APPENDIX D : CHARACTERISTICS OF DAMS WORLD-WIDE

D.1 General

In assessing the probabilistic risk of failures of dams, it is important to understand the characteristics of the dam population on which the assessment is carried out. This section summarises available information on dam populations other than UK, to allow the assessment of the value of any world-wide probability data to the population of dams under the UK Reservoirs Act 1975.

Summaries of the physical characteristics of European dams are given in the report by Le Delliou (1998, Barcelona) on the European Working Group on Legislation.

A description of the characteristics of UK dams is given in Section D.3. Comparison of UK dams with dams in other countries include Charles (1998) and Charles & Wright (1996).

In broad terms the differences between the UK population and the populations of dams in other countries include the fact that the UK has:

- a smaller qualifying size of reservoir (UK dams are included where above 25,000m^3, whilst overseas in general have a larger minimum size, as Table D.1. For example only 20% of UK dams are large enough to qualify as a large dam under the ICOLD criteria)
- temperate climate
- a significant proportion of older dams
- less variety of embankment type
- use of puddle clay as a core, commonly without filters
- different soils e.g. in UK we do not have permafrost, tropical residual soils or highly dispersive soils
- older UK dams are commonly in cascade, which introduces the risk of the failure of an upstream dam initiating the failure of downstream dams
- UK amenity dams are full almost all the time, whilst overseas dams in arid countries rarely reach their maximum reservoir level

D.2 Overseas Dams

D.2.1 Databases of dam characteristics and incidents

Table D.1 shows the databases that are known to exist on dam characteristics and dam incidents and failures respectively.

Surveys of dam incidents have been carried out and reported by ICOLD in Bulletin (1974), CDDR (1983) and Bulletin 99 (1995). Other surveys are summarised in Foster et al (2000) and include the US, UK and Australia.

A formal live database (NDD) was set up in UK in 1985, whilst in the US the National Inventory of dams for USA (NID) was set-up in 1975 and the National programme for Dam performance (NPDP) was set up in 1994. Various national agencies also maintain databases on the dams they monitor.

In UK prior to the 1975 UK reservoir safety legislation there was no Enforcement Authority, so a considerable number of reservoirs were only identified as being covered by legislation once the 1975 Act was implemented in 1985. Thus the NDD of dams has significant omissions until that date in terms of records of failures and serious incidents. It is also known that there are still significant omissions in terms of failures and serious incidents, as there is no requirement for the reporting of incidents and works to dams.

In principle tailings dams could be used as a way of extending the database; however, it is considered that the characteristics of tailings dam design and construction are sufficiently different from water retaining dams that this would not be useful and so has been discounted.

D.2.2 Surveillance and incidents

Dam failures on a world-wide basis include:

- in the USA 350 killed since 1970 (Parr & Cullen, 1988),
- the Stava dam failure in Italy which killed 250 (HSE, 1992, Tolerability of risk from nuclear power stations), and
- Vaimont in Italy in 1963 which killed 2500 (HSE, op cit).

The method of surveillance varies, often being by government employed staff.

Table D.1 : Summary of Characteristics of Dam Populations world-wide

Country	Number of dams in database		Qualifying national criteria (Viseau & Martins, 1998)			National database	Information in database on incidents		Remarks
	Large (ICOLD definition[1])	National criteria[2]	Papers on legislation and safety practice	Height (m)	Reservoir volume m^3		Failures	Incidents	
World-wide	45,000	na		15m	1,000,000		177	1105	ICOLD CDDR (1983) and ICOLD Bulletin 99 (failure, 1995) include incidents in first 5 years. Bulletin 93 (ageing) excludes first five years. Foster et al (2000) also present statistics.
Europe	3,287	-		-			(34)		Charles & Wright (1996); Lemperiere (2001) describes 34 failures
France	569	569	Delliou, 2001, p217	20m	15,000,000	EDF, CEMA-GREF			Dam safety responsibility of 3 organisations, EDF (BETCGB, Hydropower), Min. Environment (CEMAGREF; water supply & irrigation) and VNF (CETMEF, waterways)
Germany	311		Rettemeir et al, 2001 p303	5m	100,000				Each of 15 states has own legislation, see Rettemeir & Kongeter (2001), Nilkens et al (2001)
Norway	330	2,500	Molkersrod, 2001, p259	4m	500,000				2001 European Conf; Skoglund for embankment dams (p. 337-342) and Jensen for concrete (p. 201-208) give results of questionnaire on condition and incidents.
Portugal	103		da Silva, 2001, p121, p263						
Spain	1187	1300	Azanedo, 2001, p115						
UK	517	2,600		No limit	25,000	NDD	40	120/ 500	Incidents subdivided into serious/ causing concern
Elsewhere	41,700								
Australia	486								Although ANCOLD produces guidelines, each of 6 states varies this to different degrees
Canada	793			2.5m	30,000	NDPD			
China	24,670								
US	6,375	74,000		7.6m	62,000	NDPD			Several different federal agencies i.e. USACE, USBR, FREC, FEMA plus each of 62 state has responsibilities

