(M)	3	0	0	3	
CB	4	8	11	23	316
CB(M)	3	1	0	4	
MV	2	15	0	17	105
MV(M)	0	2	0	2	
Total	46	164	83	293	4663

Note (1) ICOLD (1984) world population excluding China.

Figure 4 shows the dam incidents as a percentage of the total population of dams in each country. Algeria shows a large proportion of failures to their dams. Appendix J shows the population of dams in each country as given by ICOLD (1984). The population in Algeria was taken as 14 (those in existence in 1983 plus those that failed). Due to their small populations Morocco and Turkey show high percentages of failures. India (5%) is noticeable particularly for its larger population. The USA has a failure rate of approximately 2%.

Unfortunately many of the variables for each dam remained unknown due to a lack of published information. This was often due to insufficient reporting of old dam incidents. To simplify the analysis, and improve the quality, the nature of the accidents and major repairs to dams were initially assessed to see if the incident was likely to lead to failure of the dam. These incidents were then denoted as 'significant', a term which is used in some of the results in this chapter. It would appear likely that the few numbers of major repairs in some countries might be due to inadequate data rather than the absence of major repairs.

Table 9. Number of Dam Incidents Reported in Each Country

Country	Failures	Accidents	Major Repairs	Total	Population[(1)]
	(No. of Cases)	(No. of Cases)	(No. of Cases)	(No. of Cases)	(No. of Dams)
Algeria	7	1	0	8	14
Australia	0	4	21	25	121
Austria	0	5	3	8	89
Brazil	0	2	2	4	121
Cameroon	0	1	0	1	2
Canada	0	1	9	10	219
Chin(2)	1	2	1	4	1290
Czechoslovakia	0	0	3	3	47
Finland	0	0	1	1	13
France	2	18	24	44	296
Germany	0	1	2	3	53
Great Britain	0	2	1	3	121
India	6	12	1	19	128
Ireland	0	0	1	1	8
Italy	3	21	57	81	327
Japan	1	4	11	16	703
Mexico	1	0	0	1	159
Morocco	1	0	0	1	18
New Zealand	0	0	1	1	38
Norway	0	1	0	1	108
Portugal	0	4	3	7	47
Rhodesia	0	6	3	9	19
South Africa	0	8	2	10	180
Spain	6	16	11	33	568
Sweden	1	0	0	1	45
Switzerland	0	10	4	14	106
Turkey	1	0	0	1	14
USA	16	56	102	174	754
Yugoslavia	0	1	2	3	58
TOTAL	46	176	265	487	5662

Note (1) Population from ICOLD (1984).

(2) Chinese dams excluded in statistical analysis.

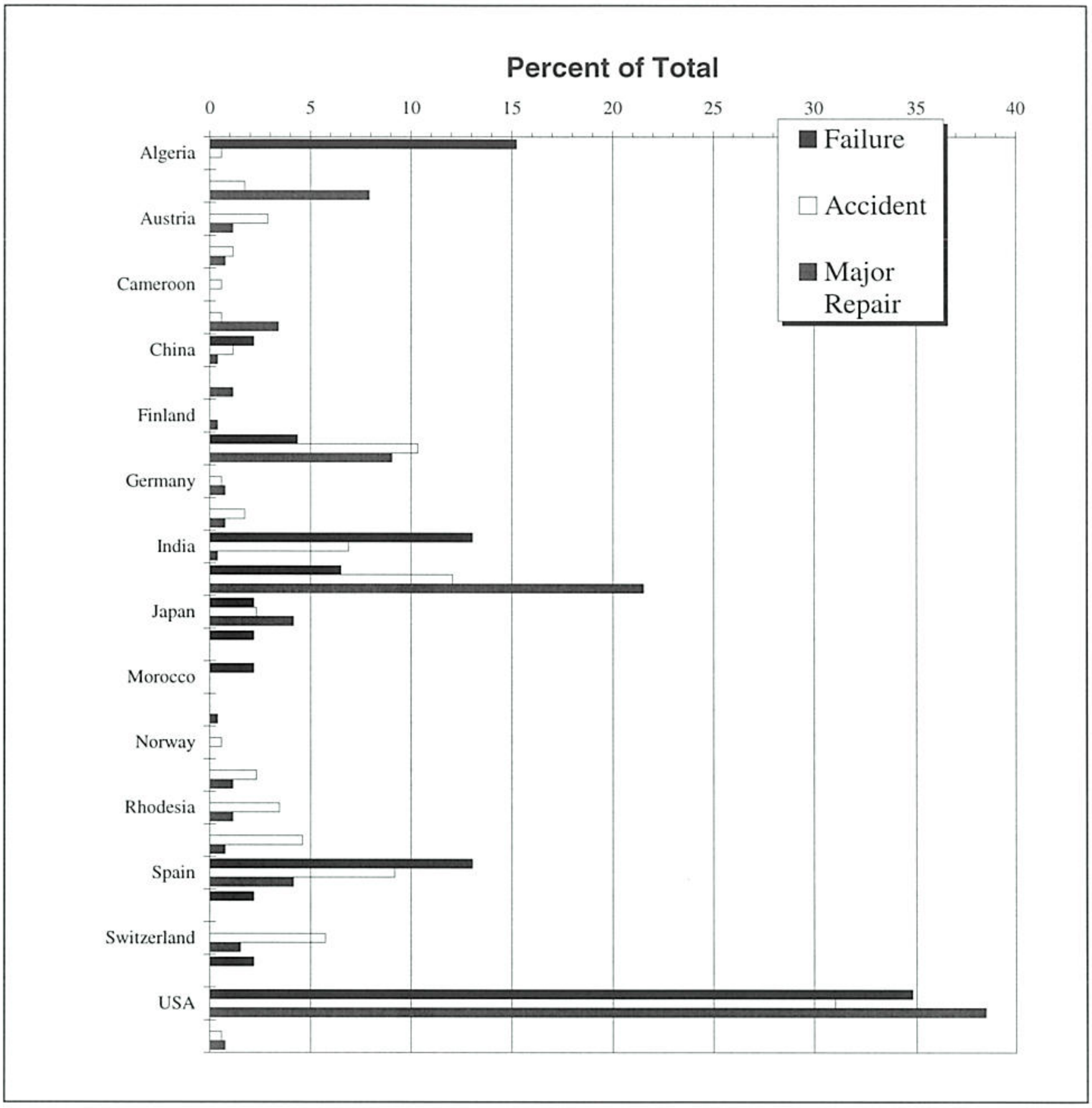


Figure 3. The Distribution of Reported Dam Incidents vs Country

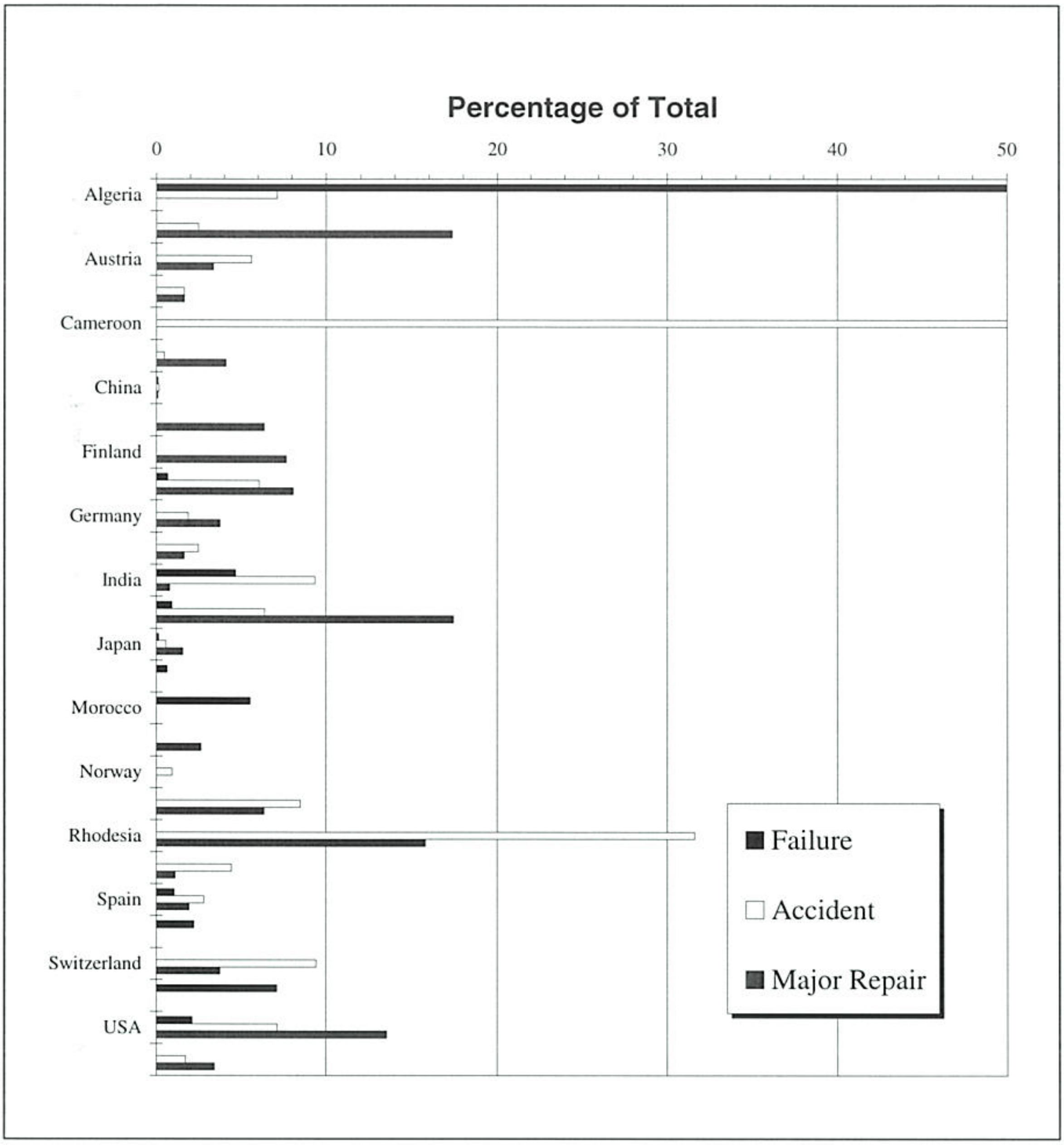


Figure 4. Reported Incidents as Percentage of Country's Dam Population from ICOLD (1984)

3.2 Year Commissioned of Dams Experiencing Incidents

Figures 5 and 6 show the year dams were commissioned (broken into decades) for concrete gravity dam and masonry gravity dam incidents respectively. There were a total of 10 failures, 44 accidents and 165 major repairs for concrete gravity dams and 21 failures, 17 accidents and 39 major repairs for masonry gravity dams. Due to their age, it is considered likely that masonry gravity dam accidents and major repairs are less likely to have been reported to ICOLD.

Concrete gravity dam failures occurred in dams commissioned in the 1900's through to the 1920's. No failures occurred in dams commissioned between 1926 and 1963. Three concrete gravity dam failures occurred in the 1960's. There was a similar lack of failures in masonry gravity dams commissioned between 1930 and 1966. These periods of no failures are likely to be a function of the number of dams built and improvement in the understanding and construction of dams.

Figure 7 shows the year commissioned for all dam incidents. This shows failures and accidents to dams commissioned in the 1930's and 1940's dropping off. This follows a similar trend to the world population shown in Figure 8.

The ICOLD World Register data does not allow for the separation of concrete and masonry gravity dams. The USA population of dams (FEMA, 1995) was used to give a rough estimate of this separation. Figure 9 shows the year commissioned for concrete and masonry gravity dams in the USA. It should be noted that the USA data has been collated from dam owner responses and there is the chance that some dams have been denoted as concrete where in fact they were masonry. The peak in construction of masonry dams correlates reasonably with the peak in masonry gravity dam incidents (Figure 6). Peaks in dam commissioning were noted in the 1880's and 1910's. Peaks in failures of masonry gravity dams are noted in dams commissioned in the 1870's to 1890's and 1910's to 1920's.

The graphs show that there were more incidents to dams commissioned in the 1910's, 1920's, 1950's and 1960's. However this appears to follow the trend in construction of dams. The incident numbers are likely to be partly a function of the number of dams built as well as design or construction deficiencies in these periods. The number of accidents and major repairs drops off prior to 1920 but this is very likely to be due to the way the data was collected. There is a much higher chance of having details of failures, from the period prior to 1900, than accidents.

Figure 10 and Tables 10 and 11 compare the failure and accident statistics with those of the population of dams as at 1983. The percentages refer to each subset (year commissioned and dam type). Generally there was a reduction in the number of failures per population with time. A small rise in the failure rate can be seen in the 1950's and 1960's. There are a number of various peaks in the percentage of failures for buttress and multi-arch dams, but there are too few incidents to make definitive judgments on this.

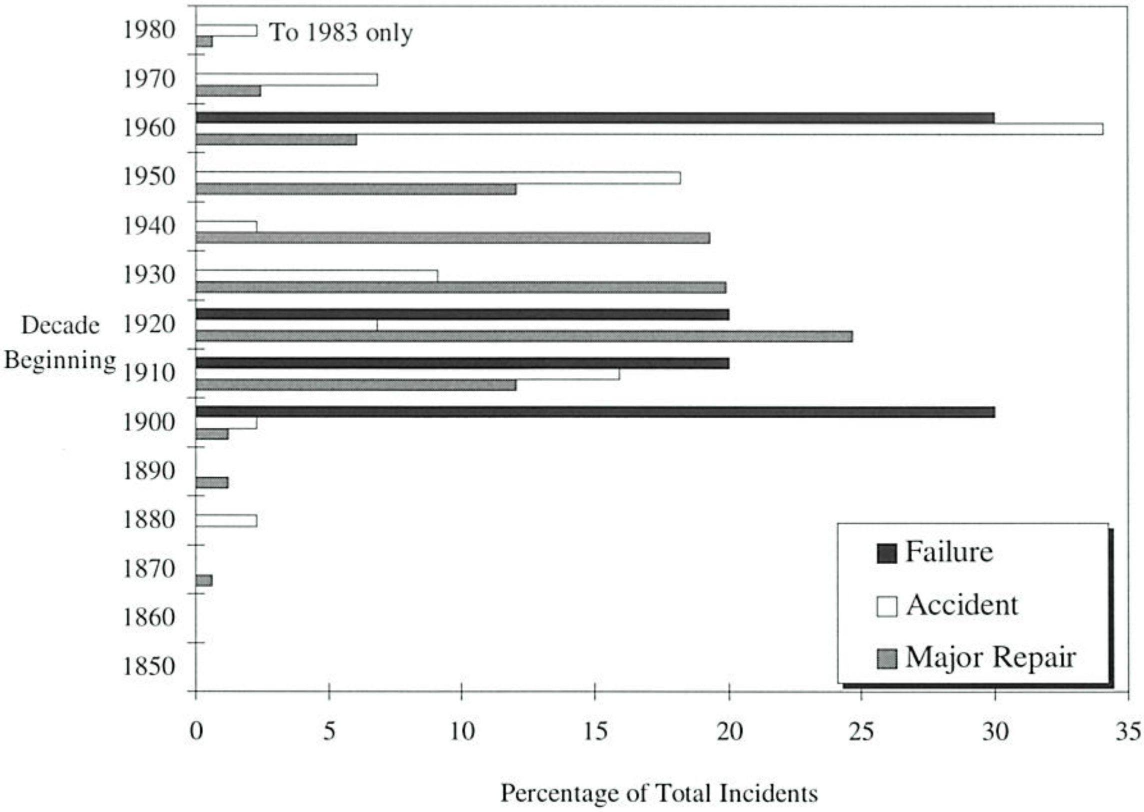


Figure 5. Year Commissioned vs Concrete Gravity Dam Incidents

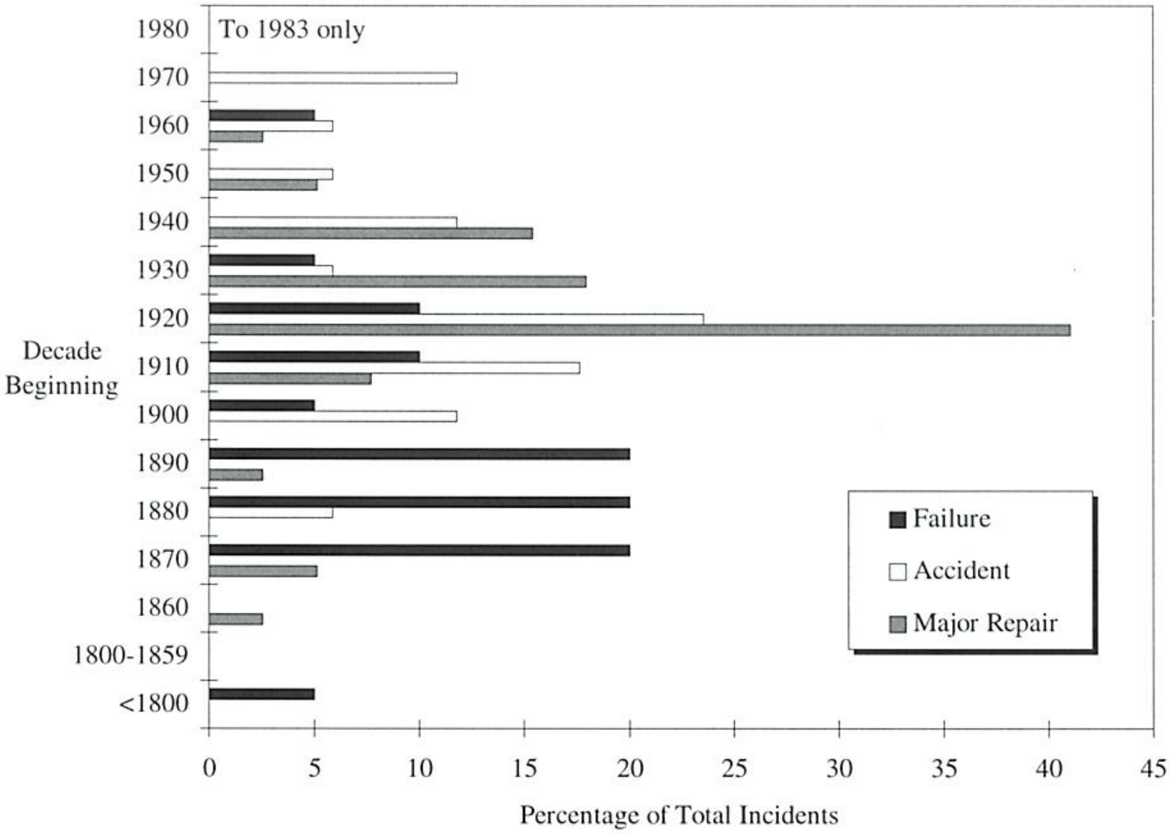


Figure 6. Year Commissioned vs Masonry Gravity Dam Incidents

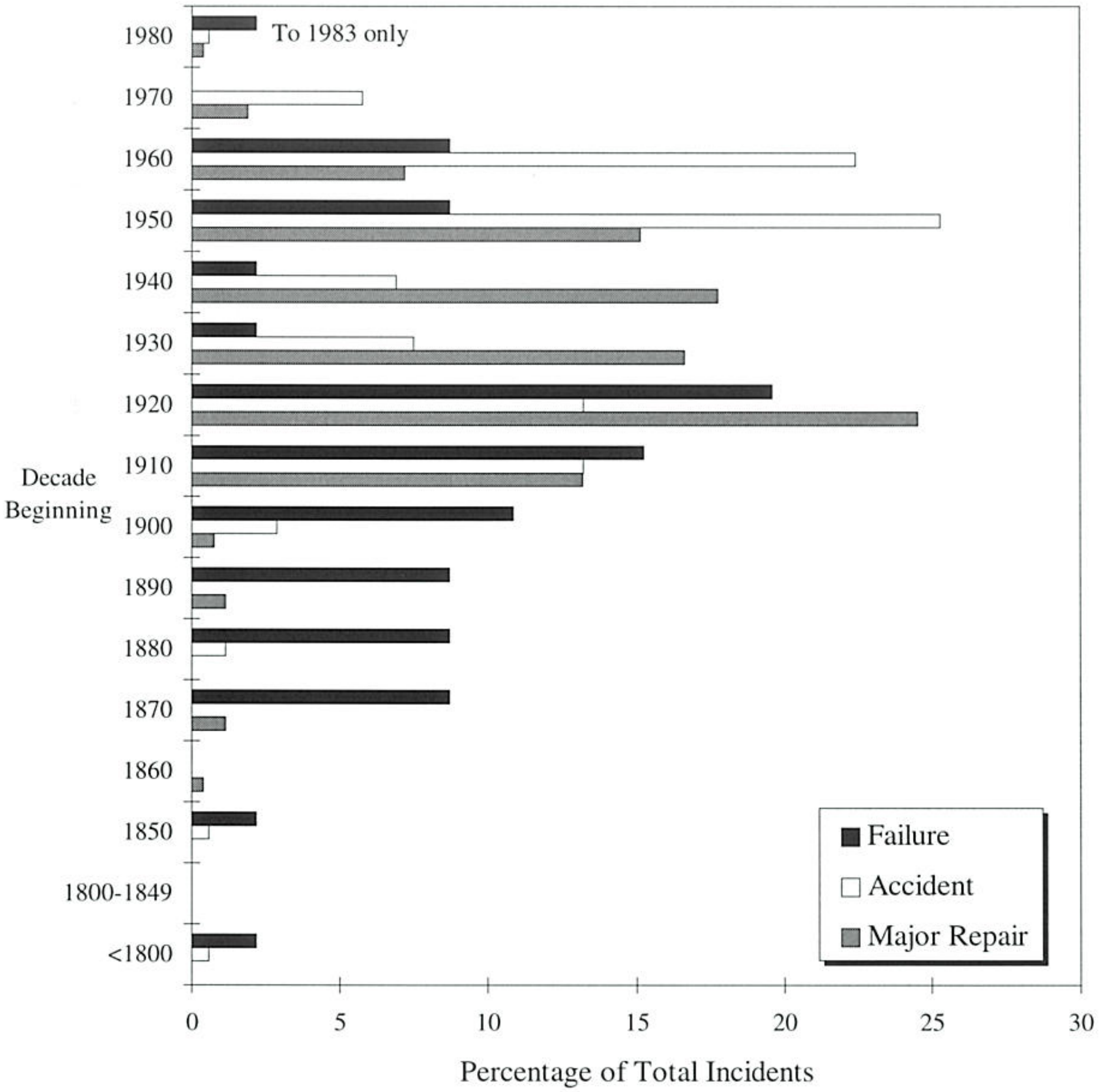


Figure 7. Year Commissioned vs All Dam Incidents

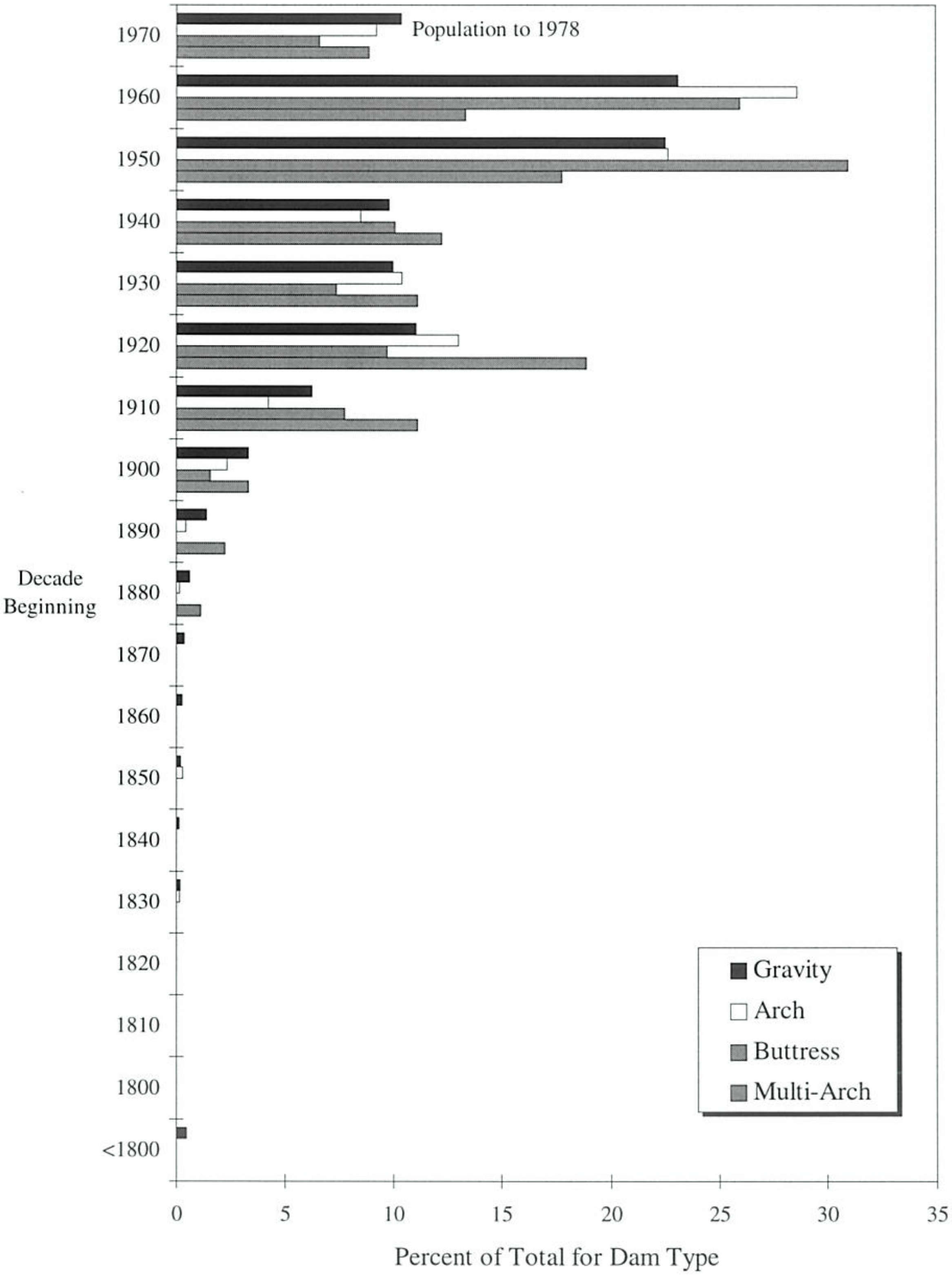


Figure 8. Year Commissioned for World Population Data Obtained from ICOLD (1979)

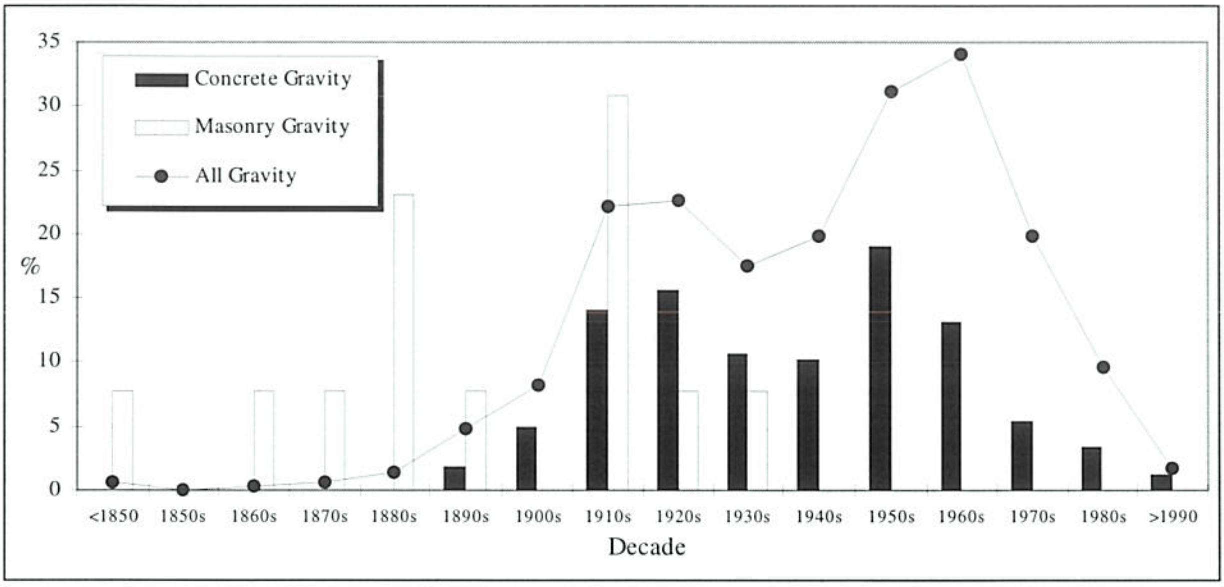


Figure 9. Year Commissioned vs Percentage of Gravity Dams Constructed in the USA

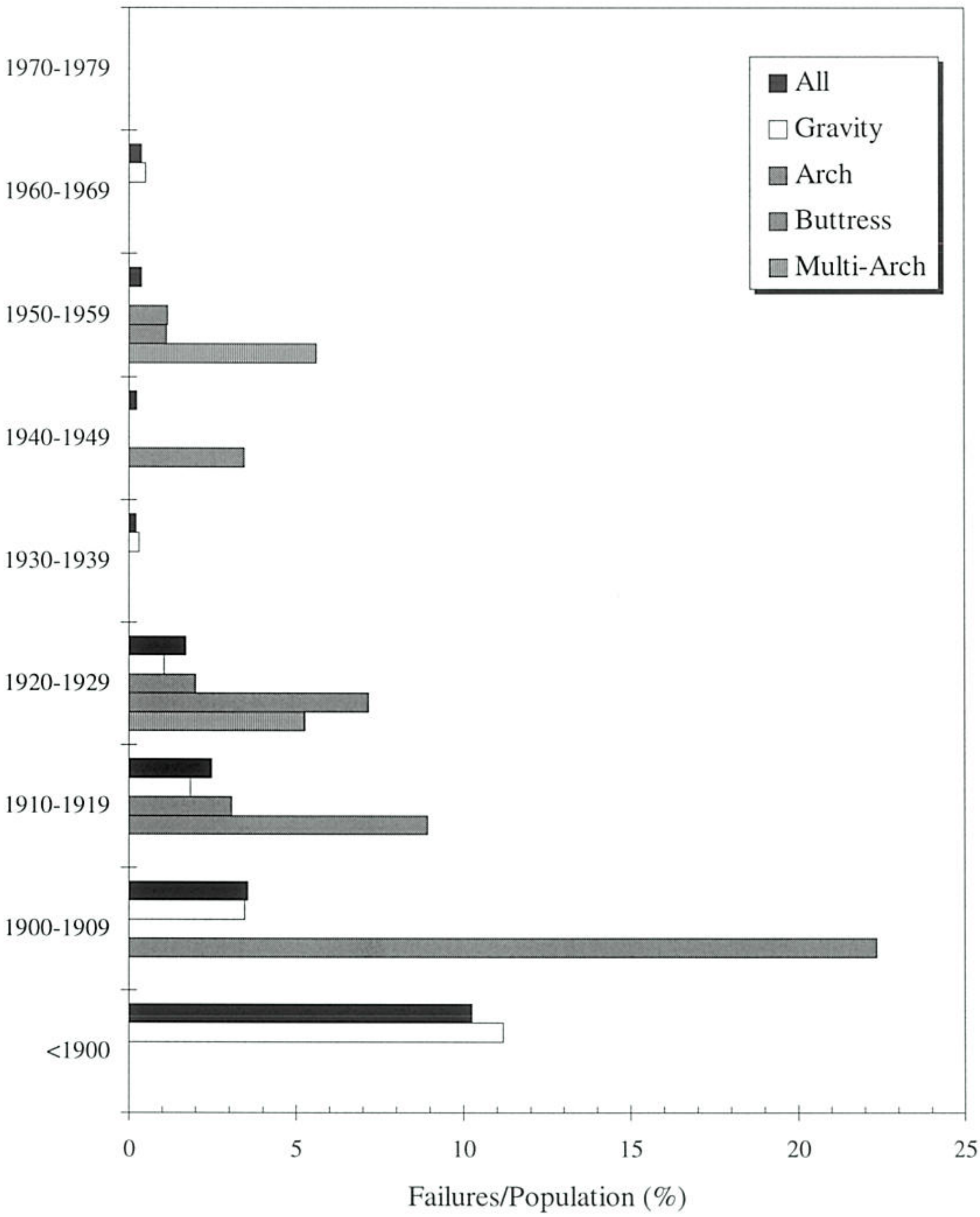


Figure 10. Year Commissioned - Failures/Population per Period

Table 10. Year Commissioned - Failures vs Population per Period

Years	Gravity	Arch	Buttress	Multi-Arch	All
NUMBER OF FAILURES					
<1900	14	0	0	0	14
1900-1909	4	0	1	0	5
1910-1919	4	1	2	0	7
1920-1929	4	2	2	1	9
1930-1939	1	0	0	0	1
1940-1949	0	0	1	0	1
1950-1959	0	2	1	1	4
1960-1969	4	0	0	0	4
1970-1979	0	0	0	0	0
1980-1983	0	1	0	0	1
FAILURES/POPULATION (%)					
<1900	11.2	-	-	-	10.3
1900-1909	3.5	-	22.4	-	3.6
1910-1919	1.9	3.1	8.9	-	2.5
1920-1929	1.1	2.0	7.2	5.3	1.7
1930-1939	0.3	-	-	-	0.2
1940-1949	-	-	3.4	-	0.2
1950-1959	-	1.2	1.1	5.6	0.4
1960-1969	0.5	-	-	-	0.4
1970-1979	-	-	-	-	-
1980-1989	-	1.8	-	-	0.2

Table 11. Year Commissioned - Accidents vs Population per Period

Years	Gravity	Arch	Buttress	Multi-Arch	All
NUMBER OF SIGNIFICANT ACCIDENTS					
<1900	2	1	1	0	4
1900-1909	3	2	0	0	5
1910-1919	8	6	2	4	20
1920-1929	6	11	1	3	21
1930-1939	4	6	0	2	12
1940-1949	2	6	0	3	11
1950-1959	7	28	3	4	42
1960-1969	15	21	2	0	38
1970-1979	5	4	0	1	10
1980-1983	1	0	0	0	1
ACCIDENTS/POPULATION (%)					
<1900	1.6	12.8	no pop	-	2.9
1900-1909	2.6	11.2	-	-	3.5
1910-1919	3.7	18.5	8.9	35.8	7.1
1920-1929	1.6	11.0	3.6	15.8	4.0
1930-1939	1.2	7.6	-	17.9	2.6
1940-1949	0.6	9.2	-	24.4	2.5
1950-1959	0.9	16.1	3.4	22.3	4.0
1960-1969	1.9	9.6	2.7	-	3.4
1970-1979	1.4	5.7	-	11.2	2.2

3.3 Height

Figure 11 shows the height range distribution for all the significant incidents in *CONGDATA*. The last two ranges were chosen as '150-199m' and '>200m'. The few dams higher than 150m were spread over a large range of heights.

The failures appear to be more prevalent in the 15-50m height range (a total of 39). There are seven reported failures for dams of height 50-70m. No reported failures have occurred in dams higher than 70m. Most accidents occurred in the dams in the height range 15-60m. The same numbers of major repairs have generally taken place per 10m height range between 15m and 80m. There is a marked drop off from 80m onwards. The number of major repairs per 10m peaks at a height range of 40-49m.

Figures 12 and 13 show the height versus number of dams for significant incidents in concrete gravity and masonry gravity dams respectively. Proportionally more failures, accidents and major repairs have occurred in higher dams for concrete gravity dams than masonry gravity dams but this may simply reflect the fact that there are fewer high masonry gravity dams.

There were no accidents reported in the range 120-199m for concrete gravity dams. No incidents were reported for masonry gravity dams higher than 100m.

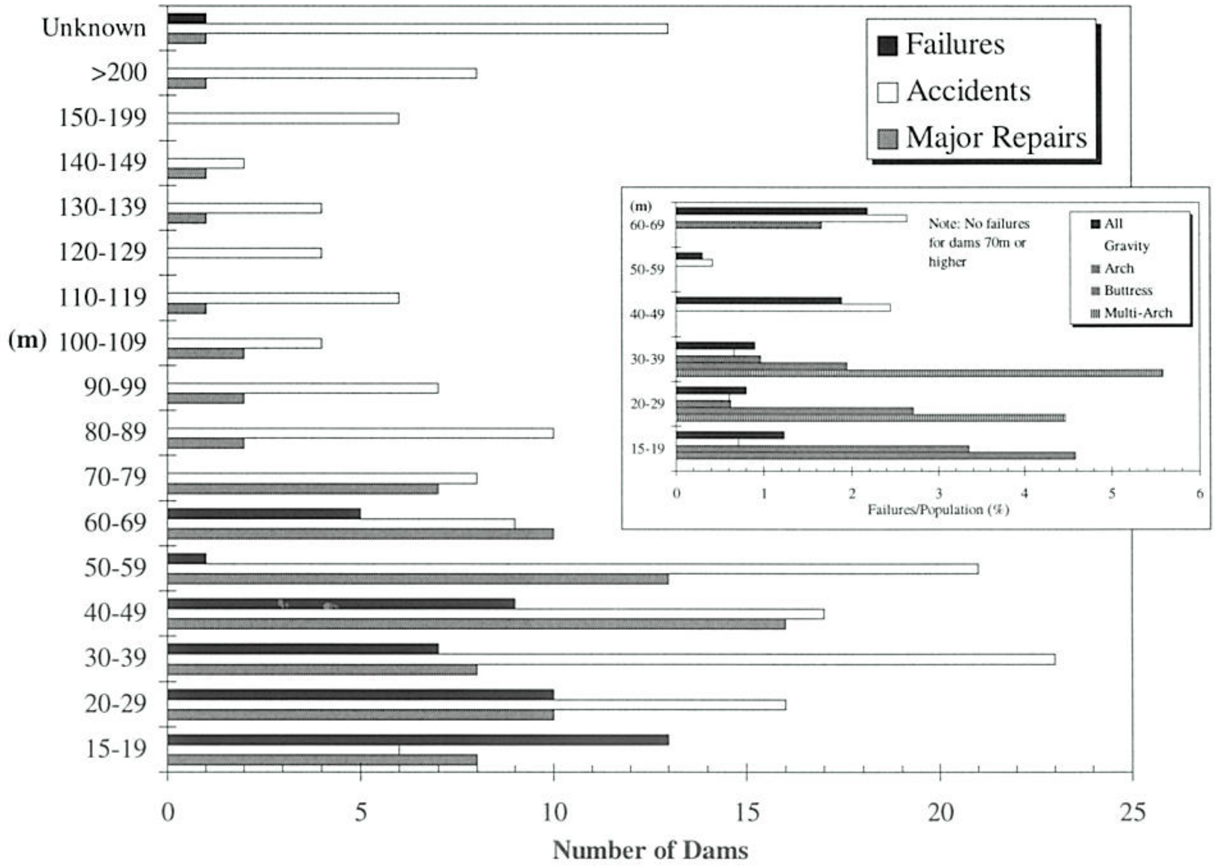


Figure 11. *CONGDATA* - Height Ranges for All Dam Significant Incidents
(Insert Figure 14. Failures/Population (%) for Comparison)

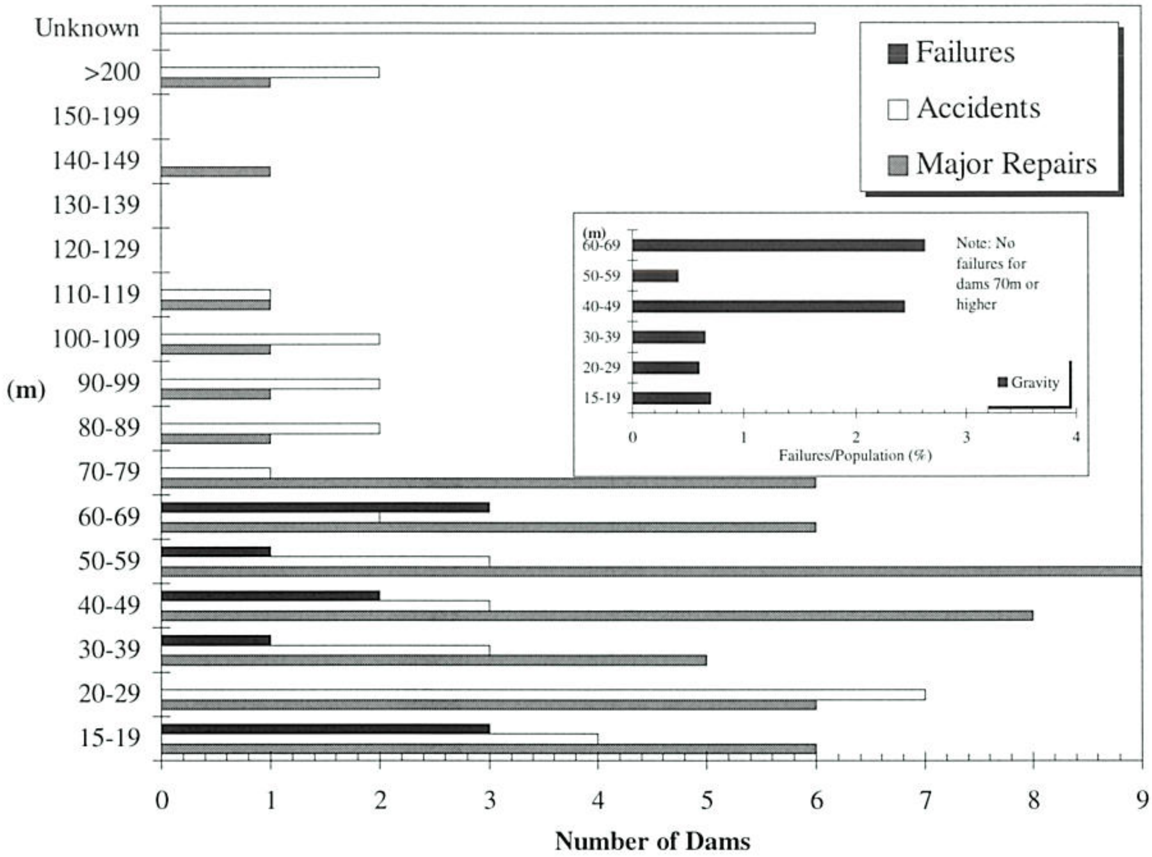


Figure 12. CONGDATA - Height Ranges for Concrete Gravity Dam Significant Incidents (Insert modified Figure 14. Failures/Population (%) for Comparison)

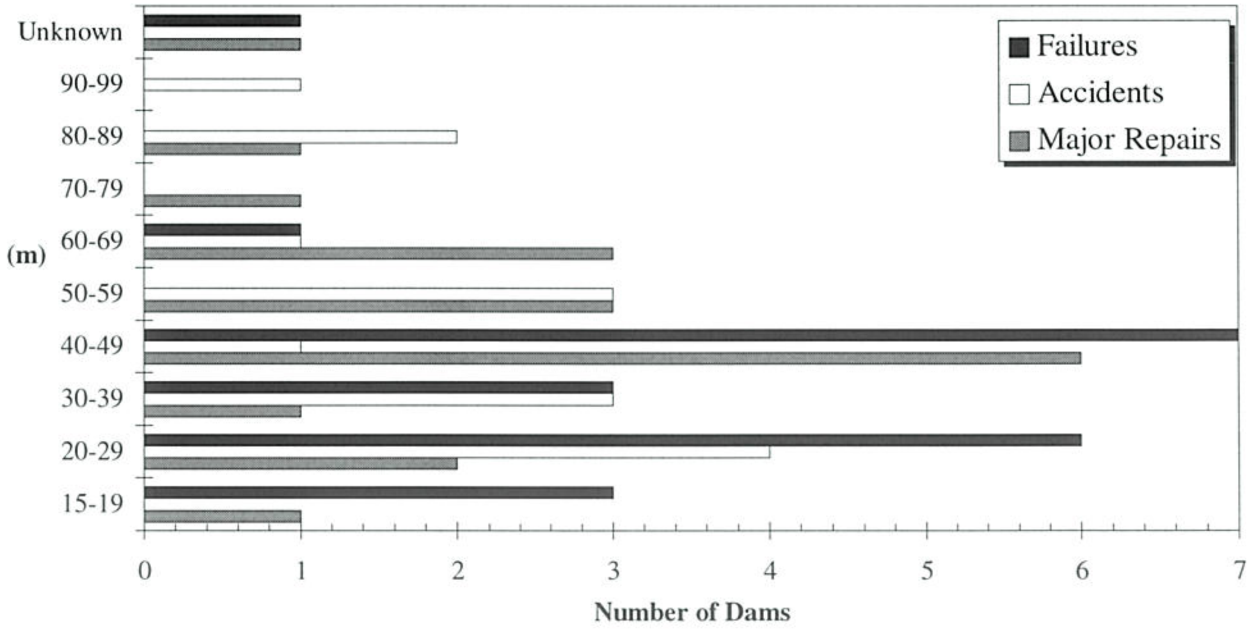


Figure 13. CONGDATA - Height Ranges for Masonry Gravity Dam Significant Incidents

Tables 12 and 13 and Figure 14 show the percentage of failures and accidents of concrete and masonry dams as a percentage of the population created from ICOLD (1979 and 1984). The database was created from the ICOLD (1979) dam population and extrapolated to the population in ICOLD (1984).

The data shows the ratio of failures to population does not exhibit any major trend. There appears to be a higher percentage of failures to population in the 40-49m and 60-69m height ranges. There is a slight trend of increasing percentage of gravity dam failures with height. Arch, buttress and multi-arch dams are shown to be more likely to have failures in the 15-39m height range.

Table 12. Percentage of Concrete & Masonry Dam Failures vs Population for Dam Height

Type	Dam Height (m)							
	15-19	20-29	30-39	40-49	50-59	60-69	Unknown	ALL
NUMBER OF FAILURES								
PG	3	-	1	2	1	3	-	10
PG(M)	3	6	3	7	-	1	1	21
VA	2	-	-	-	-	1	-	3
VA(M)	1	1	1	-	-	-	-	3
CB	3	1	-	-	-	-	-	4
CB(M)	1	1	1	-	-	-	-	3
MV	-	1	1	-	-	-	-	2
MV(M)	-	-	-	-	-	-	-	-
All concrete	8	2	2	2	1	4	-	19
All masonry	5	8	5	7	-	1	1	27
NUMBER OF FAILURES/POPULATION(1) (%)								
Gravity	0.7	0.6	0.7	2.5	0.4	2.6	N/A	0.9
Arch	3.4	0.6	1.0	-	-	1.7	N/A	0.8
Buttress	4.6	2.7	1.9	-	-	-	N/A	2.4
Multi-Arch	-	4.5	5.6	-	-	-	N/A	2.0
All	1.2	0.8	0.9	1.9	0.3	2.2	N/A	1.0

Note (1) Population height ranges from ICOLD(1979) extrapolated to population in ICOLD(1984).

Table 13. Percentage of Concrete & Masonry Dam Accidents vs Population for Dam Height

Type	Dam Height (m)												
	15-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	100-149	150-199	>200	Unknown
NUMBER OF SIGNIFICANT ACCIDENTS													
PG	4	7	3	3	3	2	1	2	2	3	-	2	6
PG(M)	-	4	3	1	3	1	-	2	1	-	-	-	-
VA	-	2	13	9	12	5	6	3	4	16	5	6	4
VA(M)	-	-	-	-	-	-	-	-	-	-	-	-	-
CB	1	1	-	-	1	-	-	1	-	1	1	-	2
CB(M)	-	-	-	-	1	-	-	-	-	-	-	-	-
MV	1	2	2	4	1	1	1	2	-	-	-	-	1
MV(M)	-	-	2	-	-	-	-	-	-	-	-	-	-
All concrete	6	12	18	16	17	8	8	8	6	20	6	8	13
All masonry	-	4	5	1	4	1	8	2	1	-	-	-	-
NUMBER OF ACCIDENTS/POPULATION(1) (%)													
Gravity	0.5	1.1	1.0	1.1	2.5	2.0	1.2	6.7	7.1	4.7	-	35.8	N/A
Arch	-	1.2	12.5	11.8	18.8	8.3	15.3	7.9	12.8	22.5	24.8	76.6	N/A
Buttress	1.1	1.4	-	-	8.9	-	-	11.2	-	25.0	no pop	-	N/A
Multi-Arch	3.0	8.9	22.3	35.8	22.3	89.4	29.8	44.7	-	-	-	-	N/A
All	0.6	1.3	2.9	3.6	6.3	3.9	6.0	9.0	9.3	14.4	21.5	55.0	N/A

Note (1) Population height ranges from ICOLD(1979) extrapolated to population in ICOLD(1984).

Figure 15 shows the height distribution for the world population at 1984. There appears to be an exponential like drop in numbers of dams per 10m height range. There were 26.8% of large dams in the range 20-29m; dropping to 0.6% at 110-119m; and to 0.4% at 140-149m. Note that the range 15-19m had 22.7% due to the smaller height range (5m c.f. 10m).

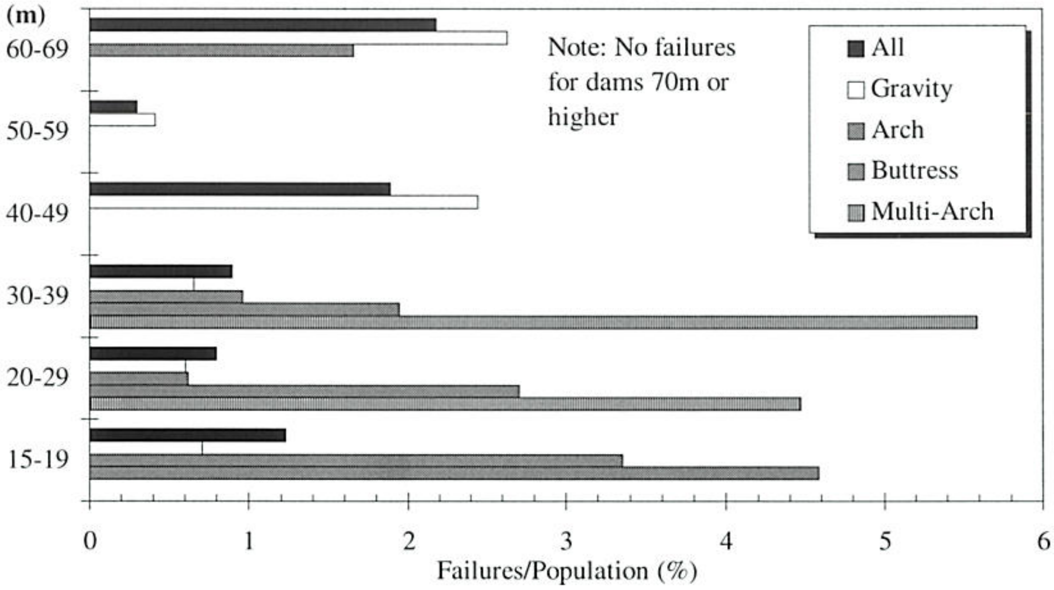


Figure 14. Height of Failed Dams - Failures/Population (%)

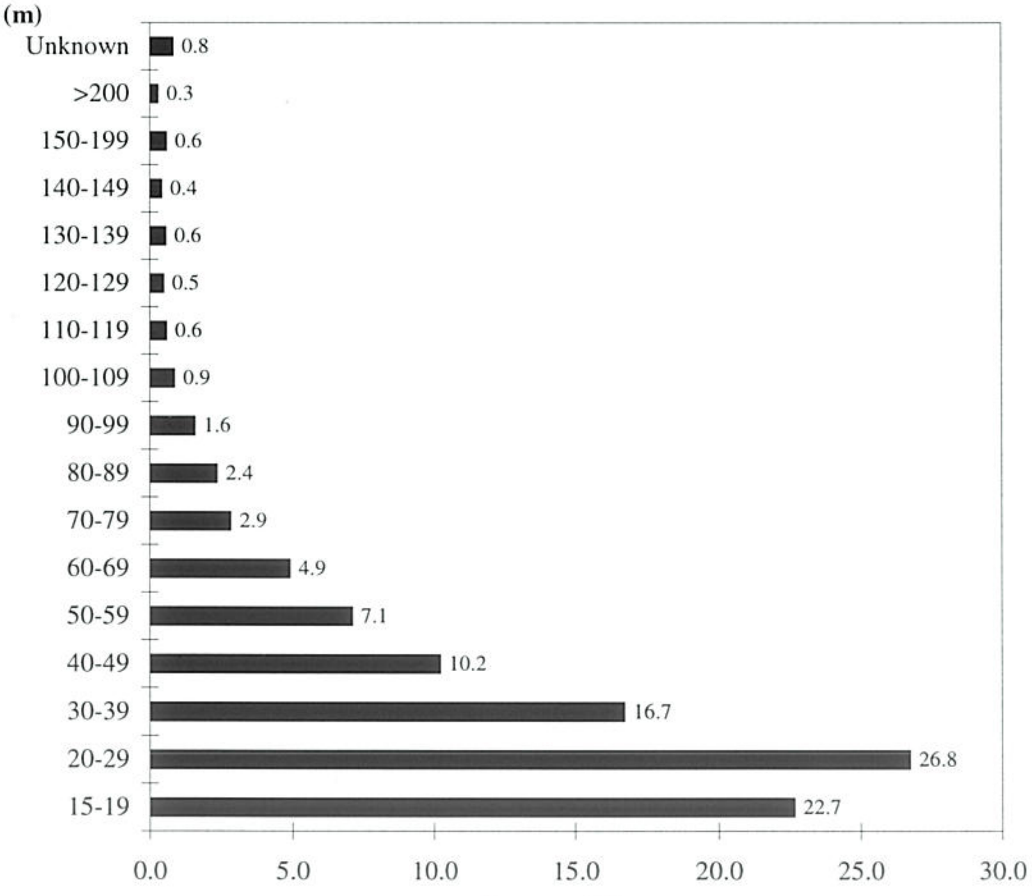


Figure 15. World Dams - Height Ranges for all Concrete & Masonry Dams

3.4 Age at Failure

Figures 16 to 18 show the age at failure for all, concrete gravity and masonry gravity dams. T2 (during first filling) is the most common time for failure to occur. Concrete gravity dams do appear to have proportionally fewer failures during first filling than do masonry gravity dams.

The term first filling may be misinterpreted and as such a further analysis was carried out. All failed dams were assessed to see whether they had failed at their maximum water level, and whether this was the first time such a level had been reached. The results of this analysis are given in Table 18.

Of the 46 dams assessed 29 had failed at their highest level ever recorded; four were not at the highest level recorded; and there were 13 cases with insufficient information. For the unknown cases four were during a flood and can be assumed to be at or near the highest water level. Of the four that did not fail at their highest recorded water level:

- Bayless (B) had been at the same level the year prior when sliding had also occurred (Bayless (A));
- Bouzey (B) had been 0.1m higher for over a year;
- Meihua had overtopped by 0.3m previously (0.8m higher than during failure); and
- Leguaseca failed at a low reservoir storage. This multi-arch structural failure was due to concrete deterioration in the acidic reservoir water.

From this analysis it is clear that the majority of failures have occurred when the reservoir was at its highest recorded level (which could be defined as 'first fill'). Note however, that several of these dams failed at water levels the same or slightly higher than those previously recorded. The water levels were often reached during a rapid stage of first filling or during flood. Of those dams where information was available, most failed within two days of reaching their final water level and several failed within six hours.

Tables 14 and 15 and Figure 21 show the age at failure versus year commissioned for various failure modes. Foundation piping failures generally occurred in the first three years. Exceptions to this were Puentes, Bacino di Rutte and Austin (A). Puentes, which was commissioned in 1790, failed in first fill which took 11 years. Bacino di Rutte failed due to piping in the foundation. During first fill a crack appeared under the dam which was filled. The dam was emptied and the silt removed 13 years later. The dam failed during refilling of the reservoir. Austin (A) failed due to a combination of scour, piping and sliding during overtopping at the highest water level the dam had experienced.

Foundation sliding occurred in less than five years in all but two cases. Zerbino dam failed after ten years due to scour and sliding during overtopping. Xuriguera failed after 42 years, unfortunately no further details on the failure were available.

Structural sliding was more evenly distributed with five failures occurring after ten years. One structural tensile/shear failure occurred after 80 years (Khadakwasla Dam that failed during overtopping due to an upstream dam failure). There are a number of dams with unknown failure modes. Most of these failed during overtopping events (see Figure 22). Most of the failures that occurred after five years were due to overtopping (12 compared to 6 non-overtopping). Prior to five years of age non-overtopping failures were more prevalent (21 compared to 4).

Figure 23 shows the age at failure versus year commissioned for different dam types. Masonry dams appear to have failed at all ages. Concrete dams, with the exception of the three below, have failed within ten years of commissioning. There is insufficient information on the exceptions to determine why they failed at a later time.

Kohodiar (India) - Combined concrete gravity/earthfill dam with unknown failure mode.
Xuriguera (Spain) - Concrete gravity dam apparently failed by foundation sliding (no other information).
Hauser Lake II (USA) - Concrete gravity dam with no failure information.