1) Definition given in Terminology; data for Europe taken from Law (1992)
2) Data as presented by working party at Geiranger, Norway 2001

D.3 Characteristics of UK reservoirs

D.3.1 Legislation

Dam failures with loss of life in 1925 led to the passing of the Reservoirs (Safety Provisions) Act 1930. This was replaced by the current legislation, Reservoirs Act 1975, which was implemented in 1986-1987. The Act applies to all reservoirs designed to hold, or capable of holding, more than 25 000m^3.

Other legislation that may impact on the way reservoir owners operate and maintain their reservoir, although not mandatory, are:

- Health and Safety at Work Act, 1974
- Security and Emergency Measures Direction (DETR, 1998)
- COMAH regulations 1 April 1999 (which supersede CIMAH) - control of major accident hazard this requires operators in certain industries to provide information to the public on the storage of dangerous goods

To date there has been no universal European legislation that impacts directly on dam safety.

D.3.2 Physical characteristics, age & ownership

Brief details of the characteristics of the 2600 reservoirs which fall within the ambit of the Reservoirs Act 1975 are given in Section 1.4.4 of the main report, with further information provided here. The distribution of British dams in terms of the date of construction, height of dam and reservoir capacity are illustrated in Tables 1.3 and 1.4 of the main report and Figure D.1 to D.4. Figure D.2 shows that older dams were generally of small reservoir capacity. British dams range from small earth embankments whose reservoirs hold just over 25,000 cubic metres to large dams such as Quoich with a reservoir capacity of 382 x 10^6 cubic metres.

Approximately half the dams are owned by water companies, however approximately 600 (25% of the total stock) are owned by owners with one dam and limited financial resources; these undertakers tend to be country landowners and fishing clubs. A significant number of farm irrigation and flood retention dams have been built in recent years.

D.3.3 Impact of Dam Failures – Historical Record in UK

Table D.2 summarises the historical record of dam failures in the UK in which there has been loss of life. Only two of these were large dams as defined by ICOLD, with the remainder too small to be included in the ICOLD register, but large enough to come under UK legislation. Only internal erosion and overtopping have resulted in the uncontrolled release of water and loss of life.

Based on Table D.2, Figure D.5 (Charles et al 1998) shows a comparison of British dam failure during the period 1831 –1930 with risk tolerability for ports as given by Health and Safety Commission Advisory Committee on Dangerous substances (1991). Although this information is of historical interest, it is of little relevance to assessing the probability of failure of the present stock of UK dams. At all the dams there were gross engineering deficiencies (particularly in spillway capacity) and poor communication.

Table D.2 : British Dam Failures Involving Loss of Life

(after Charles (1993) and Binnie & Partners (1986))

Dam	**Height m**	**Res. cap 1000m^3**	**Date Built**	**Date Failed**	**Cause**	**Deaths**
Tunnel End (Marsden)	9		1799	1799	Overtopped	1
Diggle Moss (Black Moss)			1810	1810	Internal erosion	5
Whinhill	12	262	1821	1835	Overtopped	31
Welsh Harp (Brent)	7		1835	1841	Overtopped	2
Glanderston				1842	Overtopped	8
Darwen				1848	Overtopped	12
Bilberry	20	310	1845	1852	Internal erosion	81
Dale Dyke	29	3240	1863	1864	Internal erosion	244
Rishton				1870		3
Cwm Carne	12	90	1792	1875	Internal erosion	12
Castle Malgwyn				1875	Overtopped	2
Clydach Vale				1910	Overtopped	5
Skelmorlie	5	24	1878	1925	Overtopped	5
Coedty	11	320	1924	1925	Overtopped	16

Examples of the rate of progression of internal erosion at some UK dams are shown in Table D.3.