Table 14. No. of Dam Foundation Sliding & Piping Failures vs Age at failure

Age at Failure		Sliding				Piping			
		Grav.	Arch	Butt.	Total	Grav.	Arch	Butt.	Total
T1	During construction	-	-	-	-	-	-	-	-
T2	During first fill	3	1	-	4	4	1	3	8
T3	0-5 years	1	-	1	2	-	-	-	-
T4	5-10 years	1	-	-	1	-	-	-	-
T5	10-20 years	-	-	-	-	-	1	-	1
T6	40-50 years	1	-	-	1	-	-	-	-
ALL		6	1	1	8	4	2	3	9

Table 15. No. of Structural (Shear or Tensile in the Dam) Dam Failures vs Age at failure

Age at Failure		Grav.	Arch	Butt.	Multi-Arch	Total
T1	During construction	1	-	-	-	1
T2	During first fill	1	-	2	1	4
T3	0-5 years	-	1	-	-	1
T4	5-10 years	2	-	-	-	2
T5	10-20 years	2	-	-	-	2
T6	20-30 years	-	-	-	1	1
T7	30-40 years	-	-	-	-	-
T8	40-50 years	1	-	-	-	1
T9	>50 years	1	-	-	-	1
ALL		8	1	2	2	13

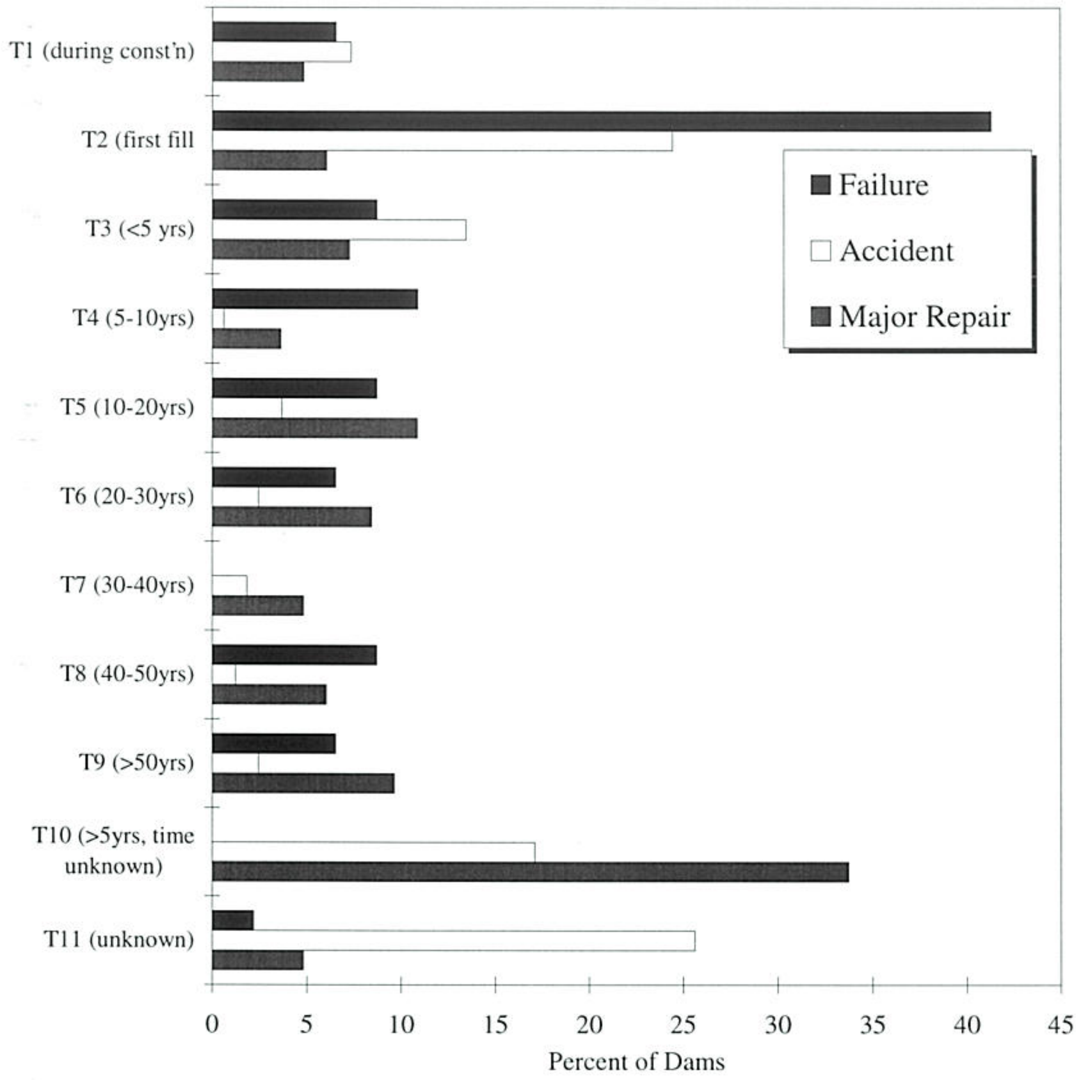


Figure 16: Age at incident - All Dams

Figures 24 and 25 show age at significant incident versus year commissioned for different dam types. As expected the accidents/major repairs tend to occur mostly after 1915. Older incidents are less likely to be recorded. Accidents and major repairs appear to occur at a later stage than that of failures. The distribution of ages to incident for both masonry and concrete dams appears to be similar.

Table 17 gives the breakdown of incidents in all types of concrete and masonry dams.

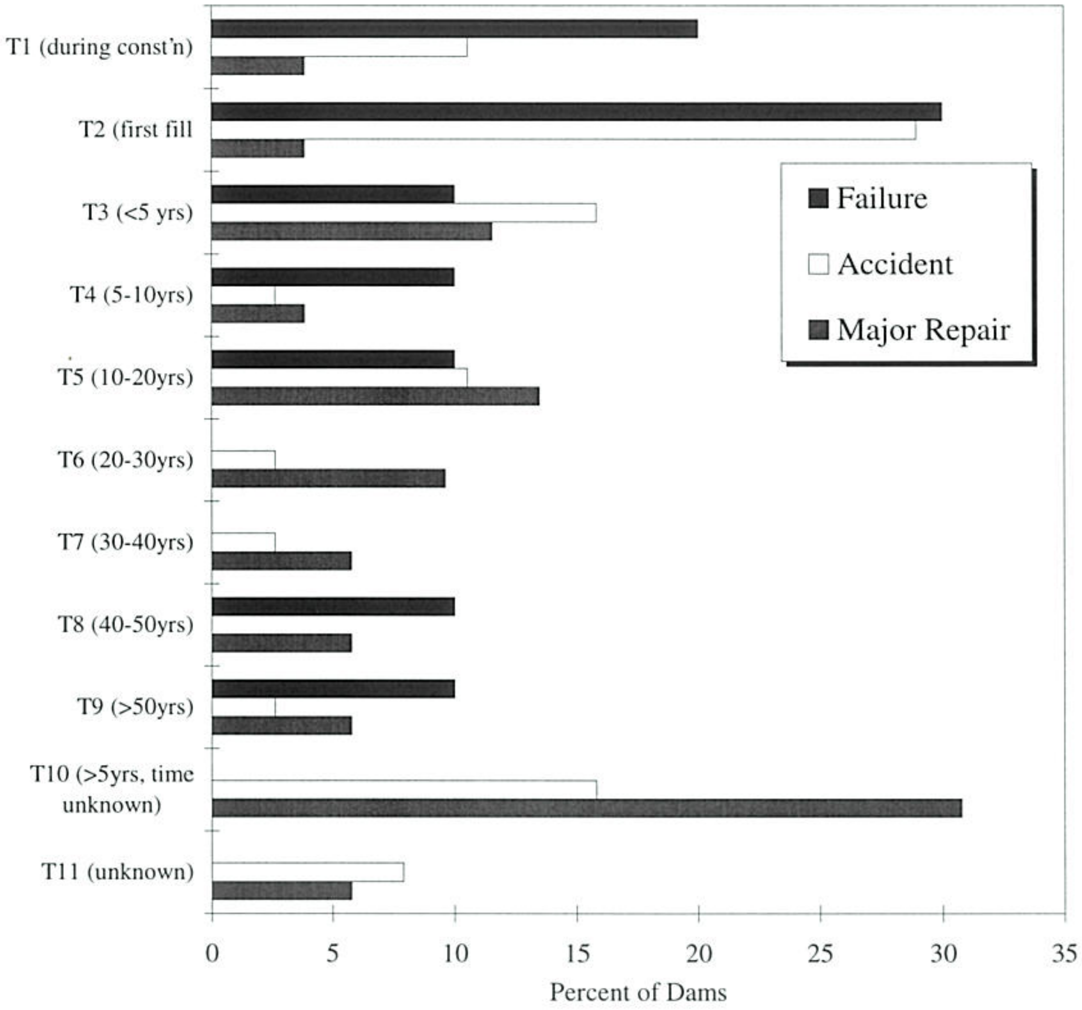


Figure 17. Age at incident - Concrete Gravity Dams

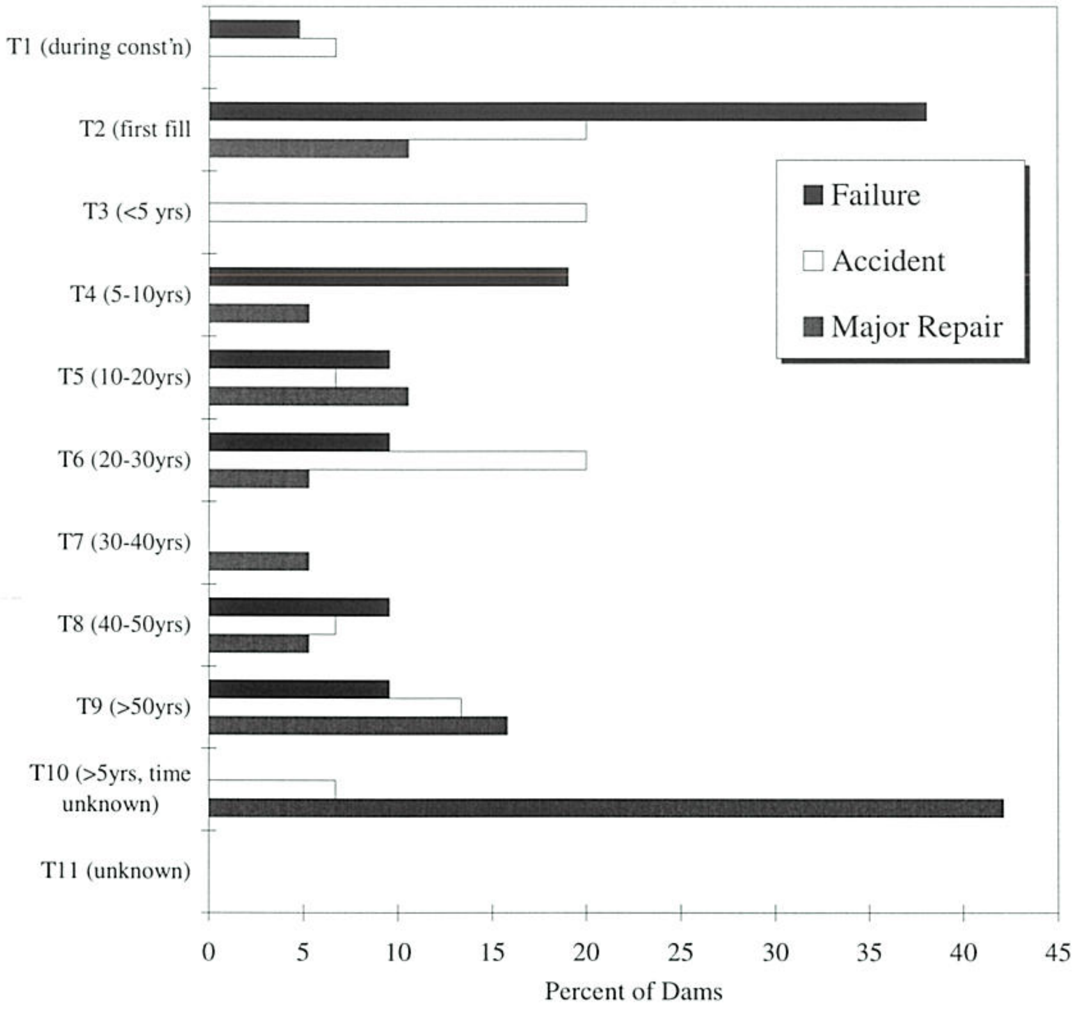


Figure 18. Age at incident - Masonry Gravity Dams

Figures 19 and 20 and Table 16 show the time to significant incidents for dams. The data is presented as the number of incidents in a time period divided by the population of dams that had survived that time period. The population was taken from ICOLD (1979) and extrapolated to 1983 dam numbers.

First filling is still the predominant failure time. There appears to be a slight rise in the rate of failures with time (ignoring T2). After 40 years of age there is a jump in the failure rate. It should be noted that the older age groups are represented by a small population.

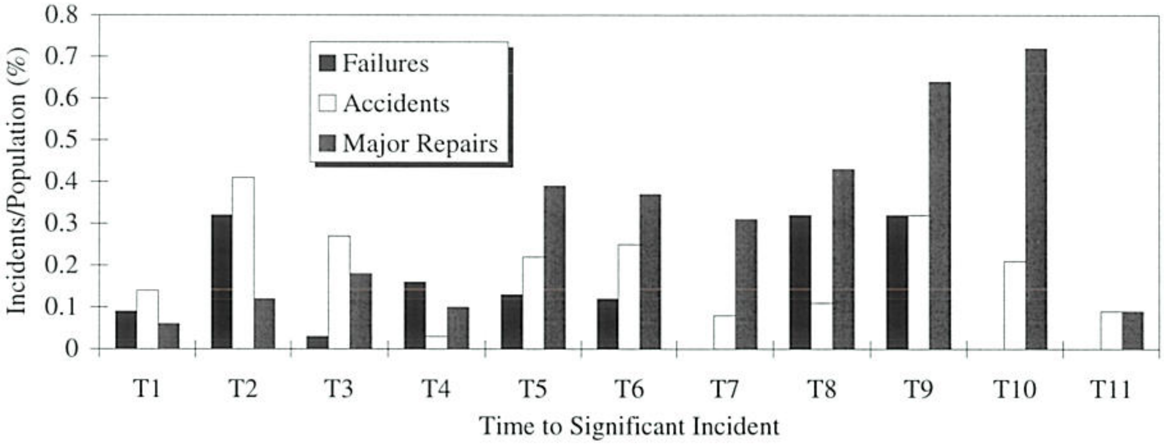


Figure 19. Time to Significant Incident - Gravity Dam Incidents/Population (%)

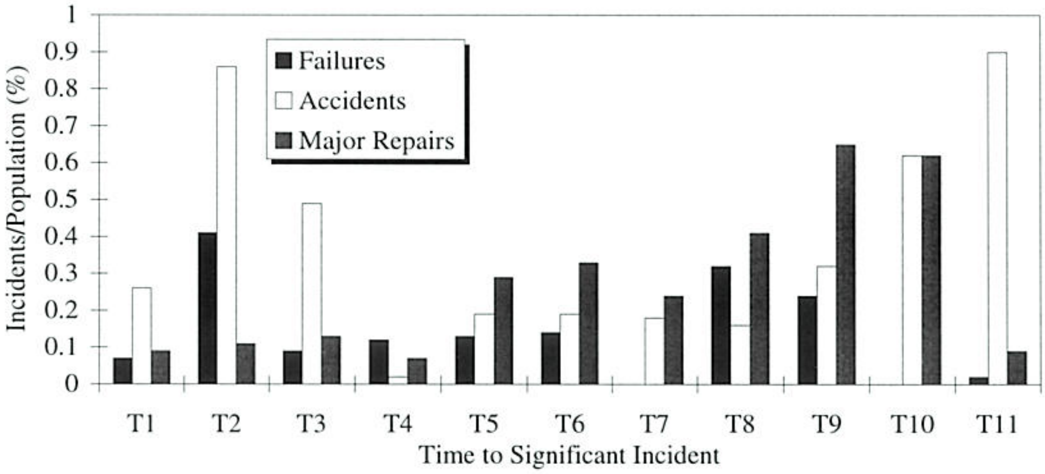


Figure 20. Time to Significant Incident - All Dam Incidents/Population (%)

Table 16. Time to Significant Incident - Incident/Population of Dams Surviving Period (%)

Age	Failures					Accidents					Major Repairs				
	Grav	Arch	Butt	MA	Total	Grav	Arch	Butt	MA	Total	Grav	Arch	Butt	MA	Total
Tot	0.90	0.75	2.24	1.87	0.99	1.54	10.69	2.88	14.02	3.47	2.06	0.13	3.53	-	1.78
T1	0.09	-	-	-	0.07	0.14	0.63	0.64	-	0.26	0.06	-	0.64	-	0.09
T2	0.32	0.25	1.60	0.93	0.41	0.41	2.39	0.32	5.61	0.86	0.12	-	0.32	-	0.11
0-5	0.03	0.13	0.66	-	0.09	0.27	1.16	0.99	0.95	0.49	0.18	-	-	-	0.13
5-10	0.16	-	-	-	0.12	0.03	-	-	-	0.02	0.10	-	-	-	0.07
10-20	0.13	0.19	-	-	0.13	0.22	0.19	-	-	0.19	0.39	-	-	-	0.29
20-30	0.12	-	-	1.52	0.14	0.25	-	-	-	0.19	0.37	-	0.87	-	0.33
30-40	-	-	-	-	-	0.08	0.38	1.09	-	0.18	0.31	-	-	-	0.24
40-50	0.32	0.53	-	-	0.32	0.11	0.53	-	-	0.16	0.43	-	1.49	-	0.41
>50	0.32	-	-	-	0.24	0.32	0.53	-	-	0.32	0.64	0.53	1.49	-	0.65
T10	-	-	-	-	-	0.21	2.06	0.33	3.81	0.62	0.72	-	1.32	-	0.62
T11	-	0.13	-	-	0.02	0.09	4.03	0.32	5.61	0.90	0.09	-	0.32	-	0.09

T1: During construction; T2: During first fill; T10: >5 years, else unknown; T11: Unknown.

Table 17. Time to Significant Incident

No.	Failures								Accidents							Major Repairs					
	PG	PG(M)	CB	CB(M)	VA	VA(M)	MV	ALL	PG	PG(M)	CB	CB(M)	VA	MV(M)	ALL	PG	PG(M)	CB	VA	ALL	TOTAL
T1	2	1	-	-	-	-	-	3	4	1	1	1	5	-	12	2	-	2	-	4	21
T2	3	8	3	2	2	-	1	19	11	3	1	-	19	-	40	2	2	1	-	5	63
T3	1	-	1	1	-	1	-	4	6	3	3	-	9	-	22	6	-	-	-	6	32
T4	1	4	-	-	-	-	-	5	1	-	-	-	-	-	1	2	1	-	-	3	9
T5	1	2	-	-	-	1	-	4	4	1	-	-	1	-	6	7	2	-	-	9	19
T6	-	2	-	-	-	-	1	3	1	3	-	-	-	-	4	5	1	1	-	7	14
T7	-	-	-	-	-	-	-	0	1	-	1	-	1	-	3	3	1	-	-	4	7
T8	1	2	-	-	-	1	-	4	-	1	-	-	1	-	2	3	1	1	-	5	11
T9	1	2	-	-	-	-	-	3	1	2	-	-	1	-	4	3	3	1	1	8	15
T10	-	-	-	-	-	-	-	0	6	1	1	-	16	2	28	16	8	4	-	28	56
T11	-	-	-	-	1	-	-	1	3	-	1	-	32	-	42	3	-	1	-	4	47
	10	21	4	3	3	3	2	46	38	15	8	-	85	2	164	52	19	11	1	83	294

Table 18. Details of Dam Failure Water Levels

Dam Name	Dam Type	Year Com.	Year Fail	Fail Type	Fail Mode	MWL (m)	Height at fail (m)	Highest record level?	Height above previous	Time (hrs)	Comments
Torrejon-Tajo	PG	1967	1965	Fa	SH						DNA
Zerbino	PG	1925	1935	Faf	S/SC	10	15	Y	≈5m>FSL		Large flood caused overtopping.
Mohamed V	PG	1966	1963	Fb	?						DNA
Elwha River	PG	1912	1912	Ff	P	31	31	Y	1st fill	240	Failure occurred 10 days after pond was first filled.
Xuriguera	PG	1902	1944	Ff	S						
Bayless (A)	PG	1909	1910	Ff	S	12.5	12.5	Y	1st fill	48	Failed 2 days after spillway began discharging.
Bayless (B)	PG	1909	1911	Ff	S	12.5	12.5	N		<6	Was at this level previous year when failure A occurred. Failed at 2-2:30 on day the reservoir filled.
St Francis	PG	1926	1928	Ff	S	61	61	Y	1st fill	170	Gradual first fill.
Hauser Lake II	PG	1911	1969	?	?						DNA
Kohodiar	PG/TE	1963	1983	?	?						DNA
Fergoug I	PG(M)	1871	1881	Fa	SC		>43	Y			Flood due to failure of Habra dam.
Fergoug II	PG(M)	1885	1927	Fa	SC?		>43	Y			Flood due to failure of Habra dam.
Sig	PG(M)	1858	1885	Fa	SC?			Y			Flood due to failure of Cheurfas dam.
Santa Catalina	PG(M)	1900	1906	Fa	?						
Cheurfas	PG(M)	1884	1885	Fb	?			Y	1st fill		
Granadillar	PG(M)	1930	1933	Fb	?						
Bouzey	PG(M)	1881	1895	Fb	T	19.7	19.6	N	0.1m	>1 year	Had been at 19.7m for over a year previously.
Khadakwasla	PG(M)	1879	1961	Fb	T/SH	28	32.7	Y*	3.9m	4	Flood due to failure of Panshet dam. * Overtopped by 2.7m and failed when overtopping had receded to 1.8m.
Habra (B)	PG(M)	1872	1881	Fba	T/SH	33	36.9	Y			Overtopping.
Angels	PG(M)	1895	1895	Ff	P						
Tigra	PG(M)	1917	1917	Ff	S	27.1	26.7	Y	1.1m	0.5	Spillway section overtopped by 1.1m. Whole dam overtopped by 0.15m.
Austin (A)	PG(M)	1893	1900	Ff	SC/P/S	20.7	24.1	Y	0.4m		Flood overtopped dam by 3.4m.
Puentes	PG(M)	1791	1802	Ffb	P	>47	47	Y	1st fill*		*1st fill took 11yrs. Dam filled from 22-47m in final 4 mths.

Note: 'Overtopping' implies first time.

Dam Name	Dam Type	Year Com.	Year Fail	Fail Type	Fail Mode	MWL (m)	Height at fail (m)	Highest record level?	Height above previous	Time (hrs)	Comments
Kundli	PG(M)	1924	1925	Fm	?			Y	1st fill		Rapid 1st fill due to floods.
Chickahole	PG(M)	1966	1972	Fm	T	27.4	26	?			Flood rise of 1.5m immediately prior to failure.
Gallinas	PG(M)	1910	1957	Fm/Fa	?			Y			Overtopped by record flood.
Lynx Creek	PG(M)	1891	1891	Fm	?						Flood.
Pagara	PG(M)	1927	1943	Fmb	T?	28.7	30	Y	1.3m	<12	Overtopped by 0.4m in flood.
Habra (A)	PG(M)	1871	1872	Fmb	T/SH	33		Y			Flood after 1st fill.
Habra (C)	PG(M)	1881	1927	Fmb	T/SH	33	37	Y			Flood overtopped, largest since repair.
Elmali I	PG(M)/TE	1892	1916	Fa	?						Overtopped.
Lower Idaho Falls	ER/PG(M)	1914	1976	Fa	?			Y			Overtopped from upstream failure of Teton.
Vaughn Creek	VA	1926	1926	Ff	P	17	17	Y	1st fill	48	
Malpasset	VA	1954	1959	Ff	S	66	65.7	Y*		3	* Just previously exceeded this by ≈ 0.1m for 3 hours.
Moyie River	VA	1924	1926	Ffa	SC	14	16-18	Y	2-4m		Storm and upstream dam failure flood overtopped dam.
Meihua	VA(M)	1981	1981	Fb			21.5	N			Previously overtopped by 0.3m (0.8m > than at failure).
Bacino di Rutte	VA(M)	1952	1965	Ff	D/P	12		Y*		<48	* Highest since sediment removed. Dam had been filling for 2 days.
Ashley	CB	1908	1909	Ff	P	17	17	Y	1st fill	>1	Just spilling when pipe failed.
Stony Creek	CB (Ambursen)	1913	1914	Ff	P	13	13	?			Unsure how long at this level or if it had been higher. Dam in service 6 months.
Komoro	CB	1927	1928	Ff	S/P						No suggestion of high water level.
Overholser	CB (Ambursen)	1920	1923	Ffa	SC			Y			Overtopped in flood.
Austin (B)	CB(M)	1915	1915	Fba	SH			Y		3	Highest since rebuilt.
Vega de Tera	CB(M)	1956	1959	Fm	T/C	33	33	Y	1.75m	<0.5	Previous year was at 31.25m. Flood had just completed 1st fill. "The dam reportedly was breached at the moment of topping of the crest"
Selsfors	CB/TE	1943	1943	Ff	P	20	18.2	Y	1st fill	≈ 6	
Gleno	MV	1923	1923	Fb	T/C	32	32	Y	1st fill	1 month	Had been at full supply level for ≈ 1 month.
Leguaseca	MV	1958	1987	Fb	T/C			N			"low reservoir storage"

Note: 'Overtopping' implies first time.

Figure 21. Failure Mode: Age at Failure vs Year Commissioned (All Dams)

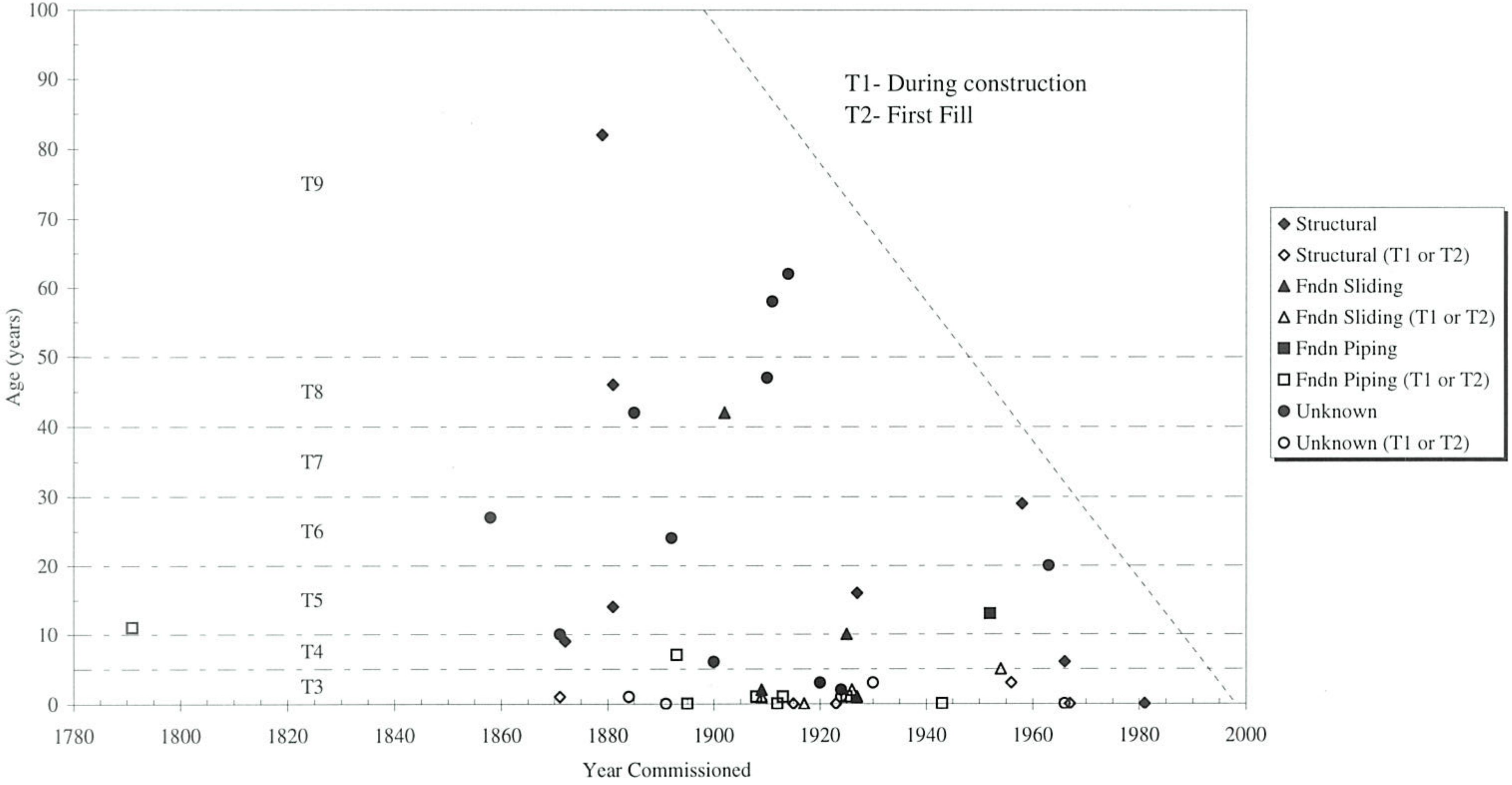


Figure 22: Over Topping: Age at Failure vs Year Commissioned (All Dams)

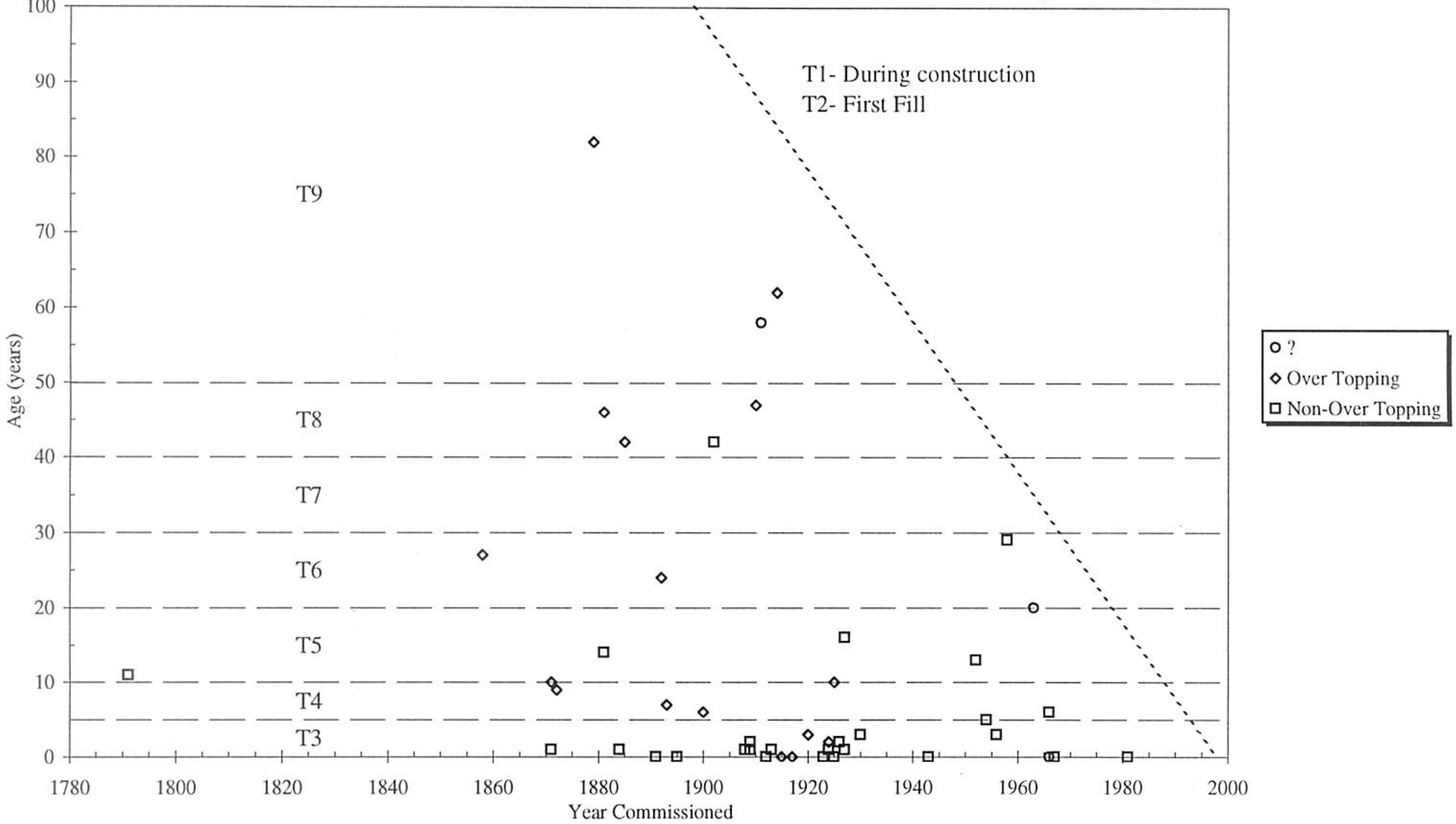


Figure 23: Dam Type: Age at Failure vs Year Commissioned

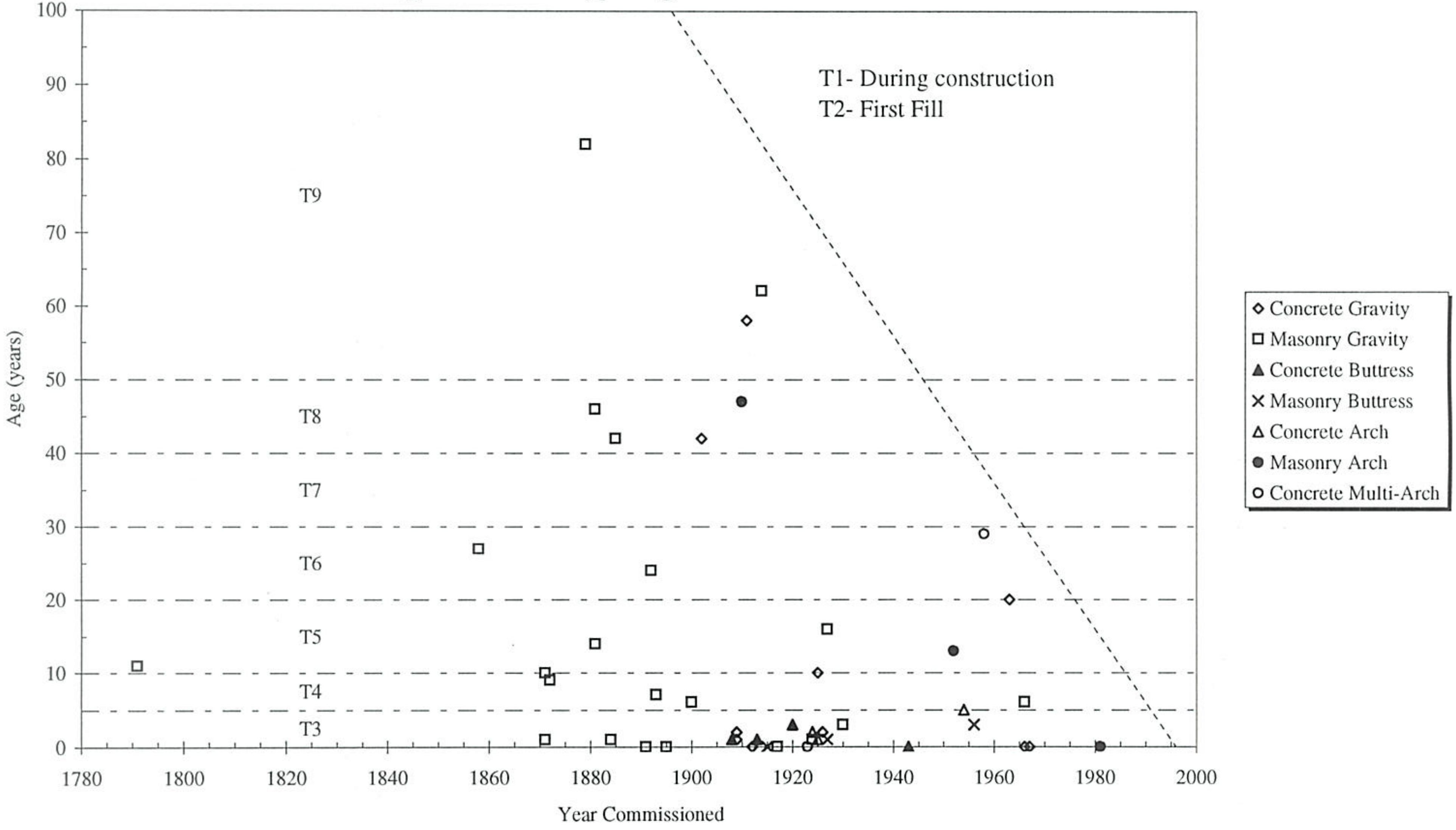


Figure 24. Age at Significant Incident vs Year Commissioned

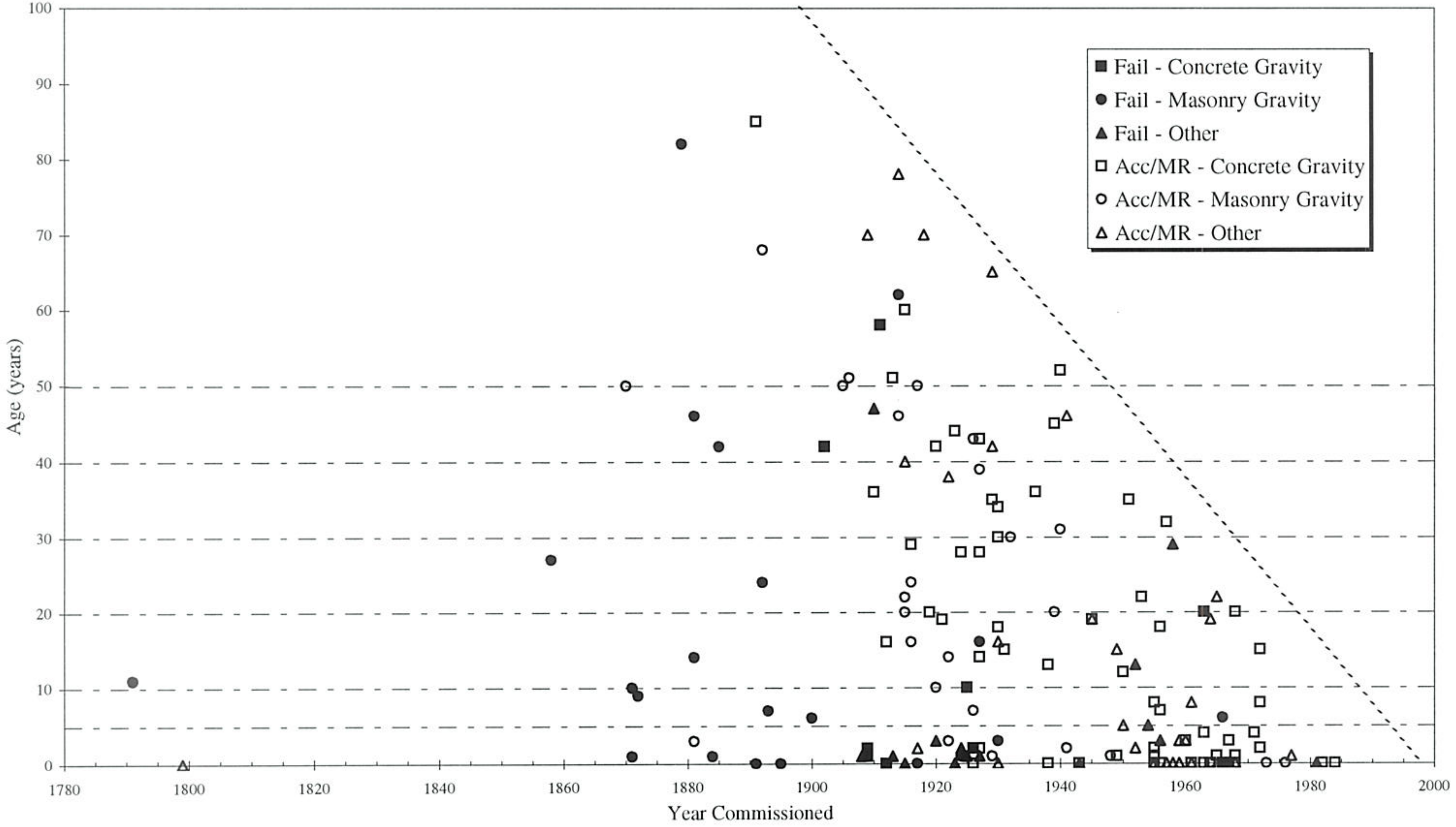
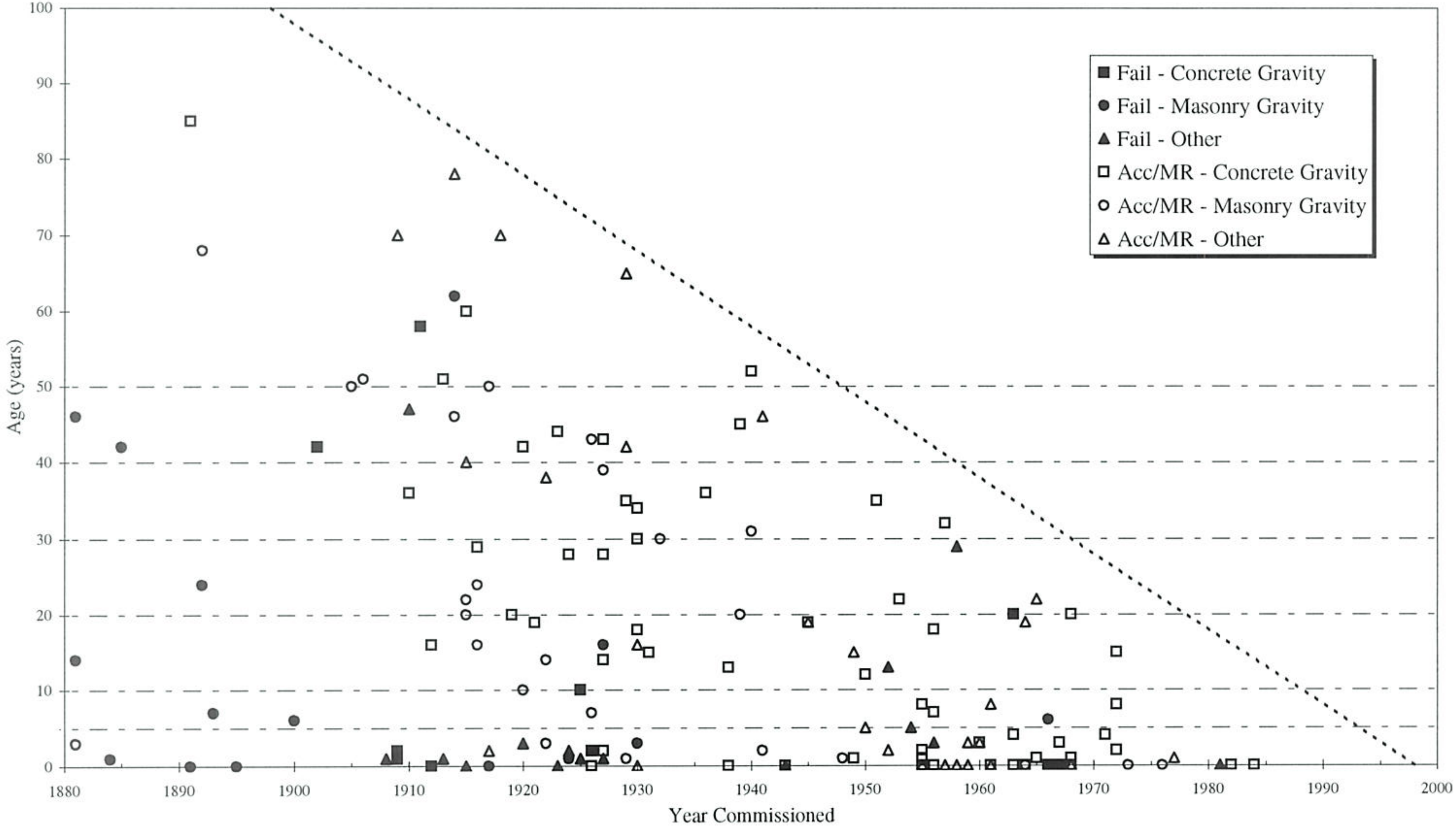


Figure 25. Age at Significant Incident vs Year Commissioned



3.5 Incident Causes

Table 19 shows that failures in the foundation are much more common in concrete dams than in masonry dams (47% compared to 19% and 68% compared to 22% when combined failure types, F_f, F_{fa} and F_{fb}, are included). Failures due to the dam body or materials are more common in masonry dams.

Table 19. Failure Types

Dam Type	Ff	Fb	Fa	Fm	Ffa	Ffb	Fbm	Fba	Unknown
PG	5	1	1		1				2
PG(M)	3	4	5	4		1	3	1	
VA	1				2				
VA(M)	1	1		1					
CB	3				1				
CB(M)	1			1				1	
MV		2							
Total Concrete	9 (47)	3 (16)	1 (5)	-	4 (21)	-	-	-	2 (11)
Total Masonry	5 (19)	5 (19)	5 (19)	6 (22)	-	1 (4)	3 (11)	2 (7)	-
Total All	14 (30)	8 (17)	6 (13)	6 (13)	4 (9)	1 (2)	3 (7)	2 (4)	2 (4)

NOTE: Figures in brackets are percentages for each dam type.

Tables F1 to F3 in Appendix F give the incident causes for all dams, concrete gravity dams and masonry gravity dams respectively. These have been derived from the ICOLD failure causes terminology shown in Section 2.3.8. Tables 20 to 22 show the most common causes of incidents to all dams, concrete gravity dams and masonry gravity dams respectively. It should be noted that the 'percentage of dams' column can total more than 100% since there can be more than one cause for each incident.

Table 20. Main Causes of Incidents in All Dams

Rank	Code	Description	No	% of Dams
		FAILURES		
1	3.4.6	overtopping	10	22
2	3.4.2	uplift	8	17
3	1.1.4	seepage in the foundation	7	15
4	1.1.5	piping through the foundation	6	13
5	4.7.1	excess rates of flow	6	13
		ACCIDENTS		
1	1.1.4	seepage in the foundation	16	9
2	4.8	local scour	16	9
3	1.1.5	piping through the foundation	13	7
4	4.7.1	excess rates of flow	13	7
5	4.11.6	discharge equipment malfunction	10	6
		MAJOR REPAIRS		
1	1.2.3	freezing and thawing	53	20
2	1.3.4	external temperature variation	28	11
3	1.2.2	reaction between concrete & environment	22	8
4	1.2.8	concrete permeability	22	8
5	3.2.2	reaction between masonry & environment	22	8

Overtopping, uplift and foundation seepage and piping are the most common causes of failure for all dams combined. Foundation problems (shear and seepage) are the major cause of failures for concrete gravity dams. Masonry gravity dams have more failures due to overtopping. Seepage and flow problems are the main causes of accidents whilst concrete reactions, temperature and freeze-thaw cause the most major repairs. These types of major repairs tend to cause only surficial damage.

Table 21. Main Causes of Incidents in Concrete Gravity Dams

Rank	Code	Description	No	% of Dams
		FAILURES		
1	1.1.3	shear strength in the foundation	4	40
2	1.1.4	seepage in the foundation	4	40
3	1.3.2	uplift	2	20
4	4.7.1	excess rates of flow	2	20
		ACCIDENTS		
1	1.1.5	piping through the foundation	8	18
2	1.1.4	seepage in the foundation	7	16
3	4.6	due to structural behaviour	7	16
4	4.7.1	excess rates of flow	5	11
5	4.11.6	discharge equipment malfunction	5	11
		MAJOR REPAIRS		
1	1.2.3	freezing and thawing	40	24
2	1.2.2	reaction between concrete & environment	15	9
3	1.2.8	concrete permeability	15	9
4	1.3.2	uplift	15	9
5	4.2.12	concrete erosion by abrasion	13	8

Table 22. Main Causes of Incidents in Masonry Gravity Dams

Rank	Code	Description	No	% of Dams
		FAILURES		
1	3.4.6	overtopping	8	38
2	3.4.2	uplift	7	33
3	2.3.9	upstream dam collapse	5	24
4	3.5.2	tensile stresses	5	24
		ACCIDENTS		
1	3.4.2	uplift	6	35
2	3.5.2	tensile stresses	3	18
3	3.1.4	seepage in foundation	2	12
4	3.2.8	mortar permeability	2	12
5	3.2.9	masonry construction (including order)	2	12
		MAJOR REPAIRS		
1	3.2.2	reaction between masonry & environment	20	51
2	3.2.8	mortar permeability	10	26
3	3.1.4	seepage in foundation	8	21
4	3.2.3	freezing and thawing	8	21
5	3.4.1	hydrostatic, silt and ice pressure	5	13

When all the dams were analysed together, similar incident codes were grouped together to better distinguish the main causes of incidents. Only 'significant incidents' were included. The incidents were separated into those with soil foundations and those with rock or unknown foundations. Figure 26 and Tables 23 and 24 show the results of this analysis. Table 23 only shows results for failures of dams with soil foundations. There were only three dam accidents where the dam was known to have a soil foundation. The results show that piping was the predominant cause of failure for dams with soil foundations.

For dams with rock or unknown foundations, the major cause of failure was overtopping followed by shear strength of the foundation. Piping was the sixth most common cause of failure with five cases noted. The causes of accidents for dams with rock or unknown foundations were seepage, scour, piping, permeability in the concrete and tensile stresses in the dam body. Major repairs were caused by reactions of the masonry/concrete with the environment, concrete/masonry permeability and construction methods.

Table 23. Main Failure Causes for Dams with Soil Foundations

Rank	**ICOLD Codes**	**Description**	**No**	**% of Dams**
1	1.1.5, 3.1.5, 4.1.5	internal erosion in the foundation (piping)	6	67
2	1.1.4, 3.1.4, 4.1.4	seepage in the foundation	2	22
2	1.1.9, 3.1.9, 4.1.8	foundation preparation	2	22

Table 24. Main Significant Incident Causes for Dams with Rock or Unknown Foundations

Rank	**ICOLD Codes**	**Description**	**No**	**% of Dams**
FAILURES				
1	1.3.7, 3.4.6	overtopping	12	32
2	1.1.3, 3.1.3, 4.1.3	shear strength in the foundation	8	22
3	1.1.4, 3.1.4, 4.1.4	seepage in the foundation	7	19
3	1.4.2, 1.5.2, 3.5.2	tensile stresses in the concrete/masonry	7	19
5	4.7.1	excess rates of flow (3 due to overtopping)	6	16
6	1.1.5, 3.1.5, 4.1.5	internal erosion in the foundation (piping)	5	14
6	1.2.6, 1.3.6	shear strength of concrete/masonry	5	14
ACCIDENTS				
1	1.1.4, 3.1.4, 4.1.4	seepage in the foundation	18	11
2	4.8	local scour	15	9
3	1.1.5, 3.1.5, 4.1.5	internal erosion in the foundation (piping)	13	8
3	1.2.8, 3.2.8, 4.2.6	permeability in the concrete/masonry	13	8
3	1.4.2, 1.5.2, 3.5.2	tensile stresses in the concrete/masonry	13	8
MAJOR REPAIRS				
1	1.2.2, 3.2.2, 4.2.2, 4.4.1	reaction between concrete/masonry & environment	21	26
2	1.2.8, 3.2.8, 4.2.6	permeability in the concrete/masonry	16	20
2	1.2.9, 1.2.10, 3.2.9, 4.2.7	method of construction (including cooling)	16	20
4	1.2.3, 3.2.3, 4.2.3	freezing and thawing	12	15
5	1.2.11, 3.2.10, 3.3.2, 4.2.10	structural joints in concrete/masonry	10	12
6	1.1.4, 3.1.4, 4.1.4	seepage in the foundation	9	11

Failure modes for incidents involving the foundation will be discussed further in Section 3.8. For the failures in the dam structure the following was noted:

- The numbers of structural failures attributed to 'poor construction' and 'design flaws' were similar. There was difficulty in separating design and construction problems as, in many cases, both contributed to the failure.
- Only one concrete gravity dam failed due to an inadequacy in the structure. The dam (Torrejon-Tajo, Spain) failure cause was traced to organics present in the aggregate, and filling of the dam by a flood during construction before the concrete had fully set.
- Overtopping preceded 5 of the failures.
- The majority of the failure cases were masonry gravity dams, probably reflecting the quality of construction and materials.

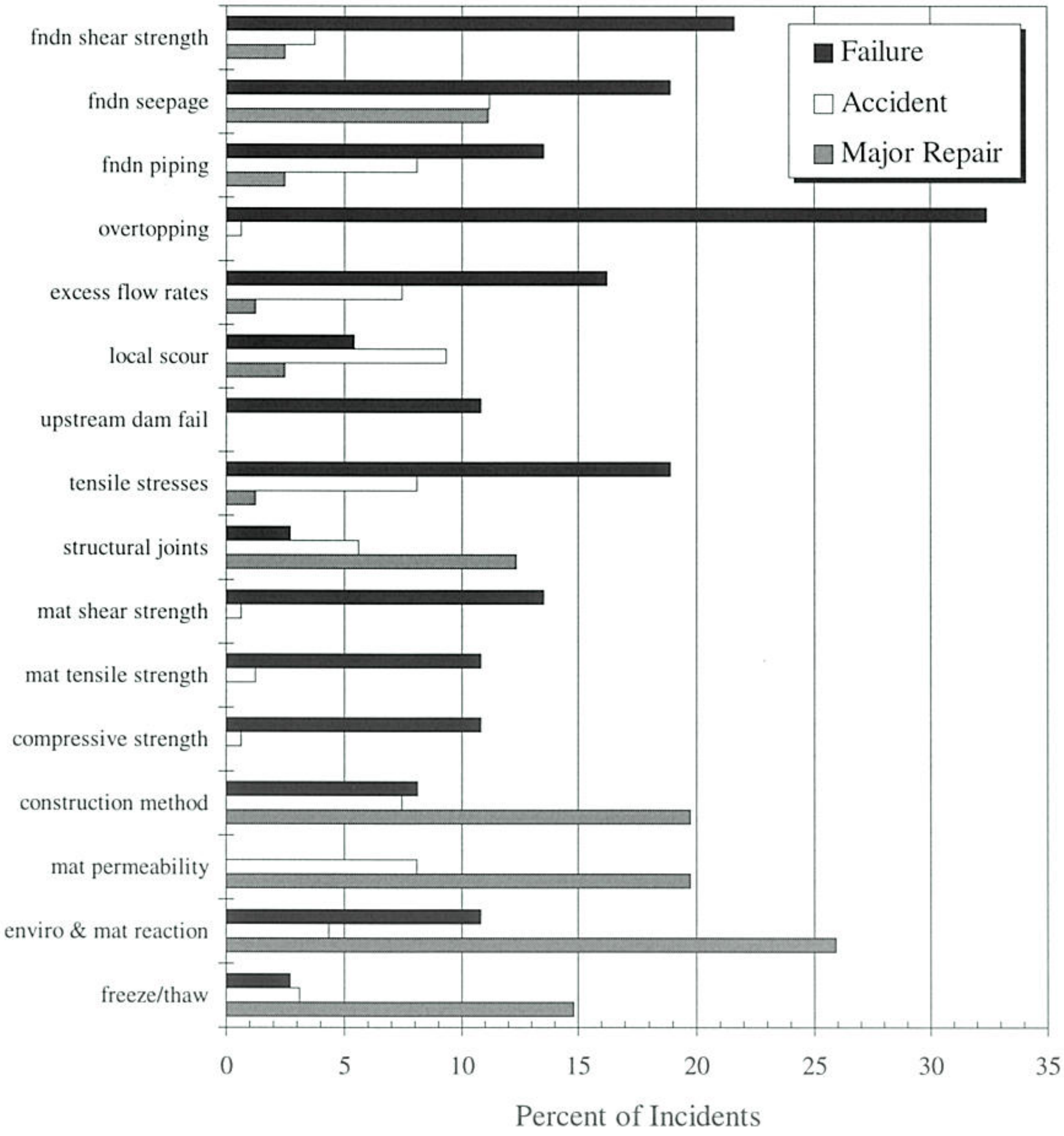


Figure 26. Causes of Significant Incidents (Rock & Unknown Foundations)

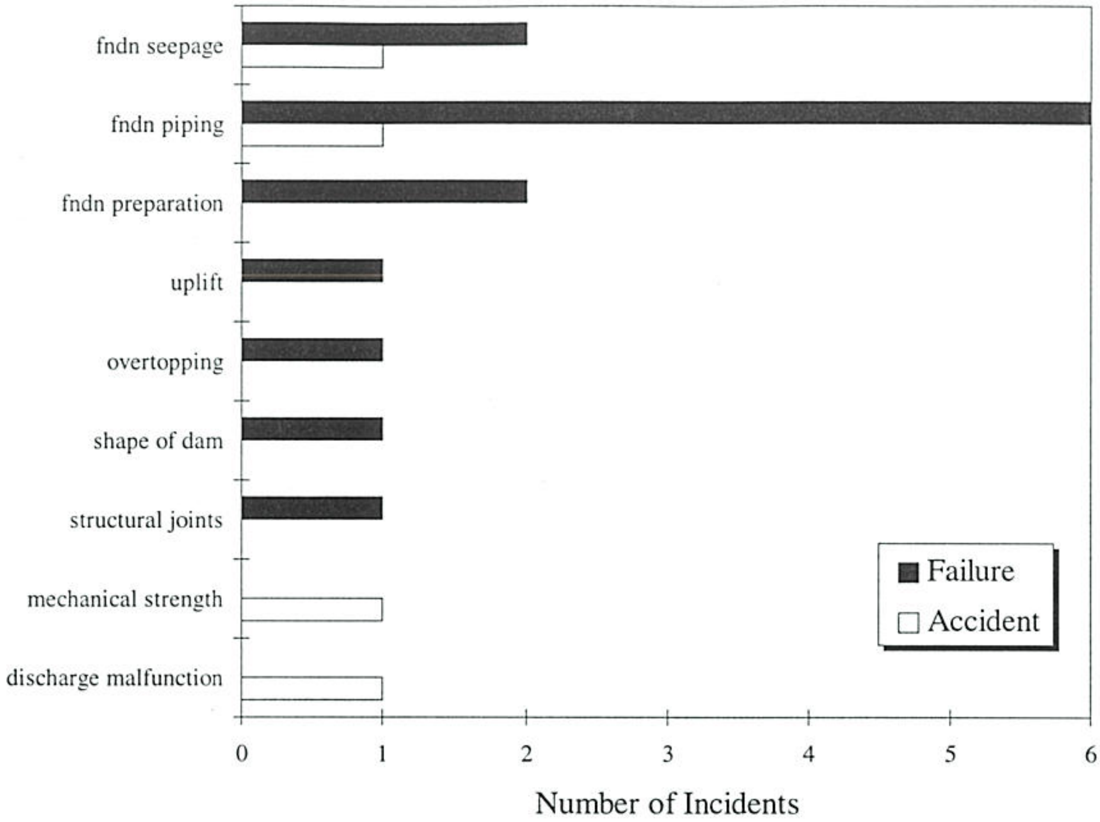


Figure 27. Causes of Significant Incidents (Soil Foundations)

3.6 Monitoring and Surveillance Data

3.6.1 Using ICOLD Terms

Overtopping was the most common failure warning type followed by dam leakage and no warning. However, as can be seen from Table 25, it is masonry dams which are most susceptible to overtopping. Dam leakages followed by cracking were the most prevalent warning in accidents. Major repairs tended to have been prompted by dam leakage or concrete deterioration. It appears that the accidents and major repairs tend to have a 'structural' warning that can be noticed, whereas the failure warnings are more difficult to notice. Figures 28 and 29 show the warning types for concrete gravity dam and all dam incidents respectively. Tables 25 to 27 show the warning types for failures, accidents and major repairs for each dam type. It should be noted here that there can be more than one warning type per dam failure.

From Section 3.5, it appears that the accidents and major repairs generally occur where there has been obvious signs of distress (e.g. surficial damage, uplift records, seepage monitoring). Whether these problems may signal potential instability in the dam is questionable. For example, it is unlikely that cavitation damage in a spillway will lead to failure of the dam. Failures have occurred where it is likely that little warning was given or where the least amount was known, that is, in the foundation.