Table D.3 : Rate of progression of internal erosion at some UK dams

Dam (reference)	Condition when first noticed	Rate of progression	Actions taken to prevent failure
Balderhead – 48m high rolled clay (Vaughan et al 1970)	On first filling depression noticed over core	Over 10 weeks extended to 3m wide x 2.5m deep hole	Reservoir lowered 9m (which increased crest settlement), grouting and diaphragm wall in core
Lluest Wen – 24m high puddle clay core constructed in 1896 (Twort 1977)	Horse fell into 2m deep hole on 23 Dec 1969	Inspected on 7th Jan when suspended clay present in cracked drain pipe	Temporary evacuation of people downstream 12th Jan; grouting of tower and cut through spillway started 19th Jan; reservoir had been lowered 9m by 29th Jan
Green Booth – 35m high Pennine dam (Flemming et al 1985)	Depression on crest noticed by public in 1983, some 20 years after construction	Over 3 days extended to 3m x 1m in plan, 0.04m settlement	Reservoir lowered from 1.65m below TWL by further 9.3m over 8 days. Core grouted, 4% by volume
Warmwithens – 10m high dam built in 1860, 1.5m dia. outlet tunnel driven through embankment in 1965 to contain new outlet pipes (Wickham, 1992; Charles & Boden 1985, para 21; Moffat, 1975 BNCOLD, p5/7)	Chart recorder shows increased leakage started 1700 on 23rd Nov 1970, with rapid increase at 0500 am on 24th Nov. Escape of water first noticed 0730 am on 24th	Maximum outflow 0900 on 24th Nov, with 115,000m^3 reservoir discharged by 13.30.	Dam failed by erosion along 'new culvert'. Breaching sufficiently slow that two reservoirs in cascade downstream could cope with inflows with only minor damage

Wright (1994) includes a list of 10 dams that experienced catastrophic failure between 1960 and 1971. Although there has been no loss of life since 1925 and the introduction of the Reservoirs (Safety Provisions) Act 1930, once a failure occurs, public trust will be compromised, even if just a few lives are lost.

D.3.4 Hazard Classification of UK Dams

The hazard posed by reservoirs to the area downstream can be currently assessed using one of three systems:-

a) the four dam flood categories, A, B, C and D, defined in the third edition of *Floods and Reservoir Safety* published by ICE in 1996.
b) the four seismic categories, which are based on ICOLD Bulletin 72, 1989
c) the three consequence classes in RMUKR

These are summarised in Table 4.3 of the main report, whilst the proportion of dams in each category is plotted on Figure 4.1.

An important point is that to date the assessment of the class of dam has, for small dams, often been based on visual inspection and judgement of the Inspecting Engineer, rather than carrying out a dam break analysis and predicting depths of inundation. Thus there has probably been some differences between different Panel Engineers. The rapid method of dam break in RMUKR should allow a greater consistency in assessing the class, such that the above may be modified.

D.3.5 Upgrading Works on UK Dams

Analysis needs to allow for the ‘improvement’ in the condition of the UK dam stock that has occurred since the 1930 Act was implemented. There has been a significant increase in the reported remedial works since 1930, before which there was little or no work reported (see Figure C.2). In part this may be due to the changes that have taken place in dam ownership – with many large dams owned by large water supply companies with a greater public awareness. Also, this is likely to reflect changes in the way in which dams have been managed and supervised – from a reservoir keeper with a gang of workmen making repairs on a regular but unreported basis to a more structured system of supervision and reporting. Even taking into account the increase in publication of information, the dramatic increase in reported remedial works may indicate that our knowledge of the risks posed by incidents has increased during this time, and our willingness to accept risk has reduced.

Slope Stability

There is no recorded case of failure in service resulting in an uncontrolled release of water which has been attributed primarily to slope instability. Whilst the rate at which major problems are reported seems almost constant or reducing since legislation has been introduced, the reported incidence of more minor problems is increasing. This may be as a result of improved surveillance and reporting and a greater understanding of geotechnics. There has been an increasing number of remedial works involving slope improvements in the last decade.

Draw-off Works

As might be expected with an ageing population of dams, the reported problems and remedial works associated with draw-off systems has increased. Most reported remedial works have been carried out on dams over 50 years old and 60% of these are associated with repairs to the valves or pipework. The most common recent repairs has been relining of the old outlet pipes which were often cast iron and may have become corroded, as well as replacement of valves.

Internal Erosion

It can be seen that the reported problems attributed to internal erosion and the remedial works associated with them have been increasing since 1950. This may be due to an improvement in monitoring and reporting but is also likely to be a result of the ageing population of dams.

Overflow Works

The remedial works associated with the overflow works can be seen to follow the trend in legislation and guidance on floods which were introduced in the 1930s and revised in the 1970s (Figure D.6). Some 77% of the reported problems have been categorised as ‘design limitation’, such as a calculated inability to survive a PMF, and 19% of the remedial works are known to have been associated with improvements in safety of this kind. This has had an impact on the instances of failure due to overtopping, which have decreased over the same period. Since 1981, Yorkshire Water Services has spent almost £25m on improving reservoir flood capacity to meet FSR design standards. This has involved work on some 50 of Yorkshire Water’s 140 impounding Reservoirs (Robertshaw, 2001).