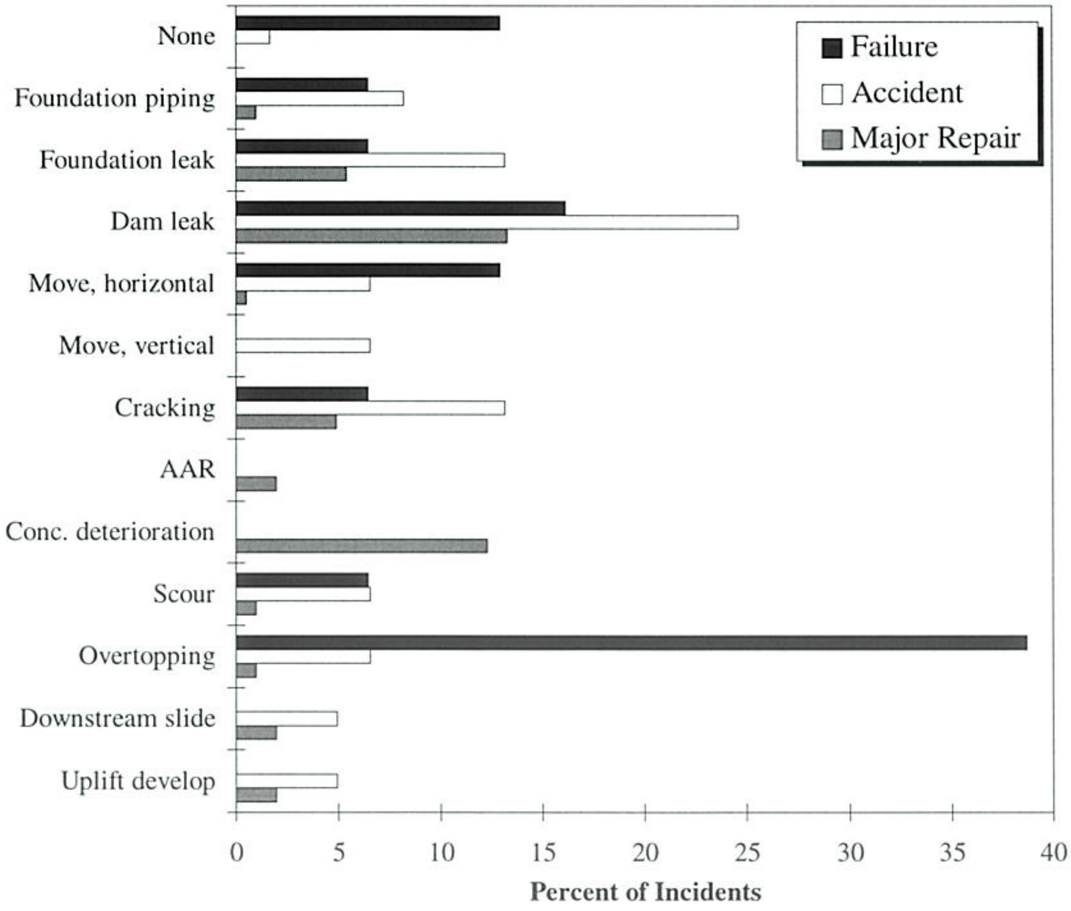


Figure 28. Warning Types - Gravity Dams

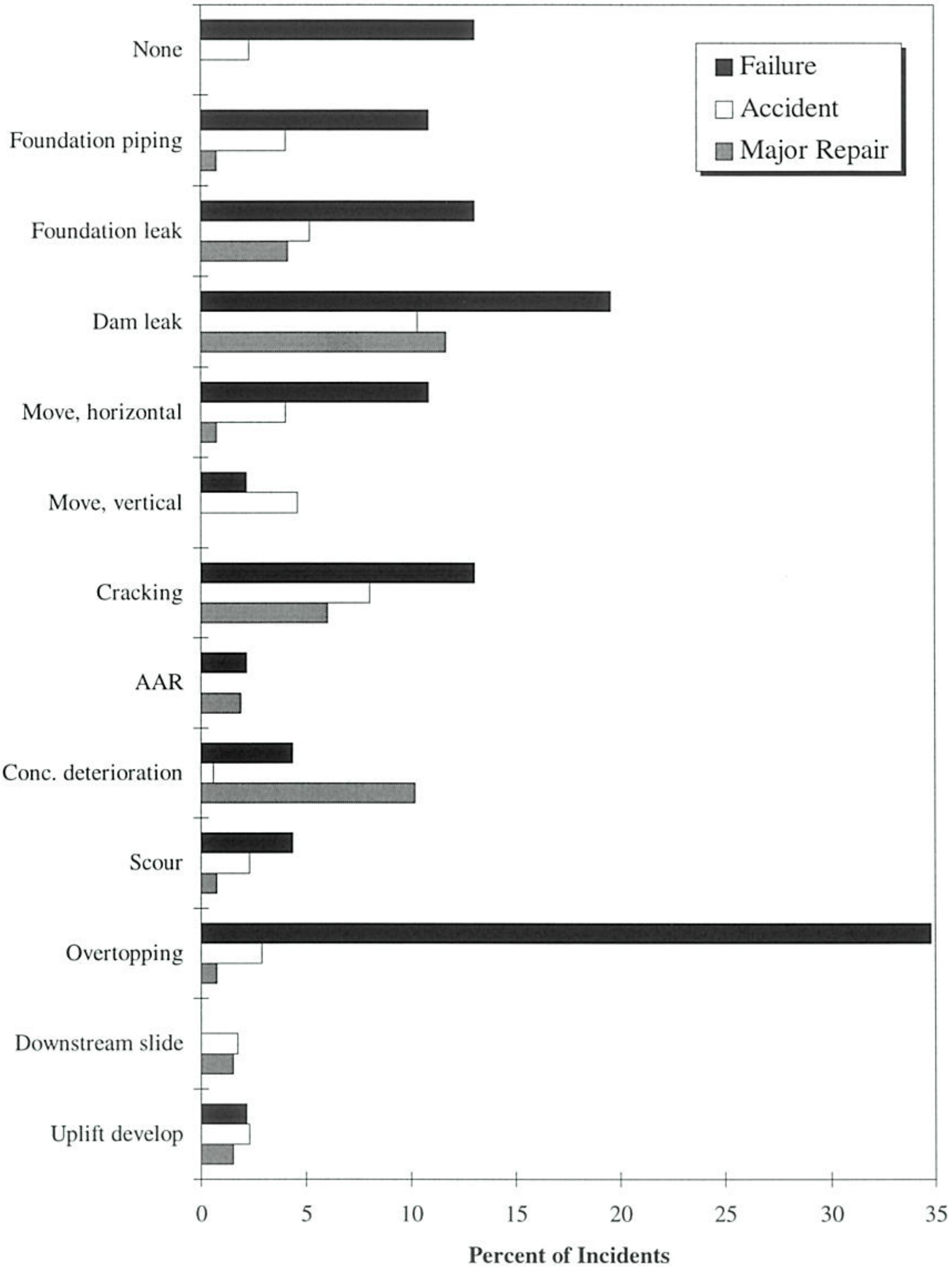


Figure 29. Warning Types - All Dams

Table 25. Warning Types vs Dam Type - Failures

Warning Type	**PG**	**PG(M)**	**CB**	**CB(M)**	**VA**	**VA(M)**	**MV**	**Total**
None	1	3	-	1	-	-	1	6
Foundation piping	-	2	1	-	2	-	-	5
Foundation leak	1	1	1	-	3	-	-	6
Dam leak	3	2	2	-	-	1	1	9
Move, horizontal	2	2	-	-	1	-	-	5
Move, vertical	-	-	1	-	-	-	-	1
Cracking	2	-	1	-	1	1	1	6
AAR	-	-	-	-	-	1	-	1
Conc deteriorate	-	-	-	-	-	-	2	2
Scour	-	2	-	-	-	-	-	2
Overtopping	1	11	1	1	1	1	-	16
Downstream slide	-	-	-	-	-	-	-	-
Uplift develop	-	-	-	-	-	1	-	1
Unknown	4	2	-	1	-	-	-	7
Total	14	25	7	3	8	5	5	67

Table 26. Warning Types vs Dam Type - Accidents

Warning Type	**PG**	**PG(M)**	**CB**	**CB(M)**	**VA**	**MV**	**MV(M)**	**Total**
None	1	-	1	-	2	-	-	4
Foundation piping	5	-	1	-	1	-	-	7
Foundation leak	7	1	1	-	-	-	-	9
Dam leak	6	9	1	-	2	-	-	18
Move, horizontal	3	1	-	-	3	-	-	7
Move, vertical	2	2	-	-	4	-	-	8
Cracking	3	5	2	-	4	-	-	14
AAR	-	-	-	-	-	-	-	0
Conc deteriorate	-	-	1	-	-	-	-	1
Scour	3	1	-	-	-	-	-	4
Overtopping	2	2	-	1	-	-	-	5
Downstream slide	3	-	-	-	-	-	-	3
Uplift develop	2	1	-	-	1	-	-	4
Unknown	20	4	4	-	77	17	2	124
Total	57	26	11	1	94	17	2	208

Table 27. Warning Types vs Dam Type - Major Repairs

Warning Type	**PG**	**PG(M)**	**CB**	**CB(M)**	**MV**	**MV(M)**	**Total**
None	-	-	-	-	-	-	-
Foundation piping	1	1	-	-	-	-	2
Foundation leak	7	4	-	-	-	-	11
Dam leak	17	10	4	-	-	-	31
Move, horizontal	1	-	1	-	-	-	2
Move, vertical	-	-	-	-	-	-	-
Cracking	9	1	6	-	-	-	16
AAR	4	-	1	-	-	-	5
Conc deteriorate	18	7	2	-	-	-	27
Scour	2	-	-	-	-	-	2
Overtopping	2	-	-	-	-	-	2
Downstream slide	4	-	-	-	-	-	4
Uplift develop	3	1	-	-	-	-	4
Unknown	110	21	21	2	6	1	161
Total	178	45	35	2	6	1	267

3.6.2 Details of Warnings

Warnings prior to dam failures are very important as they allow for the possibility of either preventing the failure if detected early enough or, importantly, they allow time for people downstream to be notified and evacuated. A warning, even a few hours prior to failure, can have a major effect on loss of life. Table 29 was created to describe each of the failures and their warnings. A subjective warning rating was given to each failure. The ratings were taken as to whether a dam failure had a sufficient warning which could have led to people downstream being advised of the impending failure. Table 29 also includes information on the failure type and failure mode.

Many of the dam failures had limited information and as such could not be given a warning rating. Table 28 shows the results of the analysis.

Table 28. Warning Ratings for Failed Dams

Warning Rating	Number of Dams
Yes	10
No	1
Maybe	9
Dam failure upstream	5
Flood	5
Unknown	16

Ashley Dam was the only dam where the failure signs were deemed insufficient to allow a warning to be given. There was some seepage 1.5 to 2 hours prior to failure but, the time was insufficient to allow for a warning to be given. Failure occurred through the alluvial foundation. Selsfors Dam had a small seepage 4.25 hours prior to collapse. The seepage increased slowly for 0.5 hour and then rapidly. The signs may have been enough to give a limited warning.

An important note to come from this analysis is that most of the warnings comprised a rapid increase in flow prior to failure. Quantity of flow appears not to be as critical.

Table 30 shows a similar analysis for significant accidents. Most of the accidents gave signs of problems developing. Blackbrook II did not, as the accident was caused by an earthquake. Bhandardara Dam which went close to failure through the dam body had insufficient warning. Cracking occurred quickly at a flood level slightly higher than that recorded previously.

Table 52. Number of Failures During Overtopping where the Failure Mode was Unknown

Year	Gravity			Arch			Buttress			Multi-Arch			Total		
Comm.	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total
1700-1799	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1800-1899	NF	3	3	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	3	3
1900-1909	NF	1	1	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	1	1
1910-1919	NF	1	1	NF	1	1	NF	NF	NF	NF	NF	NF	NF	2	2
1920-1929	NF	NF	NF	1	NF	1	1	NF	1	NF	NF	NF	2	NF	2
1930-1939	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1940-1949	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1950-1959	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1960-1969	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1970-1977	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1983-1992	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1700-1929	NF	5	5	1	1	2	1	NF	1	NF	NF	NF	2	6	7
1930-1992	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
Total	NF	5	5	1	1	2	1	NF	1	NF	NF	NF	2	6	8

Table 53. Number of Failures where the Failure Mode was Unknown (and no Overtopping)

Year	Gravity			Arch			Buttress			Multi-Arch			Total		
Comm.	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total	0-5 years	>5 years	Total
1700-1799	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1800-1899	1	NF	1	NF	NF	NF	NF	NF	NF	NF	NF	NF	1	NF	1
1900-1909	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1910-1919	NF	1	1	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	1	1
1920-1929	1	NF	1	NF	NF	NF	NF	NF	NF	NF	NF	NF	1	NF	1
1930-1939	1	NF	1	NF	NF	NF	NF	NF	NF	NF	NF	NF	1	NF	1
1940-1949	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1950-1959	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1960-1969	1	1	2	NF	NF	NF	NF	NF	NF	NF	NF	NF	1	1	2
1970-1977	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1983-1992	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1960-1982	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
1960-1992	1	1	2	NF	NF	NF	NF	NF	NF	NF	NF	NF	1	1	2
1700-1929	2	1	3	NF	NF	NF	NF	NF	NF	NF	NF	NF	2	1	4
1930-1992	2	1	3	NF	NF	NF	NF	NF	NF	NF	NF	NF	2	1	2
Total	4	2	6	NF	NF	NF	NF	NF	NF	NF	NF	NF	4	2	6

4.1.5 Gravity Dams - Separation of Concrete and Masonry Dams

The ICOLD(1984) population for gravity dams does not distinguish between dams made of concrete and those made of masonry. An estimate was made for the population taking into account the history of dam building and the USA population of dams. Dams of cyclopean concrete construction were assumed to be concrete.

According to Smith (1972), Schnitter (1994) and Lewis (1988) the first concrete dams were completed in the 1870's in Australia and the USA; the 1890's in India; and the 1900's in Great Britain. The distribution of concrete and masonry gravity dams in the USA was taken from the 567 concrete and masonry dams in the US Inventory of dams (1994) and is presented in Table 54.

Table 54. Distribution of Concrete and Masonry Gravity Dams in the USA

Year Commissioned	Concrete (%)	Masonry (%)
pre 1900	68.4	31.6
1900-1909	76.5	23.5
1910-1919	93.7	6.3
1920-1929	96.3	3.7
1930-1939	98.3	1.7
1940-1949	100	0
1950-1959	98.9	1.1
1960-1969	100	0
1970-1979	100	0
1980-1989	100	0
1990-1992	100	0

Table 54 was not used directly as this was likely to be biased towards concrete dams due to the modern nature of USA dams compared to much of the rest of the world. It is also possible that some dams denoted as 'gravity', and therefore assumed to be concrete, in the US database are masonry. Some countries such as India, which has approximately 3.2% of the world concrete and masonry dam population (ICOLD, 1994), commonly use masonry to construct their dams due to material availability and expense. Table 55 shows the distribution chosen for the analysis. It was found that the probabilities of failure were not sensitive to the assumptions in the concrete/masonry distribution for the post 1960 period.

Tables 58 to 61 show the annualised probabilities of failure for concrete and masonry dams for the various failure modes. Tables 62 and 63 show the number of failures with unknown failure modes. Table 62 shows those unknowns where failure during overtopping was known to have occurred. A distinction was made between dams commissioned prior to, and those commissioned after 1930. This represents the historical change to a better understanding of uplift pressures and materials properties for gravity dams. Table 56 summarises the annualised probabilities of failure using this distinction. As there were a number of categories without failures (denoted 'NF') a 'maximum' annual probability (assuming one failure to have occurred over the number of dam years) has been calculated and included in the last row of Table 56.

Table 57 gives suggested average annualised probabilities of failure for concrete and masonry gravity dams based on Table 56. Unknowns were accounted for by distributing them evenly through the three dam failure modes (foundation sliding and piping and failure within the dam body). This allowed for the total probability to be equal to the sum of the three modes. The probabilities have been rounded down (to one decimal place) to account for the assumptions in the analysis. In particular, the population used was that in existence as at 1992 and many dams are likely to have been decommissioned prior to this time or omitted from the ICOLD database and hence not included in the population. A larger population would result in lower probabilities of failure. This was checked for validity by assuming a larger population and re-running the analysis. Where no failures have occurred the suggested value is lower than that for the case where one failure had occurred.

Table 55. Distribution of Concrete and Masonry Gravity Dams Chosen for Analysis

Year Commissioned	Concrete (%)	Masonry (%)
pre 1900	0/30	100/70
1900-1909	60	40
1910-1919	75	25
1920-1929	90	10
1930-1939	90	10
1940-1949	95	5
1950-1959	95	5
1960-1969	97.5	2.5
1970-1979	97.5	2.5
1980-1989	97.5	2.5
1990-1992	97.5	2.5

Note (1) 1700-1799/1800-1899

Table 56. Summary of Annualised Probabilities of Failure for Gravity Dams (exc. China)

Failure	Year	Concrete Gravity			Masonry Gravity		
Mode	Commissioned	0-5 years	>5 years	Total	0-5 years	>5 years	Total
All Modes	1700-1929	1.0E-03	9.3E-05	1.5E-04	5.2E-03	3.4E-04	5.4E-04
	1930-1992	1.4E-04	1.4E-05	3.5E-05	1.6E-03	2.4E-04	4.2E-04
Foundation Sliding	1700-1929	6.7E-04	7.0E-05	1.1E-04	1.5E-03	NF	6.0E-05
	1930-1992	NF	NF	NF	NF	NF	NF
Foundation Piping	1700-1929	3.4E-04	NF	2.2E-05	1.5E-03	NF	6.0E-05
	1930-1992	NF	NF	NF	NF	NF	NF
Within Dam Body	1700-1929	NF	NF	NF	7.3E-04	1.6E-04	1.8E-04
	1930-1992	7.1E-05	NF	1.1E-05	NF	2.4E-04	2.1E-04
Max. No Fails$^{(1)}$	1700-1929	3.3E-04	2.3E-05	2.2E-05	7.3E-04	3.1E-05	3.0E-05
	1930-1992	7.0E-05	1.4E-05	1.1E-05	1.6E-03	2.4E-04	2.1E-04
Unknown (O/T)	1700-1929	-	-	-	-	6	6
	1930-1992	-	-	-	-	-	-
Unknown	1700-1929	-	1	1	3	-	3
	1930-1992	2	2	4	2	-	2

Note (1) Assuming 1 failure (for where no failures have occurred)

Table 57. Suggested Values for Annualised Probabilities of Failure for Gravity Dams (excluding China)

Failure Mode	Year Commissioned	Concrete Gravity		Masonry Gravity	
		0-5 years	>5 years	0-5 years	>5 years
All Failures	pre 1930	N/A	6.4E-05[2]	N/A	3.2E-04[2]
	1930-present	1.3E-04[2]	1.2E-05[2]	1.5E-03[2]	2.4E-04[2]
Foundation Sliding P_{SA}	pre 1930	N/A	5.0E-05[2]	N/A	6.0E-05[1]
	1930-present	2.0E-05[1]	4.0E-06[1]	5.0E-04[1]	2.0E-05[1]
Foundation Piping P_{PA}	pre 1930	N/A	7.0E-06[1]	N/A	6.0E-05[2]
	1930-present	2.0E-05[1]	4.0E-06[1]	5.0E-04[1]	2.0E-05[1]
Within Dam Body P_{BA}	pre 1930	N/A	7.0E-06[1]	N/A	2.0E-04[2]
	1930-present	9.0E-05[2]	4.0E-06[1]	5.0E-04[1]	2.0E-04[2]

Note: (1) No failures, probability estimated lower than that for one failure.
(2) Probability rounded down to account for the smaller than actual population used in the analysis.

Table 58. Annualised Probabilities of Failure for Gravity Dams - All Failures

Year	Concrete Gravity			Masonry Gravity		
Commissioned	0-5 years	>5 years	Total	0-5 years	>5 years	Total
1700-1799	NF	NF	NF	5.9E-03	NF	1.2E-04
1800-1899	NF	NF	NF	7.5E-03	5.5E-04	7.9E-04
1900-1909	3.0E-03	3.7E-04	5.2E-04	NF	2.7E-04	2.6E-04
1910-1919	1.3E-03	8.9E-05	1.7E-04	3.8E-03	2.7E-04	5.0E-04
1920-1929	6.0E-04	4.9E-05	9.0E-05	5.4E-03	4.4E-04	8.1E-04
1930-1939	NF	NF	NF	6.0E-03	NF	5.3E-04
1940-1949	NF	NF	NF	NF	NF	NF
1950-1959	NF	NF	NF	NF	NF	NF
1960-1969	5.3E-04	6.1E-05	1.5E-04	NF	2.4E-03	1.9E-03
1970-1977	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	NF	NF	NF
1983-1992	NF	NF	NF	NF	NF	NF
1700-1929	1.0E-03	9.2E-05	1.5E-04	5.1E-03	3.4E-04	5.4E-04
1930-1992	1.4E-04	1.4E-05	3.4E-05	1.6E-03	2.4E-04	4.2E-04
Total	2.9E-04	4.3E-05	7.5E-05	4.0E-03	3.3E-04	5.2E-04

Table 59. Annualised Probabilities of Failure for Gravity Dams - Sliding Failures

Year	Concrete Gravity			Masonry Gravity		
Commissioned	0-5 years	>5 years	Total	0-5 years	>5 years	Total
1700-1799	NF	NF	NF	NF	NF	NF
1800-1899	NF	NF	NF	1.9E-03	NF	6.6E-05
1900-1909	3.0E-03	3.7E-04	5.2E-04	NF	NF	NF
1910-1919	NF	NF	NF	3.8E-03	NF	2.5E-04
1920-1929	6.0E-04	4.9E-05	9.0E-05	NF	NF	NF
1930-1939	NF	NF	NF	NF	NF	NF
1940-1949	NF	NF	NF	NF	NF	NF
1950-1959	NF	NF	NF	NF	NF	NF
1960-1969	NF	NF	NF	NF	NF	NF
1970-1977	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	NF	NF	NF
1983-1992	NF	NF	NF	NF	NF	NF
1700-1929	6.7E-04	6.9E-05	1.1E-04	1.5E-03	NF	6.0E-05
1930-1992	NF	NF	NF	NF	NF	NF
Total	1.2E-04	2.6E-05	3.7E-05	1.0E-03	NF	5.2E-05

Table 60. Annualised Probabilities of Failure for Gravity Dams - Piping Failures

Year	Concrete Gravity			Masonry Gravity		
Commissioned	0-5 years	>5 years	Total	0-5 years	>5 years	Total
1700-1799	NF	NF	NF	5.9E-03	NF	1.2E-04
1800-1899	NF	NF	NF	1.9E-03	NF	6.6E-05
1900-1909	NF	NF	NF	NF	NF	NF
1910-1919	1.3E-03	NF	8.3E-05	NF	NF	NF
1920-1929	NF	NF	NF	NF	NF	NF
1930-1939	NF	NF	NF	NF	NF	NF
1940-1949	NF	NF	NF	NF	NF	NF
1950-1959	NF	NF	NF	NF	NF	NF
1960-1969	NF	NF	NF	NF	NF	NF
1970-1977	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	NF	NF	NF
1983-1992	NF	NF	NF	NF	NF	NF
1700-1929	3.3E-04	NF	2.2E-05	1.5E-03	NF	6.0E-05
1930-1992	NF	NF	NF	NF	NF	NF
Total	5.8E-05	NF	7.5E-06	1.0E-03	NF	5.2E-05

Table 61. Annualised Probabilities of Failure for Gravity Dams - Dam Body Tension/Shear Failures

Year	Concrete Gravity			Masonry Gravity		
Commissioned	0-5 years	>5 years	Total	0-5 years	>5 years	Total
1700-1799	NF	NF	NF	NF	NF	NF
1800-1899	NF	NF	NF	1.9E-03	2.7E-04	3.3E-04
1900-1909	NF	NF	NF	NF	NF	NF
1910-1919	NF	NF	NF	NF	NF	NF
1920-1929	NF	NF	NF	NF	4.4E-04	4.1E-04
1930-1939	NF	NF	NF	NF	NF	NF
1940-1949	NF	NF	NF	NF	NF	NF
1950-1959	NF	NF	NF	NF	NF	NF
1960-1969	2.7E-04	NF	4.9E-05	NF	2.4E-03	1.9E-03
1970-1977	NF	NF	NF	NF	NF	NF
1978-1982	NF	NF	NF	NF	NF	NF
1983-1992	NF	NF	NF	NF	NF	NF
1960-1982	1.6E-04	NF	3.6E-05	NF	1.8E-03	1.4E-03
1960-1992	1.3E-04	NF	3.4E-05	NF	1.8E-03	1.3E-03
1700-1929	NF	NF	NF	7.3E-04	1.6E-04	1.8E-04
1930-1992	7.0E-05	NF	1.1E-05	NF	2.4E-04	2.1E-04
Total	5.8E-05	NF	7.5E-06	5.0E-04	1.6E-04	1.8E-04

Table 62. Number of Failures During Overtopping where Failure Mode was Unknown

Year	Concrete Gravity			Masonry Gravity		
Commissioned	0-5 years	>5 years	Total	0-5 years	>5 years	Total
1700-1799	NF	NF	NF	NF	NF	NF
1800-1899	NF	NF	NF	NF	4	4
1900-1909	NF	NF	NF	NF	1	1
1910-1919	NF	NF	NF	NF	1	1
Total	NF	NF	NF	NF	6	6

Table 63. Number of Failures where Failure Mode was Unknown

Year Commissioned	Concrete Gravity			Masonry Gravity		
	0-5 years	>5 years	Total	0-5 years	>5 years	Total
1800-1899	NF	NF	NF	2	NF	2
1910-1919	NF	1	1	NF	NF	NF
1920-1929	NF	NF	NF	1	NF	1
1930-1939	NF	NF	NF	1	NF	1
1960-1969	1	1	2	NF	NF	NF
1930-1992	1	1	2	1	NF	1
Total	1	2	3	4	NF	4

4.2 General Approach for Estimating the Probability of Failure for Individual Gravity Dams

Not all dams can be considered as 'average'. Corrections can be made to the average probabilities so that they can be used for particular dams. The following describes a method to assess multiplication factors for concrete and masonry gravity dams that can be applied to the 'average' probabilities from the previous section for better or worse than 'average' dams. The method is for gravity dams that have a straight axis (no curvature) and are not post-tensioned.

Where a dam is constructed of masonry but can be shown to be of a quality comparable to that of a good concrete gravity dam, the average annual probability may be taken as somewhere between that for masonry and that for concrete.

Where a dam has been raised and the full supply level (FSL) increased, the dam should be treated as a 'new' dam and the age of the dam calculated from this time. That is, the dam should fall back into the 0-5 years category. This stems from the Section 3.4 that showed that dams have generally failed at or just above their highest recorded water level.

If the dam is of good design, is very well drained, has good uplift monitoring AND the dam foundation has been assessed by a suitably qualified rock mechanics practitioner and found to easily satisfy present day standards then a reduction factor, f_{red}, of between **0.9** and **0.1** can be used. This factor should be applied to the annual probability of failure in Equation 6. This factor can NOT be applied to dams with soil foundations and should NOT be used for initial dam screening assessments where the data available and the level of investigation and analysis are limited.

4.3 Details of the Method for Estimating the Probability of Failure for Individual Gravity Dams

The following summarises the suggested procedure for estimating the annual probability of failure of a concrete or masonry gravity dam. The annual probability of failure of the dam, P, should be calculated as the sum of the probabilities of failure for sliding, piping and through the dam body.

- Sliding through the foundation:

Step (1) Determine the average annual probability of failure, P_{SA}, from Table 57 in Section 4.1.5.
(2) Determine the multiplication factor for sliding on a soil or rock foundation, f_{SF}, from Table 69 in Section 4.4.1.
(3) If the foundation is rock go to Step (4), if it is soil go to Step (5).
(4) Determine the geology type factor, $f_{SG,}$ from Table 72 in Section 4.4.2, then go to Step (6)
(5) $f_{SG} = 1.0$
(6) Determine the structural height/width factor, $f_{H/W}$, from Table 74 in Section 4.4.4.
(7) Determine the other observations factor, f_O, from Section 4.4.5.
(8) Determine the surveillance factor, f_S, from Table 75 in Section 4.4.6.
(9) Calculate the probability of a foundation sliding failure as:

$$P_S = P_{SA} \times f_{SF} \times f_{SG} \times f_{H/W} \times f_O \times f_S \tag{3}$$

- Piping through the foundation:

Step (1) Determine the average annual probability of failure, P_{PA}, from Table 57 in Section 4.1.5.
(2) Determine the multiplication factor for piping on a soil or rock foundation, f_{PF}, from Table 69 in Section 4.4.1.
(3) If the foundation is rock go to Step (4), if it is soil go to Step (5).
(4) Determine the geological environment, $f_{GE,}$ factor from Section 4.4.3, then go to Step (6).
(5) $f_{GE} = 1.0$
(6) Determine the structural height/width factor, $f_{H/W}$, from Table 74 in Section 4.4.4.
(7) Determine the other observations factor, f_O, from Section 4.4.5.
(8) Determine the surveillance factor, f_S, from Table 75 in Section 4.4.6.
(9) Calculate the probability of a foundation piping failure as:

$$P_P = P_{PA} \times f_{PF} \times f_{GE} \times f_{H/W} \times f_O \times f_S \tag{4}$$

- Failure through the dam body:

Step (1) Determine the average annual probability, $P_{BA,}$ of failure from Table 57 in Section 4.1.5.
(2) Determine the structural height/width factor, $f_{H/W}$, from Table 74 in Section 4.4.4.
(3) Determine the other observations factor, f_O, from Section 4.4.5.
(4) Determine the surveillance factor, f_S, from Table 75 in Section 4.4.6.
(5) Calculate the probability of a failure through the dam body as:

$$P_B = P_{BA} \times f_{H/W} \times f_O \times f_S \tag{5}$$

- Total annual probability of failure:

$$P = f_{red}\left(P_S + P_P + P_B\right) \tag{6}$$

where,

f_{red} = Reduction factor, only applied when conditions described in Section 4.2 are satisfied.

4.4 Gravity Dam Probability Multiplication Factors

The following outlines the basis for assigning the multiplication factors. The factors, where possible, have been based on the failure statistics in the previous sections. Where necessary the accident statistics have been used to assist in developing the multiplication factors. It should be noted however, that most of the dam accidents were 'theoretical' (eg. a calculation was performed that indicated the dam was unsafe and it was anchored) and as such of little value to this exercise.

4.4.1 Soil/Rock Foundation Factor, f_{SF} and f_{PF}

The probability of a dam failing through the foundation is highly dependent on whether the foundation is soil and/or rock. An estimation of the multiplication factors for sliding and piping of gravity dams on soil and rock foundations is outlined below.

The percentage of soil and rock foundations in the world population was estimated from the USBR, Australia/New Zealand, and Portugal populations (Tables 64-66) and is shown in Table 67. It is recognised that this may be a somewhat biased sample but there was no way of practically obtaining data for a larger population.

Table 64. Foundation Types - USBR

Foundation	Gravity	Arch	Buttress	Multi-Arch	Total
Rock	18	31	6	-	55
Soil	1	-	1	-	2
Soil and Rock	2	-	-	-	2
Total	21	31	7	-	59

Table 65. Foundation Types - Australia/New Zealand

Foundation	Gravity	Arch	Buttress	Multi-Arch	Total
Rock	84	40	6	1	131
Soil	-	-	-	-	0
Soil and Rock	3	-	-	-	3
Total	87	40	6	1	134

Table 66. Foundation Types - Portugal

Foundation	Gravity	Arch	Buttress	Multi-Arch	Total
Rock	26	20	4	2	52
Soil	-	-	-	-	0
Soil and Rock	1	-	-	-	1
Unknown	1	-	-	-	1
Total	28	20	4	2	54

Table 67. Gravity Dam Foundation Types - Combined

Foundation	Number	%
Rock	128	94.1
Soil	1	0.7
Soil and Rock	6	4.4
Unknown	1	0.7
Total	136	100

The number of failures (both sliding and piping) in a particular foundation type is shown below.

Table 68. Foundations for Gravity Dam Failures by Sliding or Piping

Foundation	Piping		Sliding	
	PG	PG(M)	PG	PG(M)
Rock			5	2
Soil		2		
Soil and Rock	1			
Total	1	2	5	2

To determine the factors for soil and rock the following assumptions were made:

- All piping failures occurred through the soil section of the foundation.
- Combined soil/rock (S/R) foundations are taken as soil.
- Unknown foundation types are rock.

The factors were calculated as:

$$f = \frac{percent\ of\ failures}{percent\ of\ population} \tag{7}$$

For example, the factor for piping through soil foundations is:

$$f_{PF} = \frac{100\%}{5.1\%} = 19.6 \tag{8}$$

Where there are no failures (0%) the factor is zero. To overcome this problem it was assumed that 1% of all foundation failures would occur on this particular foundation type. The results of this analysis are shown in Table 69. Table 69 shows that the factor for sliding on rock is greater than that for soil. This can be justified by the fact that no sliding failures have occurred on soil. It is likely that engineers have taken the soil into account in the dam design whereas, there may be defects which drastically reduce the foundation strength, in a rock foundation that may be overlooked in the design. Historically no gravity dam piping failures have occurred in rock foundations. A number of accidents have occurred as shown in Table 70. It is likely that there is sufficient warning of the progression of piping through rock foundations to allow for action to be taken to prevent failure.

Table 69. Gravity Dam Factors for Piping and Sliding Failure on Soil and Rock, f_{SF} and f_{PF}

Foundation	Piping, f_{PF}	Sliding, f_{SF}
Rock	0.01*	1.1
Soil or Soil and Rock	19.6	0.2*

* *These values were derived by assuming 1% failures.*

Table 70. Foundation Types - Accidents

Foundation	Piping		Sliding	
	PG	PG(M)	PG	PG(M)
Rock	9	1	5	1
Soil	1			
Soil and Rock				
Unknown	1			
Total	11	1	5	1

4.4.2 Geology Types - Sliding on Rock, f_{SG}

Some rock types are more likely to have weaknesses in the foundation (Fell *et al*, 1992), so a geology type factor has been included. The geology population was calculated from a weighted average of the representative populations from the USBR, Australia/New Zealand and Portugal. The population for the whole of the USA was assessed by considering the overall geology map of the USA and comparing the distribution of geology types west of longitude 100°W (where the USBR population lies) with that east of longitude 100°W. A weighted average population was created using the number of gravity dams in the respective countries as given in ICOLD (1984) as weighting factors. Equation 9 shows the method used. Table 71 gives the weighting factors used in the analysis. Table 73 shows the weighted population and the number of sliding failures in each foundation. The calculated and adopted sliding factors are also included. Table 72 shows a summary of the factors adopted. Where there is a high chance of a through going defect beneath the dam a factor of **3** should be used. The following points should be noted:

- There were three failures in sandstone/shale foundations and none in sandstone alone.
- There was one failure in a combined limestone/dolomite foundation.

$$G = \frac{G_1\alpha_1 + G_2\alpha_2 + G_3\alpha_3}{G_1 G_2 G_3} \tag{9}$$

where,

G is the weighted geology type population
G_1, G_2 and G_3 are the geology type populations for each region
α_1, α_2 and α_3 are the weighting factors

Table 71. Weighting Factors used for Weighted Average (ICOLD (1984) Dam Population)

Population	α
Australia/ New Zealand	81
Portugal	27
USA	528

Table 72. Adopted Gravity Dam Factors for Sliding on a Rock Foundation, f_{SG}

Geology Type	Multiplication Factor	Comments
shale, claystone sandstone with shale interbeds limestone with shale interbeds default for sandstone	3	Where a dam is known to be on sandstone but it can not be proved that no shale/claystone exists then the default of **3** should be taken.
mudstone, siltstone, conglomerate schist, gneiss, phyllite, slate hornfels, limestone, dolomite	1.5	Mudstone and siltstone represent a transition from shale to sandstone. Others based on failure statistics.
granite granodiorite	0.3	A low factor has be deemed appropriate as there have been no sliding failures on granite yet there exists a large population of dams.
others	0.9	Where it can be proved that the dam foundation comprises ONLY sandstone 0.9 can be used else, a factor of 3 should be taken

Table 73. Gravity Dam Factors for Sliding on a Rock Foundation

Geology Type	Population %	Failures No.	%	Factors Calculated	Adopted	Comments
Total	100	13	100			
Sandstones	21.1	3	23.1	1.1	0.9	No sandstone *only* failures so treated as no failures
Shale	8.0	4	30.8	3.9	3	Based on failure data, includes shale & sandstone
Siltstone	0.5		0.0	0.0	1.5	Assumed transitional between shale & sandstone
Conglomerate	3.6	1	7.7	2.1	1.5	Based on failure data
Limestone	3.6	1	7.7	2.1	1.5	Based on failure data
Claystone	0.3		0.0	0.0	3	Similar properties to shale
Mudstone	0.4		0.0	0.0	1.5	Assumed transitional between shale & sandstone
Chert	0.2		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Breccia	0.2		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Dolomite	3.6	1	7.7	2.1	1.5	Based on failure data
Marl	3.6		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Schist	11.4	2	15.4	1.4	1.5	Based on failure data
Quartzite	0.8		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Gneiss	0.7		0.0	0.0	1.5	Similar properties to schist
Phylitte	0.5		0.0	0.0	1.5	Similar properties to schist
Slate	0.3		0.0	0.0	1.5	Similar properties to schist
Hornfels	3.3	1	7.7	2.4	1.5	Based on failure data
Argillite	0.1		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Granite	20.1		0.0	0.0	0.3	Factor would be 0.4 assuming 1 failure
Basalt	5.0		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Tuff	2.4		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Dolerite	0.8		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Rhyolite	1.9		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Andesite	0.3		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Porphyry	0.2		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Diorite	3.4		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Granodiorite	0.3		0.0	0.0	0.3	Similar properties to granite
Greenstone	3.4		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Agglomerate	0.1		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$
Pumice	0.1		0.0	0.0	0.9	No fails so adjusted such that $\Sigma(Pop \times Factor) \approx 1$

4.4.3 Geology Type - Piping on Rock, f_{GE}

As there have been no piping failures of concrete dams on rock foundations it was decided to take all factors as unity. Another factor, which takes account of problem geological environments, was used as a better indicator of variations of likelihood of failure from the average. The environments considered for this were those that allowed for the possibility of open joints and include:

- Granitic foundations with sheet joints;
- very steep sided narrow valleys with likely stress relief joints parallel to the ground surface;
- sedimentary sequences with stress relief effects;
- very weak erodible volcanics; and
- limestone or dolomite. (Reference Fell, MacGregor and Stapledon, 1992)

The factor should be chosen on a site by site basis but should not exceed **2**. The minimum multiplication factor should be **1**. The default value (where the environment is unknown) should also be taken as **1**.

4.4.4 Height on Width Ratio, $f_{H/W}$

The structural height to width ratio (h_d/W) is used to take account of the stockiness/slenderness of the gravity dam. Hence the h_d/W ratio offers a first order guide to the relative likelihood of failure by sliding and within the body of the dams. A database of h_d/W ratios was collected from the Australia/New Zealand, USBR populations and from selected ICOLD international conferences (Questions 26, 30, 45, 52, 56, 59, 65). Where found, dams with any curvature were excluded. Figures 75 and 76 show scatter plots of h_d/W versus year commissioned and h_d respectively for the population and failed dams. Failures are scattered amongst the population, although the majority appear to be more concentrated above the average h_d/W ratio. The h_d/W population does not show any correlation with year commissioned. However, as h_d increases h_d/W approaches approximately 1.2. It was decided to apply factors as shown in Table 74 and Figure 77. These factors have been derived by dividing the percentage of failures (due to sliding or in the dam body) by the percentage of the population in each h_d/W range, in a similar manner to those for sliding and piping in Section 4.4.1.

Table 74. Multiplication Factors for Structural Height/Width Ratio of Gravity Dams, $f_{H/W}$

h_d/W	<1.0	1.0-1.19	1.2-1.39	1.4-1.59	1.6-1.79	1.8-1.99
Factor	0.1	0.5	0.9	1.3	3	6

Figure 43. h_d/W versus Year Commissioned

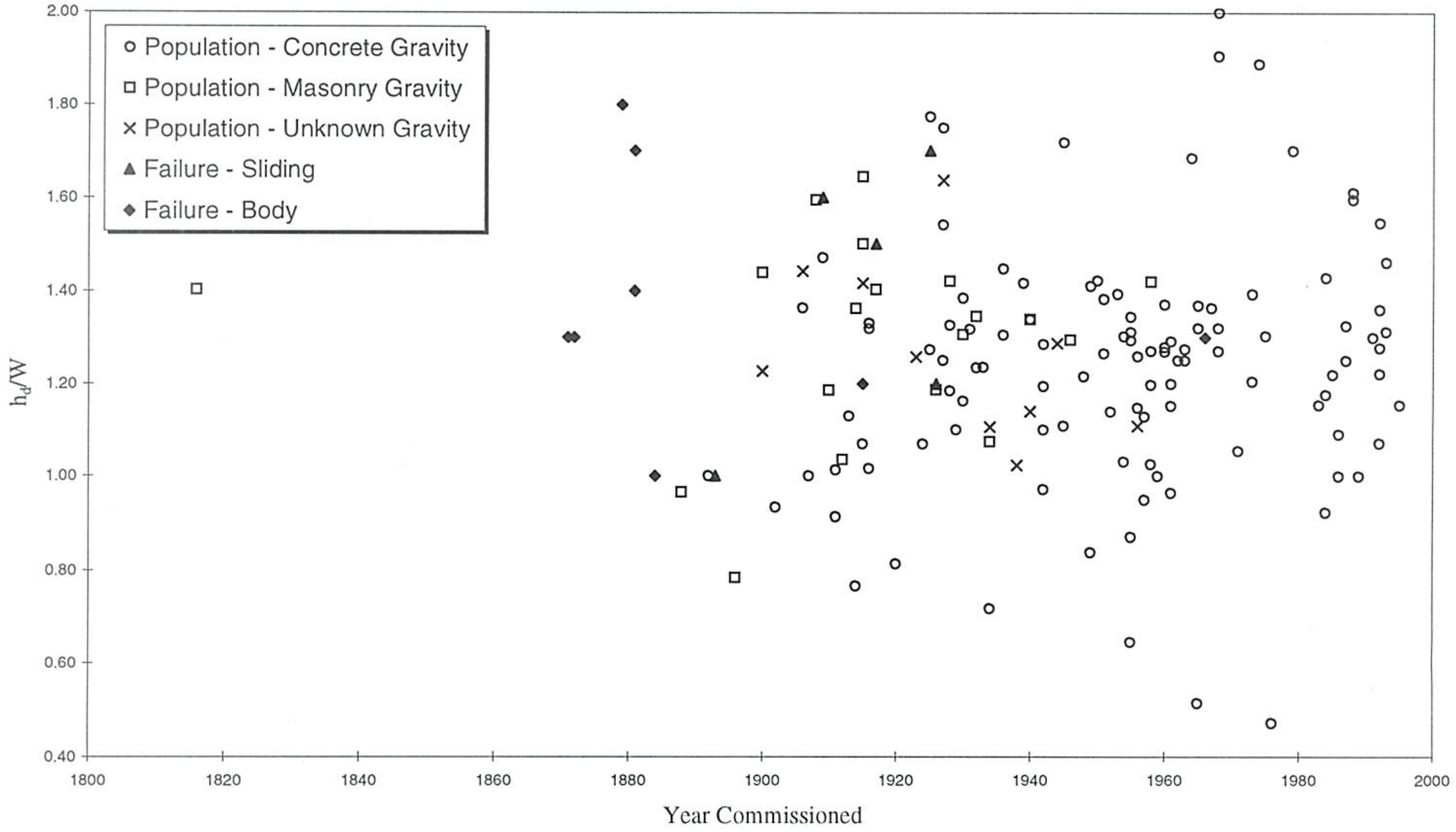


Figure 44. h_d/W versus h_d

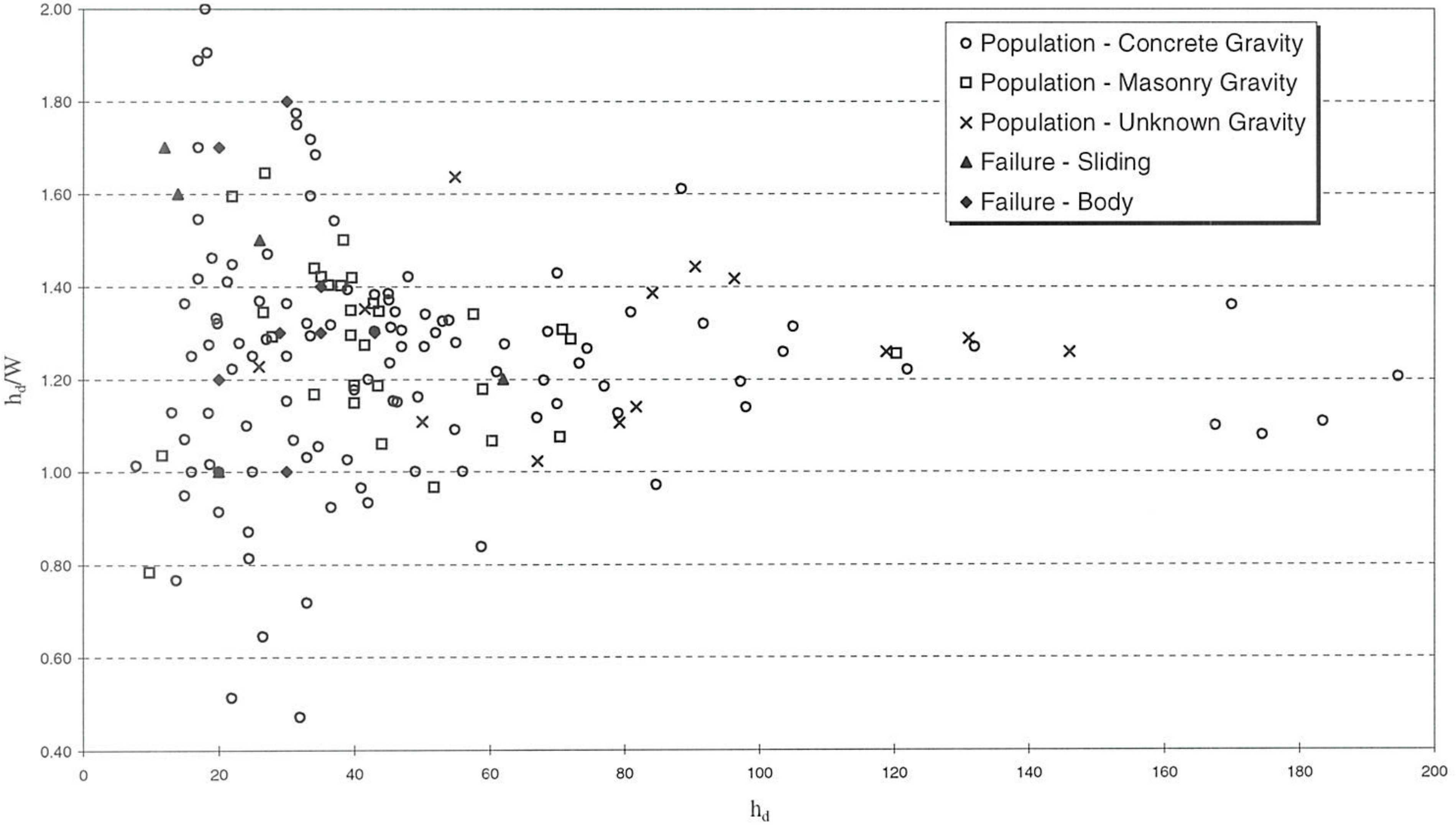
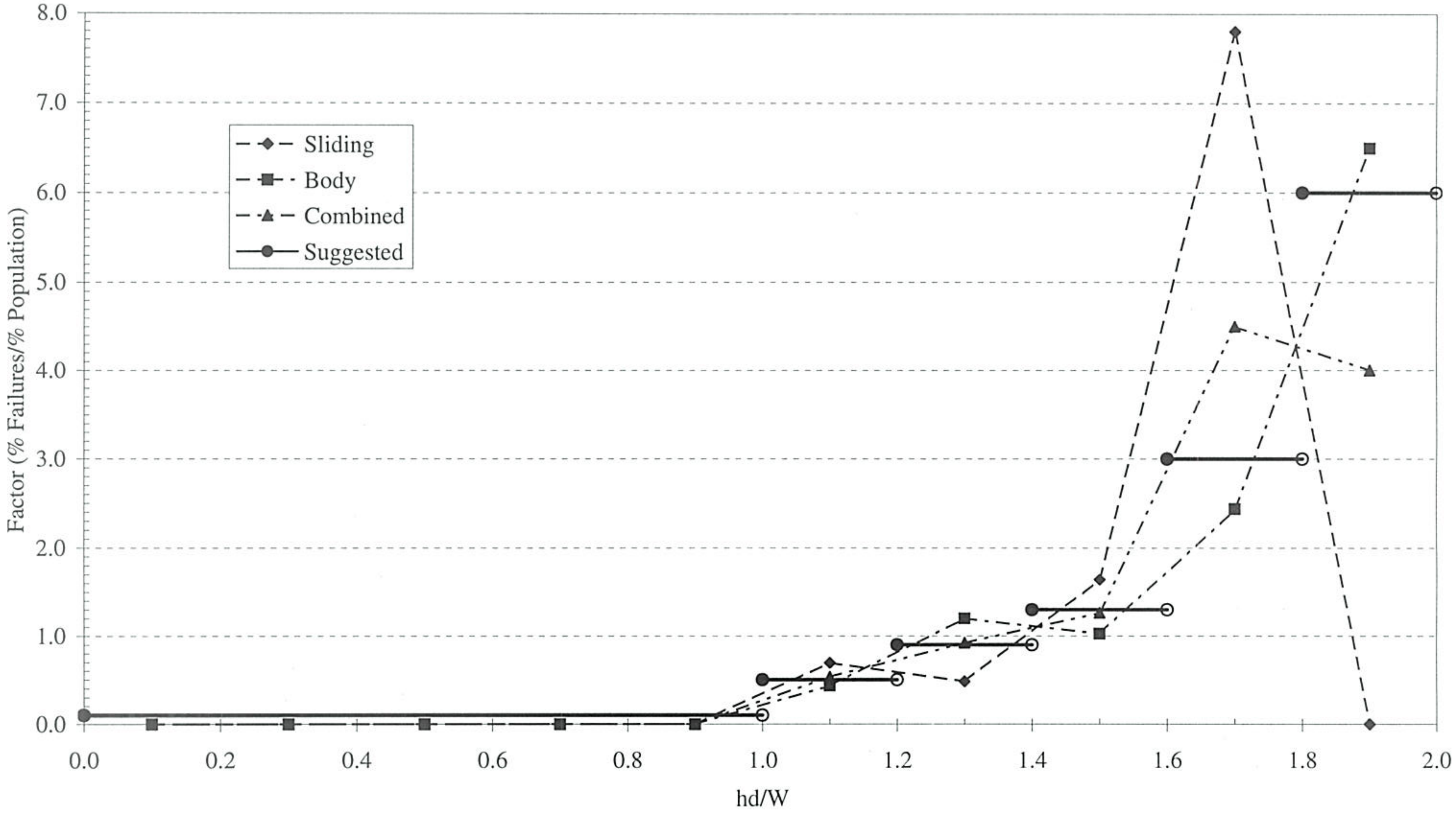


Figure 45. hd/W Factors



4.4.5 Other Observations, f_O

This section allows for a multiplication factor to be applied for observed conditions or special features of the dam. These features will vary with each dam and must be assessed on a dam by dam basis. The minimum value for any dam should be **0.9** (no signs of distress, no or very little leakage). The default value should be **1.0**. Conditions, which would warrant a higher multiplication factor (up to a maximum of 10), include:

- Sudden increases in seepage through the dam or foundation
- Cracking (of a nature that could effect the dam's stability)
- High or non-linear uplift pressures (also blocked drains)
- Alkali aggregate reaction (AAR) or alkali silica reaction (ASR)
- Extensive calcite deposits
- Large/non-linear dam movements

4.4.6 Surveillance, f_S

Historically, unlike embankment dams, most gravity dams have failed with only a short amount of warning. This warning may be enough to warn people downstream but, is usually insufficient to enable the dam to be saved from failure. However dams will sometimes begin to show some signs of problems developing, allowing intervention (eg by controlling the water level, or by remedial works). Hence it is considered reasonable to apply a factor to allow for the quality of monitoring and surveillance. Table 78 shows the multiplication factors recommended. The multiplication factors have been modified from those given by Foster *et al* (1998) for embankment dams.

Table 75. Monitoring and Surveillance Multiplication Factors, f_S

Surveillance	Embankment Dam Factor	Factor f_S
Inspections annually	2.0	1.5
Inspections monthly	1.2	1.1
Irregular seepage observations, inspections weekly	1.0	1.0
weekly seepage monitoring, weekly inspections	0.8	0.9
Daily monitoring of seepage, daily inspections	0.5	0.8

4.5 Results

Figures 1 and 2 show the potential ranges for the annual probabilities of failure for various cases. The 'average' dam has been taken as a dam that has: a geology type factor, f_{SG}, of 0.9; a height to width ratio, h_d/W, of 1.3; and the remaining multiplication factors as unity. A number of dams that have failed have been plotted together with dams from the Australia/New Zealand population and USBR population of concrete and masonry gravity dams. None of the dams plotted have the f_{red} reduction factor, as it could not be proven that they satisfied the criteria described above. Where unknown, multiplication factors were taken as their default or unity. For the most common type of dam (commissioned after 1930, greater than five years in age and on a rock foundation) the potential average probabilities using the method range from 4 x 10^{-8} to 1 x 10^{-3}.

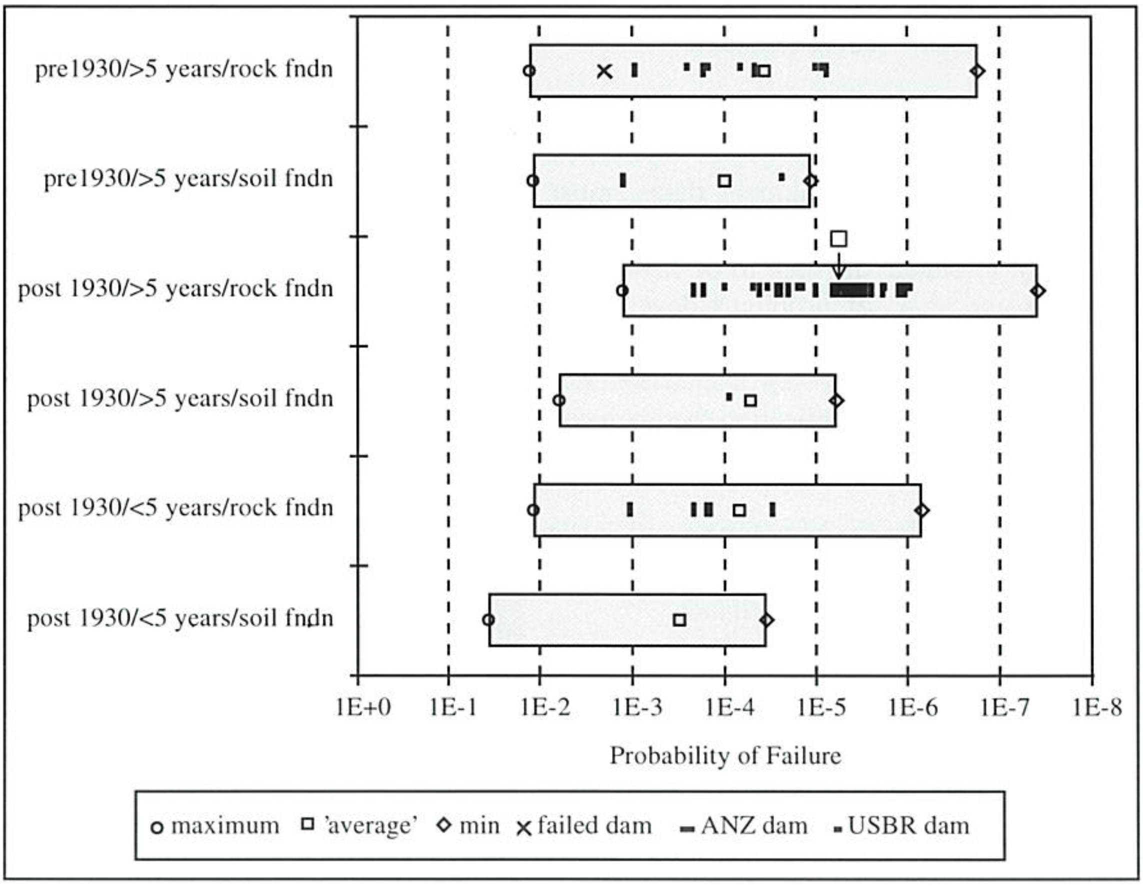


Figure 46. Range of Annual Probability of Failure for Concrete Gravity Dams

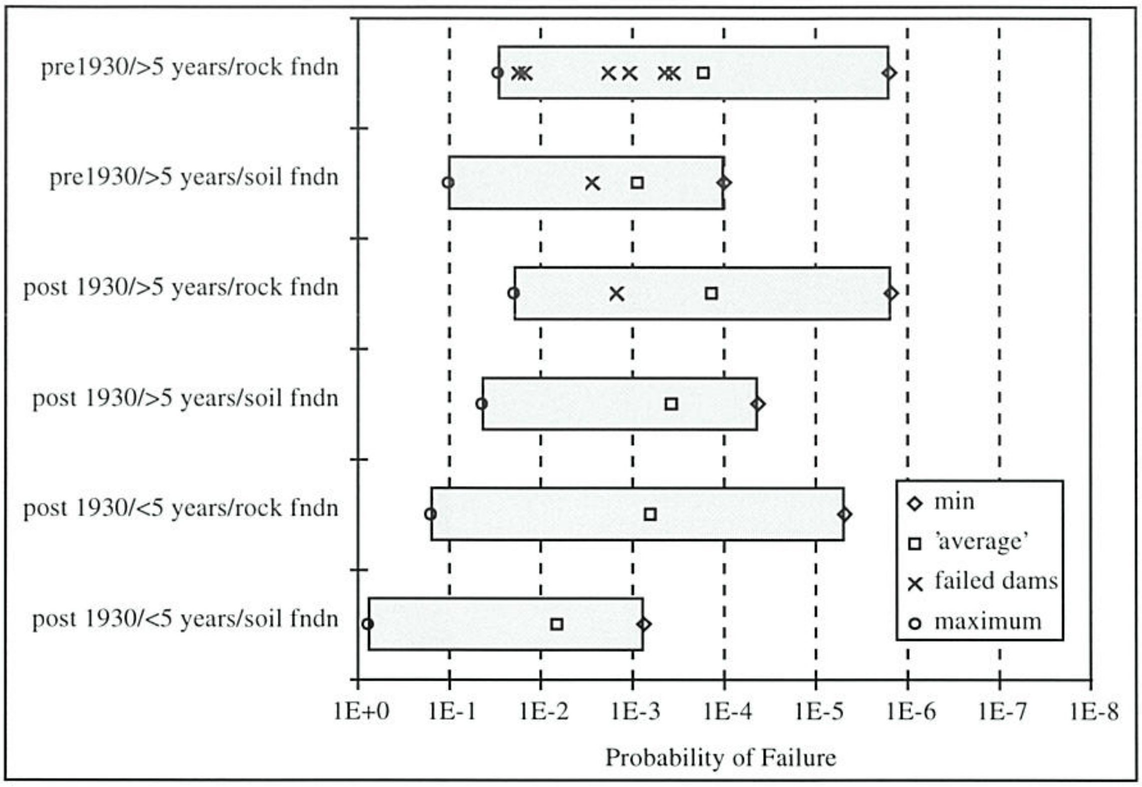


Figure 47. Range of Annual Probability of Failure for Masonry Gravity Dams

5 DISCUSSION AND CONCLUSIONS

Most of the results have been discussed to some degree in Chapter 3. Below is a brief discussion of the major components of *CONGDATA*.

- *Year commissioned*

The data shows a distinct increase in incidents for all concrete/masonry dam types in the 1920's. Another peak occurred in the 1960's for concrete gravity and concrete arch dams. There were no failures in gravity dams commissioned between 1930 and 1963. Based on the population data there appears to be a reduction in the failure rate with time. Buttress and multi-arch dams show some various peaks due to their limited populations.

- *Height*

No concrete or masonry dams greater than 70m are reported to have failed. Failures in masonry gravity dams appear to be concentrated below 50m in height. Concrete gravity dams tend to be spread out more. Accidents and more particularly major repairs are more evident in greater height concrete dams than masonry gravity dams. This however, is likely to be due to the lower height at which masonry dams are constructed.

The ratio of failures to population does not exhibit any major trend. There appears to be a higher percentage of failures to population in the 40-49m and 60-69m height ranges. Arch, buttress and multi-arch dams are shown to be more likely to have failures in the 15-39m range.

- *Age at failure*

There is a large proportion of dams that have failed during first filling. An analysis of the water levels at failure show most dams failed at their highest recorded water level. Several of these were only slightly higher than that recorded previously. There appears to be a slight rise in the rate of failures with time (ignoring first filling). After 40 years of age there is a jump in the failure rate. It should be noted that the older age groups are represented by a small population. Concrete gravity dams of less than five years age appear to have a greater chance of failure compared to older concrete gravity dams. Masonry gravity dams are more evenly distributed throughout the ages.

A noticeable problem with the accident/major repair data is its bias to the post 1920's whereas failures occur much further back. This can be put down to a lack of detailed dam information in the period prior to 1920. Large dam failures would still have been published during these times.

Piping tends to occur early in a dams life (<5 years, with one exception). Sliding of the foundation also tends to occur early but is not as restricted as piping. Structural problems seem to be more likely than foundation problems with age. Concrete dams have a tendency to fail at younger ages than masonry dams. Most older (masonry) dam failures have overtopping as a component. Unfortunately there is usually little information as to the actual mode of failure.

- *Incident causes*

Foundation problems (sliding, leakage and piping) are the main causes of failure to concrete dams, overtopping tends to play a bigger part in the failure of masonry dams. Accidents and major repairs are more likely to come about due to surficial damage to the dam structure or noticeable uplift or leakage in the foundation.

Piping is the main cause of failure for dams with soil foundations. Overtopping and foundation shear strength are the main causes of failure for dams with rock or unknown foundations.

- *Warning types*

Overtopping was the most common failure warning type. This was mainly due to the masonry gravity dams which are more susceptible to overtopping failure. This could be due to the poorer quality downstream face of masonry dams which can be eroded during overtopping events and/or the higher permeability of masonry dams which results in a more rapid increase in uplift pressures. For accidents, and even more so for major repairs, the warning signs tend to be visual damage of the dam or excessive leakage.

An analysis of all dam failures showed that, where information was available, most had some warning which could have resulted in the warning and evacuation of residents downstream. Often the warning was a sudden increase in the amount and rate of leakage.

- *Remedial measures*

Where a dam has failed it is usually abandoned or reconstructed with a new design. In the case of accidents and major repairs it is most common that the damaged section is replaced with no effect to the dam structure as a whole.

- *Geology*

Soils and limestones are more likely to have piping problems. The alluvial soils have a tendency to pipe under the high gradients imposed. No dam has been reported to have failed by sliding on alluvial soils. Normally a large concrete or masonry dam would not be built on a soil foundation.

Shale (interbedded with other sedimentary units) has a greater tendency to be involved with sliding failure because of the likely presence of weaknesses in the bedding such as bedding surface shears. It is interesting that sandstone does not appear to be over represented when the population is taken into account. Failures tend not to occur in sandstone alone but only when the sandstone is interbedded with shale. Shale and limestone (often interbedded) have a high incidence for failing. The limestone has a high proportion of accidents generally due to excessive leakage through dissolution. Another point of note is that no incidents have occurred in basalt foundations. These conclusions agree with the general knowledge regarding the geology types (e.g. as described in Fell *et al*, 1992[11]).

- *Other design factors*

The factors in Section 3.9 suffered from a lack of information. Generally these could only be obtained if a dam's cross section was available. From the data collected it appears that the failed dams suffered from a lack of 'good engineering'. Very few dams were found with galleries (1 dam); drainage (1 dam); grout curtains (4 dams);and shear keys (1 dam). The downstream slopes appeared to be too steep. Six gravity failures had downstream slopes of 0.6:1 (H:V) or less. Failed dams, particularly gravity dams, were usually located in relatively wide valleys or were composite sections with earthfill dams. Three dimensional effects are unlikely to have contributed any strength in these cases. h_{wf}/W ratios ranged from 0.6 to 2.1 with an average of 1.35.

Generally, unlike embankment dams, concrete and masonry dams are analysable and hence can readily be checked for stability. The major unknowns for these dams lie in the foundation where sliding and piping failures can occur.

Section 4 gives a method for assessing the first order probability of failure of masonry or concrete gravity dams. The method accounts for dam age, year commissioned and type; failure mode; foundation geology; height to width ratio; and monitoring and surveillance. General probabilities of failure for arch, buttress and multi-arch dams, based on failure and population statistics, are included.

The authors caution that this approach should only be used as a first order approximation of the annual probabilities of failure. It is clearly very approximate, and suffers from being based on small numbers of failures, and limited quality data. Where significant decisions on dam safety are being made, detailed deterministic and/or probabilistic methods should be used.

The results from the analysis of *CONGDATA* are subject to the limitations mentioned earlier. Whilst all care has been taken in compiling data, it should be remembered that the information in *CONGDATA* has come from numerous sources, not all of which could be validated. The analysis of dams in CONGDATA does not take into account such things as: surveillance; quality of construction; and quality of geological description. It is therefore recommended that this work be used in a qualitative sense only.

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- Goulburn Murray Water;
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APPENDICES

APPENDIX A: REFERENCES BY FAILED DAM NAME

Angels **USA**

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Gleno **Italy**

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Torrejon Tajo **Spain**

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Vega de Tera **Spain**

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Xuriguera **Spain**

Berga, L. (1997) Failures and hydrological incidents of dams in Spain. In *Dix-neuvième Congrès des Grands Barrages*, Florence, ICOLD. Vol. Q75 pp. 417-430.

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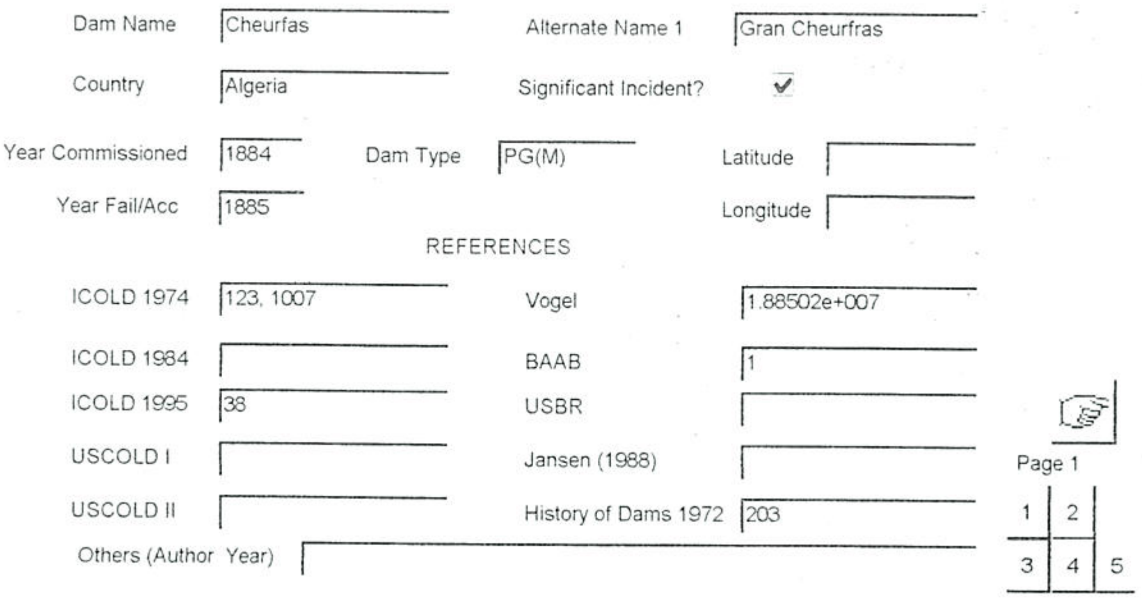
APPENDIX B: SAMPLE FORMS FOR CONGDATA



Dam Name Cheurfas

Alternate Name 1 Gran Cheurfras

Country Algeria

Significant Incident? ☑

Year Commissioned 1884

Dam Type PG(M)

Latitude

Year Fail/Acc 1885

Longitude

REFERENCES

ICOLD 1974 123, 1007

Vogel 1.88502e+007

ICOLD 1984

BAAB 1

ICOLD 1995 38

USBR

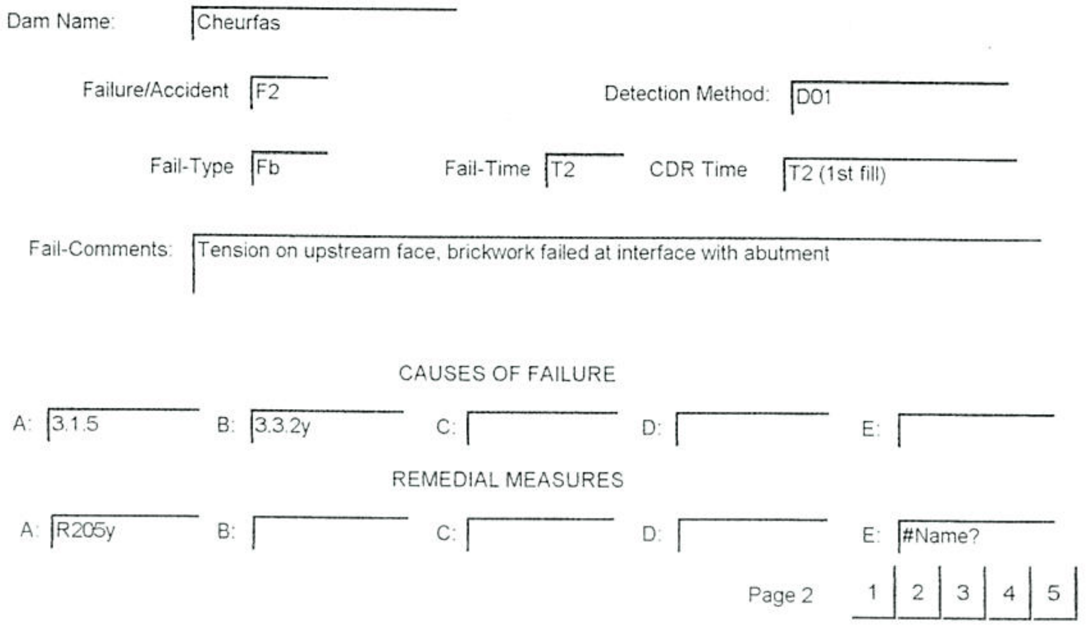
USCOLD I

Jansen (1988)

USCOLD II

History of Dams 1972 203

Others (Author Year)



Dam Name: Cheurfas

Failure/Accident F2

Detection Method: D01

Fail-Type Fb

Fail-Time T2

CDR Time T2 (1st fill)

Fail-Comments: Tension on upstream face, brickwork failed at interface with abutment

CAUSES OF FAILURE

A: 3.1.5

B: 3.3.2y

C:

D:

E:

REMEDIAL MEASURES

A: R205y

B:

C:

D:

E: #Name?

CONGDATA1

Page 2 of 935

Dam Name: Cheurfas

Concrete/ Masonry: Stone mas.

FOUNDATION

Geology A: Limestone

Geology B:

Geology C:

Geology Comments: Some medium caverns in limestone

Rock/Soil: R

HEIGHTS

Hlowfndn(m): 42

Hd (m):

hFSL (m):

htoe (m):

Hfail (m):

hwf (m):

WIDTHS

W (m):

Wfail (m):

SLOPES

Upstream (xH:1V):

Downstream (yH:1V):

Page 3

1 2 3 4 5

Dam Name: Cheurfas

WIDTH

Spillway (m):

Non-Overflow Section (m):

Width of Failed Section:

Where Failed:

VALLEY SHAPE

L1 (m): 155

L2 (m):

L3 (m):

L4 (m):

Shear Key (Yes/No): No

Radius of Curvature (m):

Gallery (Yes/No): No

Gallery Elevation:

Drain Depth (m):

Drain Spacing (m):

Grouting Type: Curtain

Grout Depth:

Page 4

1 2 3 4 5

Dam Name: Cheurfas

Warning Type 1:

Warning Time (weeks)

Warning Type 2:

Post-Tensioned? (Y/N)

Warning Type 3:

No. of victims: 10

Page 5

1 2 3 4

APPENDIX C: PARAMETERS IN CONGDATA

Variable	Description	Codes
ID	Identification number	
Significant Incident? (Y/N)	Whether incident is significant	
Dam Name	Name of dam	
Country	Country dam is in	
Alternate Name 1	Other name	
Dam Type	Type of dam	Section 2.3.2
Year Commissioned	Year dam commissioned	
Fail Acc	Year of incident	
Failure/Accident	Incident Category	Section 2.3.1
Fail-Time	Time to incident	Section 2.3.3
CDR Time	Time to incident	Section 2.4.1
Fail-Type	Where incident occurred	
Fail-Mode	How incident occurred	
Cause A-E	Causes of incident	Tables 1-5
Detection Method	Method of detecting incident	
Fail-Comments	Comments about incident	
Remedial Measures A-D	Methods of remediation	Table 6
Concrete/ Masonry	Type of concrete/masonry	
Foundation	Whether foundation soil/rock	Section 2.3.5
Geology A-C	Types of foundation geology	Section 2.4.4
Geology Comments	Comments about foundation	
Hlf(m)	Height above lowest foundation	Figure 1
Hd (m)	Structural height	Figure 1
hwu (m)	Height of water upstream - FSL	Figure 1
hwt (m)	Height of water at toe	Figure 1
Hf (m)	Height to failure plane	Figure 1
hwf (m)	Height of water at failure	Figure 1
W (m)	Width of dam base	Figure 1
Wf (m)	Width at failure plane	Figure 1
Width of Spillway (m)	Length of spillway	
Width of Non-Overflow Section (m)	Crest length - spillway	
Width of Failed Section	Length of failed section	
Where Failed	Location of failure	
Upstream (xH:1V)	Upstream slope of dam	Figure 1
Downstream (yH:1V)	Downstream slope of dam	Figure 1
Valley Shape, L1 (m)	Crest length	Figure 2
L2	Left abutment length	Figure 2
L3	Main valley width	Figure 2
L4	Right abutment length	Figure 2
Radius of Curvature (m)	Radius of curvature of dam	
Warning Type 1-3	Type of warning given	Section 2.4.8
Warning Time (weeks)	Time from warning to incident	
Post-Tensioned? (Y/N)	Whether post-tensioned	
Gallery (Y/N)	Whether there is a gallery	
Gallery Elevation	Height to gallery from dam base	
Drain Depth (m)	Depth of drains into foundation	
Drain Spacing (m)	Spacing of drains along dam	
Shear Key (Y/N)	Whether there is a shear key	
Grouting Type	Type of grouting	

Variable	Description	Codes
Grout Depth	Depth of grouting into foundation	
No. of victims	Number of deaths due to incident	
References:	Main references	

APPENDIX D: DAM LIST - INCIDENTS

Table D1. Dam List - Failures

Dam Name	**Country**	**Dam Type**	**Year Commissioned**	**Year Failed**	**Hlf (m)**
Kohodiar	India	PG/TE	1963	1983	36
Zerbino	Italy	PG	1925	1935	16
Mohamed V	Morocco	PG	1966	1963	62
Torrejon-Tajo	Spain	PG	1967	1965	62
Xuriguera	Spain	PG	1902	1944	42
Bayless (A)	USA	PG	1909	1910	17
Bayless (B)	USA	PG	1909	1911	17
Elwha River	USA	PG	1912	1912	51
Hauser Lake II	USA	PG	1911	1969	40
St Francis	USA	PG	1926	1928	62
Cheurfas	Algeria	PG(M)	1884	1885	42
Fergoug I	Algeria	PG(M)	1871	1881	43
Fergoug II	Algeria	PG(M)	1885	1927	43
Habra (A)	Algeria	PG(M)	1871	1872	40
Habra (B)	Algeria	PG(M)	1872	1881	40
Habra (C)	Algeria	PG(M)	1881	1927	40
Sig	Algeria	PG(M)	1858	1885	21
Bouzey	France	PG(M)	1881	1895	26
Chickahole	India	PG(M)	1966	1972	30
Khadakwasla	India	PG(M)	1879	1961	33
Kundli	India	PG(M)	1924	1925	45
Pagara	India	PG(M)	1927	1943	30
Tigra	India	PG(M)	1917	1917	28
Santa Catalina	Mexico	PG(M)	1900	1906	15
Granadillar	Spain	PG(M)	1930	1933	22
Puentes	Spain	PG(M)	1791	1802	69
Elmali I	Turkey	PG(M)/TE	1892	1916	23
Angels	USA	PG(M)	1895	1895	16
Austin (A)	USA	PG(M)	1893	1900	21
Lower Idaho Falls	USA	ER/PG(M)	1914	1976	15
Lynx Creek	USA	PG(M)	1891	1891	15
Komoro	Japan	CB	1927	1928	16
Selsford	Sweden	CB/TE	1943	1943	21
Ashley	USA	CB	1908	1909	18
Overholser	USA	CB	1920	1923	17
Vega de Tera	Spain	CB(M)	1956	1959	35
Austin (B)	USA	CB(M)	1915	1915	20
Stony River	USA	CB(M)	1913	1914	15
Gleno	Italy	MV	1923	1923	35
Leguaseca	Spain	MV	1958	1987	20
Malpasset	France	VA	1954	1959	66
Moyie River	USA	VA	1924	1926	16
Vaughn Creek	USA	VA	1926	1926	20
Meihua	China	VA(M)	1981	1981	22
Bacino di Rutte	Italy	VA(M)	1952	1965	15
Gallinas	USA	VA(M)	1910	1957	32

Table D1. Dam List - Accidents

Dam Name	**Country**	**Dam Type**	**Year Commissioned**	**Year Accident**	**Hlf (m)**
Zardezas	Algeria	PG	1938	1932	64
Burrinjuck (C)	Australia	PG	1956		78
Chichester (B)	Australia	PG	1923		41
Don Marco	Brazil	PG	1971	1975	13
Piabanha	Brazil	PG	1908		
M'bakau	Cameroon	PG/TE	1969		
Hugh Keenleyside	Canada	PG/TE	1972	1987	58
Fengman	China	PG	1943	194?	91
Upper Glendevon	Great Britain	PG	1955	1956	55
Bhakra (A)	India	PG	1963	1959	226
Kawanata	India	PG	1965	1966	
Koshibu	India	PG	1968	1969	
Koyna	India	PG	1963	1967	103
Quarto Sul Savio	Italy	PG	1925		
Rochemolles (B)	Italy	PG	1930		63
Akiba	Japan	PG	1958		
Wachi	Japan	PG	1968	1967	25
Mullardoch	Scotland	PG	1951	1986	48
Saulsport	South Africa	PG	1968	1988	24
Agueda	Spain	PG	1931		38
Aguilar	Spain	PG	1963	1963	48
Castrelo	Spain	PG	1968		29
Mequinenza	Spain	PG	1966	1966	84
San Martin	Spain	PG	1956	1974	25
Santa Teresa	Spain	PG	1960	1963	59
Torrejon-Tajo	Spain	PG	1967		62
Villagarcia	Spain	PG	1961	1961	16
Albigna	Switzerland	PG	1959	1959	115
Raterichsboden	Switzerland	PG	1950	1962	94
Bankhead Lock	USA	PG	1915	1975	
Bartlett	USA	PG	1939	1984	88
Bingham	USA	PG	1882		10
Cedar Falls	USA	PG	1914	1918	66
Dworshak (B)	USA	PG	1972	1980	219
Folsom	USA	PG	1955	1953	104
Great Falls (A)	USA	PG	1916	1945	28
Great Falls (B)	USA	PG	1916		28
Great Falls (C)	USA	PG	1916	1925	28
Green Peter	USA	PG	1965		
Hales Bar	USA	PG	1913	1964	34
Logan Martin	USA	PG/TE	1964	1964	30
Richard B Russell	USA	PG/TE	1984	1982	
Wilbur	USA	PG	1921	1940	21
Woodbridge (A)	USA	PG	1910		10
Bouzey (A)	France	PG(M)	1881	1884	26
Blackbrook II	Great Britain	PG(M)	1906	1957	30
Bhandardara	India	PG(M)	1926	1969	82
Canada	India	PG(M)	1955	1972	

Dam Name	Country	Dam Type	Year Commissioned	Year Accident	Hlf (m)
Kuttiadi	India	PG(M)	1973	1973	36
Mulshi	India	PG(M)	1927	1966	51
Shirawata	India	PG(M)	1920	1930	39
Talakalale	India	PG(M)	1964	1964	62
Thokarwadi	India	PG(M)	1922	1925	59
Walman	India	PG(M)	1916	1932	26
Gela (A)	Italy	PG(M)	1948	1949	48
Gela (B)	Italy	PG(M)	1948		
El Gasco (B)	Spain	PG(M)	1976	1976	54
Jandula	Spain	PG(M)	1932	1962	88
Austin (C)	USA	PG(M)	1915	1935	20
Austin (D)	USA	PG(M)	1915	1937	20
New Croton	USA	PG(M)	1905	1955	90
Hsinfengkiang	China	CB	1959	1962	105
Roselend	France	CB/VA	1961		150
Olef	Germany	CB	1959	1959	59
Names of Several Schemes Omitted	Norway	CB/VA	1916		
Miranda	Portugal	CB	1961	1961	80
Estremera	Spain	CB	1950	1955	13
Ayers Islands	USA	CB	1922	1960	23
Rock Creek (1)	USA	CB/MV	1916		
Grandval (A)	France	MV	1959		88
Grandval (B)	France	MV	1959		88
La Girotte (A)	France	MV	1951		48
La Girotte (B)	France	MV	1951		48
Migoelou	France	MV	1958		29
Lago Venina	Italy	MV	1926		61
Molato (B)	Italy	MV/PG	1928		
Odivelas	Portugal	MV	1973		55
Beervlei	South Africa	MV	1957		31
Churchill	South Africa	MV	1943		40
Agnew Lake	USA	MV	1916		
Los Verjels (A)	USA	MV	1915	1965	18
Los Verjels (B)	USA	MV	1915		18
Mountain Dell	USA	MV	1917	1919	46
Murray	USA	MV	1918		35
Waddell	USA	MV	1927	1928	78
Webber	USA	MV	1924		
Honenike (A)	Japan	MV(M)	1930	1946	30
Honenike (B)	Japan	MV(M)	1930		30
Umberumba	Australia	VA	1915	1955	41
Dobra	Austria	VA	1952	1954	52
Gerlos	Austria	VA	1945	1964	39
Kolnbrein	Austria	VA	1977	1978	200
Ottenstein	Austria	VA	1956		65
Zemm	Austria	VA	1971		130
Bort-Les-Orgues	France	VA	1952		121
Gage I	France	VA	1954		47
Grangent	France	VA	1957		
Hautefage	France	VA	1958		57

Dam Name	Country	Dam Type	Year Commissioned	Year Accident	Hlf (m)
Lanau	France	VA	1962		30
Mervent	France	VA	1956		29
Monceaux-La-Virole (A)	France	VA	1946		34
Monceaux-La-Virole (B)	France	VA	1946		34
Tolla	France	VA	1961	1961	90
Vaussaire	France	VA	1953		31
Zola	France	VA	1854		42
Ambiesta	Italy	VA	1957		59
Barcis	Italy	VA	1953		50
Corfino	Italy	VA	1914		37
Flumendosa	Italy	VA	1957	1957	115
Fortezza	Italy	VA	1940		64
Maissa Di Sauris	Italy	VA	1947		136
Muro Lucano (A)	Italy	VA	1917		50
Muro Lucano (B)	Italy	VA	1917		50
Muro Lucano (C)	Italy	VA	1917		50
Ponte Della Serra	Italy	VA	1909		44
Ponte Pia	Italy	VA	1956		54
Pontesei	Italy	VA	1956		93
Senaiga	Italy	VA	1954		68
Vajont	Italy	VA	1960	1963	265
Val Gallina	Italy	VA	1951		92
Cabril	Portugal	VA	1951		136
Picote	Portugal	VA	1958		100
Bangala	Rhodesia	VA	1966		50
Kariba (A)	Rhodesia	VA	1959		128
Kariba (B)	Rhodesia	VA	1959		128
Kariba (C)	Rhodesia	VA	1959		128
Kariba Cofferdam	Rhodesia	VA	1958	1958	40
Kyle	Rhodesia	VA	1960		67
Ceres	South Africa	VA	1950		
Groendal (A)	South Africa	VA	1932		45
Groendal (B)	South Africa	VA	1932		45
Roode Els Berg	South Africa	VA	1968		72
Swart River	South Africa	VA	1955	1955	34
Canelles	Spain	VA	1960		150
Montejaque	Spain	VA	1924		74
San Esteban	Spain	VA	1955		115
Valdecanas	Spain	VA	1965		98
Grande Dixence	Switzerland	VA	1964		285
Isola	Switzerland	VA	1960		45
Les Toules	Switzerland	VA	1963		86
Palagnedra	Switzerland	VA	1953		72
Punt dal Gall	Switzerland	VA	1969		130
Santa Maria	Switzerland	VA	1968	1968	117
Zevreila	Switzerland	VA	1957		151
Zoi	Switzerland	VA	1967		36
Big Santa Anita	USA	VA	1927		72
Calderwood	USA	VA	1930	1930	71
Cushman No.1 (A)	USA	VA	1926		84
Cushman No.1 (B)	USA	VA	1926		84

Dam Name	Country	Dam Type	Year Commissioned	Year Accident	Hlf (m)
Cushman No.2	USA	VA	1930	1930	72
Donnels	USA	VA	1958		148
Early Intake	USA	VA	1925		25
Flaming Gorge	USA	VA	1964		153
Gene Wash	USA	VA	1937		42
Gibralter (A)	USA	VA	1920		50
Gibralter (B)	USA	VA	1920		50
Glen Canyon (A)	USA	VA	1964		216
Glen Canyon (B)	USA	VA	1964	1983	216
Glen Canyon (C)	USA	VA	1964		216
Kerckhoff Diversion	USA	VA	1920		33
Matilija	USA	VA	1949	1964	50
Mayfield (B)	USA	VA	1963		
Morrow Point	USA	VA	1968		143
Mountain Park	USA	VA	1975		
New Bullards Bar	USA	VA	1970		194
North Fork	USA	VA	1909	1979	63
Pacoima (A)	USA	VA	1929	1971	113
Pacoima (B)	USA	VA	1929	1994	113
Railroad Canyon	USA	VA	1928		30
Stewart Mountain (A)	USA	VA	1930		37
Warm Springs	USA	VA	1919		32
Yellowtail (A)	USA	VA	1966		160
Idbar	Yugoslavia	VA	1959	1959	39

Table D1. Dam List – Major Repairs

Dam Name	**Country**	**Dam Type**	**Year Commissioned**	**Hlf (m)**
Avon	Australia	PG	1927	72
Burrinjuck (A)	Australia	PG	1927	78
Burrinjuck (B)	Australia	PG	1956	78
Burrinjuck (D)	Australia	PG	1956	78
Cataract	Australia	PG	1907	59
Chichester (A)	Australia	PG	1923	41
Harvey	Australia	PG/TE	1930	24
Hume (C)	Australia	PG/TE	1936	51
Lake Magaret (A)	Australia	PG	1918	17
Lake Magaret (B)	Australia	PG	1918	17
Manly	Australia	PG	1892	20
Nepean	Australia	PG	1935	81
Ord Diversion	Australia	PG/ER	1963	
Warren	Australia	PG	1916	26
Wyangala - Original(A)	Australia	PG	1936	61
Wyangala - Original(B)	Australia	PG	1936	61
Wyangala - Original(C)	Australia	PG	1936	61
Erlaufklause	Austria	PG	1911	
Pack	Austria	PG/TE	1930	33
Raggal	Austria	PG	1967	
Piau	Brazil	PG	1947	
Cascade Control	Canada	PG	1942	
Cascade Powerhouse Tailrace	Canada	PG	1942	
Ghost Plant	Canada	PG	1929	
Great Falls Generating Station (A)	Canada	PG	1926	20
Great Falls Generating Station (B)	Canada	PG	1926	
Horseshoe	Canada	PG	1911	
Kananaskis	Canada	PG	1913	
Pocaterra	Canada	PG	1955	
Skins Lake	Canada	PG	1953	17
Klicava	Czechoslovakia	PG	1955	
Imatra	Finland	PG	1929	
Castelnau	France	PG	1949	
Chambon (A)	France	PG	1935	
Chambon (B)	France	PG	1935	
Eguzon (A)	France	PG	1926	61
Eguzon (B)	France	PG	1926	61
Etroit	France	PG	1933	
Guerledan (A)	France	PG	1929	54
Guerledan (B)	France	PG	1929	54
Roche-Talamie	France	PG	1931	
Sarrans	France	PG	1934	
St Etienne Cantales	France	PG	1945	
St Marc	France	PG	1930	46
Agger (A)	Germany	PG	1929	45
Agger (B)	Germany	PG	1929	45
Loch Dubh	Great Britain	PG	1955	20
Bhakra (B)	India	PG	1963	226
Altnaheglish	Ireland	PG	1934	

Dam Name	Country	Dam Type	Year Commissioned	Hlf (m)
Alpe Gera	Italy	PG	1964	
Beauregard	Italy	PG	1957	
Careser	Italy	PG	1934	66
Cavia	Italy	PG	1949	
Ceresole Reale	Italy	PG	1930	
Cignana (A)	Italy	PG	1928	
Cignana (B)	Italy	PG	1928	
Lago Nero	Italy	PG	1929	43
Morasco	Italy	PG	1940	
Nuraghe Arrubio	Italy	PG	1957	
Pian Barbellino	Italy	PG	1931	66
Pieve De Cadore	Italy	PG	1949	
Rochemolles (A)	Italy	PG	1930	63
Salto (A)	Italy	PG	1940	
Salto (B)	Italy	PG	1940	
Turano	Italy	PG	1938	75
Juso	Japan	PG	1945	16
Kakkomi	Japan	PG	1955	
Kose	Japan	PG	1940	
Miwa	Japan	PG	1959	
Moriyoshi	Japan	PG	1953	
Nakaiwa (A)	Japan	PG	1923	26
Nakaiwa (B)	Japan	PG	1923	26
Ohara Reservoir	Japan	PG	1942	
Whakamaru	New Zealand	PG/TE	1956	56
Laing	South Africa	PG	1951	
Spioenkop	South Africa	PG	1973	
Arlanzon	Spain	PG	1933	47
Cuerda del Pozo	Spain	PG	1941	
El Vado	Spain	PG	1954	
Mansilla	Spain	PG	1960	80
Maria Cristina	Spain	PG	1920	59
Villameca	Spain	PG	1947	
Barberine	Switzerland	PG	1925	
Rempen	Switzerland	PG	1924	
Schrah	Switzerland	PG	1924	
Bagnell	USA	PG	1931	45
Barker (A)	USA	PG	1910	53
Barker (B)	USA	PG	1910	53
Black Canyon	USA	PG	1924	56
Blanchard (A)	USA	PG	1925	
Blanchard (B)	USA	PG	1925	
Bonneville (A)	USA	PG	1938	60
Bonneville (B)	USA	PG	1938	60
Boyd's Corner	USA	PG	1873	18
Buck Power House	USA	PG	1912	15
Canyon Ferry	USA	PG	1954	
Chief Joseph	USA	PG	1958	
Condit	USA	PG	1913	38
Conowingo	USA	PG	1928	32
Cresta	USA	PG	1949	

Dam Name	Country	Dam Type	Year Commissioned	Hlf (m)
Douglas (A)	USA	PG	1943	
Douglas (B)	USA	PG	1943	
Douglas (C)	USA	PG	1943	
Douglas (D)	USA	PG	1943	
Dworshak (A)	USA	PG	1972	219
Flambeau	USA	PG	1951	22
Fond Du Lac	USA	PG	1925	29
Fontana	USA	PG	1944	146
Fort Peck	USA	PG/TE	1939	
Friant	USA	PG	1942	
Glen	USA	PG	1907	23
Grand Coulee (A)	USA	PG	1942	168
Grand Coulee (B)	USA	PG	1942	168
Guntersville	USA	PG/TE	1939	
Hiwassee (A)	USA	PG	1940	
Hiwassee (B)	USA	PG	1940	
Hiwassee (C)	USA	PG	1940	
Hiwassee (D)	USA	PG	1940	
Holter	USA	PG	1918	45
Jackson Lake	USA	PG/TE	1911	21
Lake Purdy	USA	PG	1911	60
Lake Superior Compensat. Works	USA	PG	1921	
Libby	USA	PG	1972	107
Little Goose	USA	PG	1970	
Melton Hill (A)	USA	PG	1963	
Melton Hill (B)	USA	PG	1963	
Mississipi River Old Rock No. 14	USA	PG	1922	
Mississipi River Old Rock No. 19	USA	PG	1913	
Narrows	USA	PG	1947	
Nepang	USA	PG	1918	46
Nolichucky	USA	PG	1913	29
Norris (A)	USA	PG/TE	1936	
Norris (B)	USA	PG/TE	1936	
Norris (C)	USA	PG/TE	1936	
Ocoee No. 1	USA	PG	1911	
Old American Falls	USA	PG/TE	1927	32
Pandee	USA	PG	1929	105
Pickwick	USA	PG/TE	1938	34
Pit No. 6	USA	PG	1965	52
Pit No. 7	USA	PG	1965	70
Rock Creek (2)	USA	PG	1950	
Rocky Reach	USA	PG	1962	
Ryan	USA	PG	1915	26
Safe Harbor	USA	PG	1931	19
San Dimas (A)	USA	PG	1922	39
San Dimas (B)	USA	PG	1922	39
Shaver Lake (A)	USA	PG	1927	56
Shaver Lake (B)	USA	PG	1927	56
Stevenson	USA	PG	1919	44
Thompson Falls	USA	PG	1915	16
Tugalo	USA	PG	1923	47

Dam Name	Country	Dam Type	Year Commissioned	Hlf (m)
Tuscaloosa Lock	USA	PG	1940	
Wallenpaupack	USA	PG	1926	20
Wheler	USA	PG	1936	
Wilson (A)	USA	PG	1924	
Wilson (B)	USA	PG	1924	
Wilson (C)	USA	PG	1924	
Zvornik	Yugoslavia	PG	1956	40
Cordeaux	Australia	PG(M)	1926	58
Janov	Czechoslovakia	PG(M)	1914	
Labska	Czechoslovakia	PG(M)	1916	
Bissorte	France	PG(M)	1935	65
Caillaouas	France	PG/PG(M)	1940	24
Chartrain	France	PG(M)	1892	54
Gnioure	France	PG(M)	1941	72
Izourt	France	PG(M)	1939	43
La Rive (A)	France	PG(M)	1870	48
La Rive (B)	France	PG(M)	1870	48
Les Mesce	France	PG(M)	1917	65
St Sernin	France	PG(M)	1921	
Ternay	France	PG(M)	1868	34
Agaro	Italy	PG(M)	1940	
Campliccioli (A)	Italy	PG(M)	1929	80
Campliccioli (B)	Italy	PG(M)	1929	
Campliccioli (C)	Italy	PG(M)	1929	
Camposecco	Italy	PG(M)	1930	
Cingino	Italy	PG(M)	1930	
Diavolo	Italy	PG(M)	1931	
Gabiet (A)	Italy	PG(M)	1922	
Gabiet (B)	Italy	PG(M)	1922	43
Gela (C)	Italy	PG(M)	1948	
Giacopiane	Italy	PG(M)/PG/TE	1926	45
Lago Baitone	Italy	PG(M)	1930	
Lago D'arno	Italy	PG(M)	1927	
Lago D'aviasco (A)	Italy	PG(M)	1929	
Lago D'aviasco (B)	Italy	PG(M)	1929	
Lago D'avio Grande	Italy	PG(M)	1929	
Lago Salarno	Italy	PG(M)	1928	
Lago Truzzo (A)	Italy	PG(M)	1927	
Lago Truzzo (B)	Italy	PG(M)	1927	
Monte Pranu (A)	Italy	PG(M)	1951	
Monte Pranu (B)	Italy	PG(M)	1951	
Pian Casere	Italy	PG(M)	1946	
Toggia	Italy	PG(M)	1932	
Guadamelato	Spain	PG(M)	1928	61
Los Molinos	Spain	PG(M)	1960	16
Pontillon de Castro	Spain	PG(M)	1943	23
Austin (D)	USA	PG(M)	1915	20
Oberon	Australia	CB/TE	1949	
Ancipa	Italy	CB	1952	
Bau Muggeris	Italy	CB	1949	
Casoli (A)	Italy	CB	1958	

Dam Name	Country	Dam Type	Year Commissioned	Hlf (m)
Casoli (B)	Italy	CB	1958	
Corbara	Italy	CB	1963	
Eugio	Italy	CB	1959	
Fedaia	Italy	CB	1955	
Gioveretto	Italy	CB	1956	
Lago Trona	Italy	CB	1942	
Liscia	Italy	CB	1961	
Malga Bissiana	Italy	CB	1957	
Malga Boazzo	Italy	CB	1956	
Montagna Spaccata	Italy	CB/VA/PG(M)	1957	
Pantano D'avio	Italy	CB	1956	
Sabbione	Italy	CB	1953	
Marunuma	Japan	CB	1930	38
Mitaki	Japan	CB	1937	
Caia	Portugal	CB	1967	
Pracana	Portugal	CB	1959	60
Dutchman's Pool Dam	Rhodesia	CB	1955	16
Sebakwe (A)	Rhodesia	CB	1957	40
Sebakwe (B)	Rhodesia	CB	1957	40
Alcantara	Spain	CB	1973	130
Aracena	Spain	CB	1969	
Possum Kingdom	USA	CB	1941	58
Lago Inferno	Italy	CB(M)	1944	
Molato (A)	Italy	MV/PG	1928	
Santa Chiara	Italy	MV/PG(M)	1924	70
Bartlett	USA	MV	1939	88
Bear Valley	USA	MV/CB	1912	29
Florence Lake	USA	MV	1926	47
Gem Lake	USA	MV	1917	34
Lake Hodges	USA	MV	1918	42
Victoria	Australia	PG/VA	1891	19
Peti	Brazil	VA	1946	
Aigue Blanche (Chute Randens)	France	VA	1954	
Bimont	France	VA	1952	
Odeaxere	Portugal	VA	1958	
Spitallamm	Switzerland	PG/VA	1931	114
Bowman (1)	USA	VA	1927	41
Cooper Basin	USA	VA	1938	
Drum Afterbay	USA	VA	1924	30
Flower Creek	USA	VA	1946	18
Huntington Lake No. 1	USA	VA	1917	52
Huntington Lake No. 2	USA	VA	1917	52
Huntington Lake No. 3	USA	VA	1917	52
Lake Spaulding No. 1	USA	VA	1913	84
Manitou	USA	VA	1914	16
Manitou	USA	VA	1914	19
Mayfield (A)	USA	VA	1963	76
Minewawa	USA	VA	1924	18
Pacoima	USA	VA	1929	113
Pacoima (B)	USA	VA	1929	113
Salmon Creek F.P.C. No.2307	USA	VA	1913	51

Dam Name	Country	Dam Type	Year Commissioned	Hlf (m)
Stewart Mountain (B)	USA	VA	1930	37
Yellowtail (B)	USA	VA	1966	160

APPENDIX E: DAM LIST - POPULATION OF DAMS

Table E1. Dam List - USBR Population

Dam Name	Type	Year Commissioned	Height (m)
Altus	PG	1945	33.5
American Falls	PG	1927	31.5
Angostura	PG	1949	58.8
Black Canyon	PG	1924	55.8
Brantley	PG	1988	33.5
Camp Dyer	PG	1929	24.1
Canyon Ferry	PG	1954	68.6
Elephant Butte	PG	1916	91.7
Folsom	PG	1956	103.6
Friant	PG	1942	97.2
Grand Coulee	PG	1942	167.6
Jackson Lake	PG	1911	20
Keswick	PG	1950	47.9
Kortes	PG	1951	74.4
Marshall Ford	PG	1942	84.7
Nimbus	PG	1955	26.5
Olympus	PG	1949	21.3
Savage Rapids Diversion	PG	1921	13.1
Shasta	PG	1945	183.5
Upper Stillwater	PG	1988	88.4
Yellowtail Afterbay	PG	1965	21.9
Bartlett	CB/MV	1939	94
Coolidge (BIA)	CB/MV	1928	75.9
Minidoka	CB	1906	26.2
Pueblo	CB	1975	76.2
Red Bluff Diversion	CB	1963	15.8
Stony Gorge	CB	1928	42.4
Thief Valley	CB	1932	22.3
Anchor	VA	1960	63.4
Arrowrock	VA	1915	106.7
Buffalo Bill	VA/PG	1910	106.7
Clear Creek	VA	1914	25.6
Crystal	VA	1976	98.5
Deadwood	VA	1931	50.3
East Canyon	VA	1966	79.2
East Park	VA	1910	42.4
Flaming Gorge	VA	1964	153
Gerber	VA	1925	26.8
Gibson	VA	1929	60.7
Glen Canyon	VA	1964	216.4
Hoover	VA	1936	221.4
Horse Mesa	VA	1927	93
Hungry Horse	VA	1953	171.9
Monticello	VA	1957	92.7
Mormon Flat	VA	1926	68.3

Dam Name	**Type**	**Year Commissioned**	**Height (m)**
Morrow Point	VA	1968	142.6
Mountain Park	VA	1975	40.5
Nambe Falls	VA	1976	45.7
Owyhee	VA/PG	1932	127.1
Parker	VA	1938	97.5
Pathfinder	VA(M)	1909	65.2
Santa Cruz	VA	1929	46
Seminoe	VA	1939	89.9
Stewart Mountain	VA	1930	63.1
Swift	VA	1967	62.5
Theodore Roosevelt	VA(M)	1911	108.5
Warm Springs	VA	1919	32.3
Wild Horse	VA	1967	33.5
Yellowtail	VA	1966	160

Table E2. Dam List - Australia/New Zealand Population

Dam Name	Type	Year Commissioned	Height (m)
Bendora	VA	1961	47
Cotter	PG	1915	31
Lower Molongolo	PG	1994	32
Scrivener	PG	1963	33
Wrights	PG	1989	16
Avon	PG	1927	72
Back Creek	VA	1937	15
Borenore Creek	VA	1928	18
Bundanoon	VA	1960	35
Burrinjuck	PG	1928	93
Captains Flat	PG	1939	19
Carcoar	VA	1970	58
Cataract	PG	1907	56
Chichester	PG	1923	44
Coeypolly Creek No I	VA	1932	19
Cordeaux	PG	1926	67
Crookwell	PG	1937	16
Danjera	CB	1971	36
Deep Creek	PG	1961	21.3
Dunn Swamp	VA	1930	16
Flat Rock Creek	VA	1933	16
Fountaindale	VA	1915	15
Glenquarry Cut	PG	1974	18
Greaves Creek	VA	1942	19
Guthega	PG	1955	33.5
Happy Jack	PG	1959	76.2
Hume	PG	1936	
Ingleburn	MV	1933	16
Island Bend	PG	1965	48
Junction Reefs	MV	1897	19
Keepit	PG	1960	55
Lake Medlow	VA	1907	21
Lake Rowlands	CB	1953	25
Lithgow No 2	VA	1907	26
Loyalty Road	PG	1995	30
Maldon Weir	PG	1968	20
Manly	PG	1892	20
Medway	VA	1964	25
Middle Cascade (No 1)	VA	1915	15
Molong	PG	1987	16
Mooney Upper	VA	1961	28
Moore Creek	VA	1898	19
Murray 2	VA	1968	42.7
Nepean	PG	1935	82
Oaky River	PG	1956	18
Oberon	CB	1949	35
Parramatta	VA(M)	1857	15
Porters Creek	PG	1968	18
Puddledock Creek	VA	1928	19
Redbank Creek	VA	1899	15
Rylstone	VA	1953	20

Dam Name	Type	Year Commissioned	Height (m)
Suma Park	VA	1962	35
Tallowa	PG	1976	43
Tantangara	PG	1960	45.1
Timor	VA	1961	22
Tumut 2	PG	1961	46.3
Tumut 3 Pipeline	PG	1971	34.7
Tumut Pond	VA	1959	86.3
Umberumberka	PG	1914	41
Upper Cordeaux No 2	VA	1915	22
Warragamba	PG	1960	142
Warragamba Weir	PG	1940	21
Wellington	VA	1933	15
Winburndale	PG	1936	22
Woodford Creek	VA	1928	16
Woronora	PG	1941	74
Wyangla	PG	1971	85
Atiamuri	PG	1958	46
Aviemore	PG	1968	57
Clyde	PG	1993	105
Lake Onslow	VA	1982	17
Mangahao No. 1	PG	1926	36
Mangahao No. 2	PG	1924	32
Marslin	VA	1982	19
Roxburgh	PG	1956	70
Waihopai	VA	1927	34
Waitaki	PG	1934	37
Whakamaru	PG	1956	
Beardmore	PG	1972	17
Boggabilla Weir	PG	1991	16
Burdekin Falls	PG	1987	55
Burton Gorge	PG	1992	34
Cedar Pocket	PG	1984	20
Chinaman	PG	1993	19
Cooloolabin	PG	1979	20
Copperfield	PG	1984	40
Dumbleton	PG	1992	15
Ibis	PG	1906	16.5
Julius	MV	1976	38
Koombooloomba	PG	1961	52
Kroombit	PG	1992	23
Lake Manchester	PG	1916	38
Leslie	PG	1965	33
Little Nerang	PG	1961	47
Moogerah	VA	1961	37
North Pine	PG	1975	46
Rifle Creek	VA	1929	21
Somerset	PG	1955	50
Theresa Creek	PG	1982	19
Tinaroo Falls	PG	1958	47
Greenstone Ck Dam	VA	1969	20
Wappa	PG	1961	20
Wuruma	PG	1969	46
Aroona	PG	1955	26.2

Dam Name	Type	Year Commissioned	Height (m)
Barossa	VA	1902	36
Beetaloo	PG	1890	31
Clarendon Weir	PG(M)	1896	15
Middle River	PG	1968	20
Mount Bold	VA	1938	58
Myponga	VA	1962	52
Sturt	VA	1966	41
Ullabidinie	PG	1914	22
Ulbana	PG	1911	11.1
Warren	PG	1916	26
Yeldulknie	PG	1913	17
Bowden		1984	18
Catagunya	PG	1962	49
Clark	VA	1949	67
Cluny	PG	1967	30
Craigbourne	PG	1986	25
Devils Gate	VA	1969	84
Gordon	VA	1974	140
Henty	PG	1988	23
Lake Margaret	PG	1918	17
Liapootah	PG	1960	40
Meadowbank	CB	1966	43
Mount Paris	CB	1936	18
Pine Tier	PG	1953	39
Repulse	VA	1968	42
Ridgeway	VA	1919	59
Trevallyn	PG	1954	33
Clover	CB	1956	20
Dartmouth	PG	1980	25
Evansford	PG	1887	17
Glenmaggie	PG	1927	37
Goulburn Weir	PG	1891	15
Hume Weir		1919	
Junction	CB	1945	26
Lauriston	CB	1941	33
Lower Stoney Creek	PG	1875	21
Maroondah	PG	1927	46
Mt Cole	PG	1903	28
Nicholson River	CB	1976	16
Rocklands	PG	1953	28
Swingler	PG	1977	18
Yallourn Storage	CB	1961	21
Canning	PG	1940	70
Conjurunup	PG	1992	
Harvey	PG	1916	24
Kununurra Diversion		1963	20
Mundaring	PG	1902	71
New Victoria	PG	1991	52
Serpentine Pipehead	PG	1957	16
Wellington	PG	1933	37

Table E3. Dam List - Portugal Population

Dam Name	**Type**	**Year Commissioned**	**Height (m)**
Alto Cavado	PG	1964	29
Alem da Fazenda	PG	1967	20
Carrapatelo	PG	1972	57
Corgas	PG	1991	25
Cova do Viriato	PG	1962	28
Fratel	PG	1973	43
Monte Novo	PG	1982	30
Penha Garcia	PG	1980	25
Pocinho	PG	1982	49
Raiva	PG	1981	36
Ranhados	PG	1986	41
Regua	PG	1973	42
Torrao	PG	1988	70
Touvedo	PG	1996	43
Valeira	PG	1975	48
Gameiro	PG/TE	1960	20
Andorinhas	PG(M)	1945	25
Burgaes	PG(M)	1940	30
Covao do Ferro	PG(M)	1956	35
Freigil	PG(M)	1955	17
Guilhofrei	PG(M)	1938	49
Idanha	PG(M)	1949	54
Lagoa Comprida	PG(M)	1958	29
Poio	PG(M)	1932	18
Povoa	PG(M)	1928	32
Vale do Rossim	PG(M)	1956	27
Penide	PG(M)	1951	15
Caia	CB/PG/TE	1967	52
Roxo	CB/PG/TE	1968	49
Miranda	CB	1961	80
Pracana	CB	1951	60
Odivelas	MV/TE	1972	55
Aguieira	MV	1981	89
Alto Lindoso	VA	1993	110
Bravura	VA	1958	41
Cabril	VA	1954	136
Caldeirao	VA	1996	39
Fagilde	VA	1984	27
Fronhas	VA	1984	62
Funcho	VA	1991	49
Picote	VA	1958	100
Varosa	VA	1976	76
Vilarinho das Furnas	VA	1972	94
Alto Rabagao	VA/PG	1964	94
Bemposta	VA/PG	1964	87
Castelo do Bode	VA/PG	1951	115
Covao do Meio	VA/PG	1953	25
Venda Nova	VA/PG	1951	97
Alto Ceira	VA	1949	36

Dam Name	Type	Year Commissioned	Height (m)
Bouca	VA	1955	65
Canicada	VA	1955	76
Salamonde	VA	1953	75
Santa Luzia	VA	1942	76

APPENDIX F: CAUSES OF INCIDENTS

Table F1. Causes of Incidents - All Dams

Cause	Failures	Accidents	Major Repairs	Total
1.1.1	1	2		3
1.1.2	1	8	4	13
1.1.3	5	5	2	12
1.1.4	7	16	7	30
1.1.5	6	13	1	20
1.1.5.1	4	2		6
1.1.5.2	1	1		2
1.1.6		1		1
1.1.8	1	2		3
1.1.9	1	1		2
1.1.10			1	1
1.1.11		4	3	7
1.1.12		3	4	7
1.1.14	1			1
1.2.1		6	13	19
1.2.2	1	6	22	29
1.2.3	1	6	53	60
1.2.5	1	1		2
1.2.6	1			1
1.2.7		1		1
1.2.8		9	22	31
1.2.9		9	17	26
1.2.10		3	4	7
1.2.11		7	13	20
1.2.13	1		2	3
1.3.1		1	4	5
1.3.2	4	3	15	22
1.3.3		6	1	7
1.3.4		4	28	32
1.3.5		5	16	21
1.3.7	3	1		4
1.3.7.2	1			1
1.3.7.3	1			1
1.4.1		1	1	2
1.4.2		8		8
1.4.3	1	1		2
1.4.4	1	1		2
1.4.6		1	2	3
1.4.7		2	3	5
1.5.1	1	2	2	5
1.5.2	2	4	6	12
1.5.4		2	3	5
1.5.5			2	2
1.5.6	1	1	4	6
1.6.1			2	2
1.7.1			1	1
3.1.2	1		1	2
3.1.3	3	1	2	6
3.1.4	2	3	9	14
3.1.5	5		1	6
3.1.9	2	1	1	4
3.1.12	1		2	3
3.2	1			1
3.2.2	3	1	22	26
3.2.3			9	9
3.2.5	3			3
3.2.6	4	1		5
3.2.7	4	1		5
3.2.8		3	10	13
3.2.9	3	2	1	6
3.2.10			3	3
3.3.2	1	1	2	4
3.4.1			5	5
3.4.2	8	6	1	15
3.4.3		1		1
3.4.4			4	4
3.4.5		1		1
3.4.6	10			10
3.5.1	2	2		4
3.5.2	5	3	1	9
3.5.3		1		1
3.5.4	1		1	2
3.5.5		1	3	4
3.7.2			1	1
4.1.5		2		2
4.1.8				0
4.2.1			1	1
4.2.2			1	1
4.2.3			6	6
4.2.4			1	1
4.2.5	1	1		2
4.2.6		1		1
4.2.7		1	2	3
4.2.8		4	1	5
4.2.9		1	2	3
4.2.10		1		1
4.2.12		3	13	16
4.2.13		2	12	14
4.4.2		1		1
4.4.3		1		1
4.4.4		3	1	4
4.5.1			1	1

Cause	Failures	Accidents	Major Repairs	Total
1.7.2			8	8
2.3.9	5			5
4.6.1	1			1
4.6.2	1		1	2
4.6.3	1			1
4.7.1	6	13	10	29
4.7.2		4	1	5
4.7.3			1	1
4.7.4			1	1
4.7.6		1	1	2
4.7.7			1	1
4.7.8		4	9	13
4.7.9	1		3	4
4.8	2	16	6	24

Cause	Failures	Accidents	Major Repairs	Total
4.5.5			4	4
4.6	1	10	5	16
4.9.1		2	2	4
4.9.2		2	2	4
4.11.1			1	1
4.11.6		10	6	16
4.11.7		1	4	5
4.12.6		1		1
5.1		5		5
5.3		4	1	5
5.4		9	2	11
6.1			1	1
6.2		5	2	7
Total	**121**	**283**	**450**	**854**

Table F2. Causes of Incidents - PG Dams

Cause	Failures	Accidents	Major Repairs	Total
1.1.1		1		1
1.1.2		2	2	4
1.1.3	4	3	1	8
1.1.4	4	7	5	16
1.1.5	1	8	1	10
1.1.5.1	1	2		3
1.1.5.2		1		1
1.1.6		1		1
1.1.9		1		1
1.1.10			1	1
1.1.11		1	3	4
1.1.12			4	4
1.2.1			8	8
1.2.2		1	15	16
1.2.3		1	40	41
1.2.5		1		1
1.2.7		1		1
1.2.8		2	15	17
1.2.9		2	11	13
1.2.10		1	3	4
1.2.11		1	7	8
1.3.1			4	4
1.3.2	2	2	15	19
1.3.4		1	6	7
1.3.5		1	2	3
1.3.7	1			1
1.4.1			1	1
1.4.6			2	2
1.5.1	1	1	2	4
1.5.2	1	1	3	5
1.5.4			1	1
1.5.5			2	2
1.5.6			4	4
1.6.1			2	2
1.7.1			1	1
1.7.2			8	8
3.1.4			1	1
3.2.2			1	1
3.2.8		1		1
4.1.5		2		2
4.1.8				0
4.2.1			1	1
4.2.2			1	1
4.2.3			6	6
4.2.4			1	1
4.2.5	1	1		2
4.2.7		1	2	3
4.2.8		1	1	2
4.2.9			1	1
4.2.12		1	13	14
4.2.13			11	11
4.4.3		1		1
4.4.4		1		1
4.5.1			1	1
4.5.5			4	4
4.6	1	7	4	12
4.6.2			1	1
4.7.1	2	5	10	17
4.7.2		1	1	2
4.7.3			1	1
4.7.4			1	1
4.7.6			1	1
4.7.7			1	1
4.7.8			9	9
4.7.9			2	2
4.8		4	3	7
4.9.1		1	1	2
4.9.2			2	2
4.11.1			1	1
4.11.6		5	4	9
4.11.7			4	4
4.12.6		1		1
5.1		2		2
5.3		2		2
5.4		2	2	4
6.1			1	1
6.2		3	1	4
Total	**19**	**82**	**263**	**364**

Table F3. Causes of Incidents - PG(M) Dams

Cause	Failures	Accidents	Major Repairs	Total
1.1.3		1		1
1.1.5		1		1
1.2.2			1	1
1.2.3			1	1
1.2.8			1	1
1.3.1		1		1
1.3.3		1		1
1.3.7	1	1		2
1.4.7		1		1
1.5.6		1		1
2.3.8	1			1
2.3.9	5			5
3.1.12	1		2	3
3.1.2	1		1	2
3.1.3	3	1	1	5
3.1.4	1	2	8	11
3.1.5	4		1	5
3.1.9	2	1	1	4
3.2	1			1
3.2.2	3	1	20	24
3.2.3			8	8
3.2.5	2			2
3.2.6	4	1		5
3.2.7	4	1		5
3.2.8		2	10	12
3.2.9	3	2	1	6
3.2.10			3	3
3.3.2	1		2	3
3.4.1			5	5
3.4.2	7	6	1	14
3.4.3		1		1
3.4.4			4	4
3.4.6	8			8
3.5.1	2	2		4
3.5.2	5	3		8
3.5.3		1		1
3.5.4			1	1
3.5.5		1	3	4
3.7.2			1	1
4.2.8		1		1
4.6		1		1
4.6.2	1			1
4.7.1	2	1		3
4.7.8		1		1
4.7.9			1	1
4.8		1		1
4.9.1			1	1
4.11.6			1	1
5.3			1	1
5.4		2		2
Total	**62**	**39**	**80**	**181**