A similar example is Woodhead dam, built in 1847-1876, the highest dam in the cascade in the Longdendale Valley supplying Manchester, where the design floods have increased as shown in Table D.4.

Table D.4 : Example of upgrading of spillway capacity with time for a UK dam (Chalmer, 1990)

Date	Design Flood Inflow (m^3/s)	Results
1847	28.3 (1000 ft^3/s)	Highest flood of record
1848	42.5 (1500 ft^3/s)	Large flood in nearby Blackburn
1874-80	?	Heavy rainfall showed spillway inadequate, so level of reservoir held down by 1.52m to provide flood storage
1938	204	Follow recommendations of ICE 1933 Flood Committee
1986	550 (PMF)	Further upgrading, following FSR
after 1986	*	Further works to downstream reservoir, following issue of FSR Supplementary Report No 10 for reservoir in cascade

D.4 Published data on probability and annual probability of failure and incidents

D.4.1 General

A summary and comparison of the characteristics of UK dams with overseas dams is given in Section D.1; this is relevant to the interpretation of the statistics for the performance of overseas dams for their relevance to UK dams.

ICOLD Bulletin 99 (1995) reports that

- since the definition of failure varies between countries, the Bulletin adopted the definition of "collapse or movement of part of a dam or its foundation so that the dam cannot retain water. In general a failure results in the release of large quantities of water" (this definition varied from that in ICOLD CDDR (1983, page 31) which related to major damage to the dam)
- the failure rate for large dams built before 1950 (5,268 number), after the first five years of life, was approximately 2.2% and for those built after 1950 (12,138 number) was 0.5%.
- for dams which failed the timing was as follows (Figures 7 and 8 of the Bulletin):-

	Years after construction					Total
	Construction/ first year	2, 3	4, 5	6 - 10	> 10	
Number of failures	59	21	13	16	56	165**
% of those known	36%	13%	8%	10%	23%	

** age at date of failure not known for 12 of these dams

ICOLD Bulletin 109 (1997) provides useful information on failures of dams less than 30m high, including both embankment and concrete dams; the main points being summarised below.

D.4.2 Embankment dams

Table D.5 summarises published data on the probability of failure of embankment dams. It can be seen that the probability of failure due to internal erosion is similar to that of floods. The annual probability of failure of pre and post 1930 dams is not directly comparable to whole life probability, as the older dams have been in place longer. Nevertheless assuming that the pre 1930 dams have a typical age of 100 years and the post 1930 say 30 years it can be seen that the probability of failure has reduced significantly.

Table D.5 : Whole life probability of failure of embankment dams (from ICOLD Bulletin 109)

Dam/reservoir size	Threat	Whole life probability of failure 10^{-5}	
		built before 1930	built after 1930 (industrialised countries)
Dams >30m	piping	2,000	200
	floods (operation)	3,000	50
dams 15-30m, storage > $10Mm^3$	piping	6,000	400
	floods (operation)	8,000	100
dams 15-30m, storage < $10Mm^3$	piping	>2,000	200
	floods (operation)	>1,000	100

Table D.6 summarises published information on the relative annual probability of the different failure modes, which includes failure both in the wear-in period and subsequently. It can be seen that overall the proportion of failure by internal erosion is similar to that by external erosion, with sliding being relatively uncommon. Failure initiated by the appurtenant works is not differentiated as a separate failure mode; presumably fractures in pipes are therefore classified as internal erosion although the primary cause of failure was the pipe. For flood dykes overtopping is reported as the major cause of failure, presumably because the short term infrequent loading rarely allows steady state seepage and degradation to occur.

There are a number of papers by Foster, Fell and others which present the results of studies on internal erosion and slope stability using statistics to analyse historical performance. The data was primarily from ICOLD being entered into the ERDATA1 database, and then extended by obtaining more detail on embankment fills and zoning and foundation geology. They managed to get this detailed information on 1462 dams, or 13% of the ICOLD database. The most accessible summary is that in the Canadian Geotechnical Journal (Foster, Fell & Spangle, 2000). A sample of the data available is summarised in Tables D.7 and D.8.

It is important to note that in their paper at the 1998 ANCOLD conference Foster et al include proposed correction factors to obtain a dam specific annual probability of failure, from the average for a given type of dam. Similar corrections for dam specific features are also believed to be suggested from the 1985 work at Stanford University, reproduced with the dam specific features to be considered (but without the corrections!) as Figure 4 in Dise (1998).

They state definitions of failure and accidents are as the ICOLD CDDR (1983), however, it should be noted that the definition of failure varies from the later ICOLD Bulletin 99 (see above) and we have been unable to locate a definition of accident in CDDR. Nevertheless Foster & Fell (1998) describe three types of accident, reported as based on ICOLD (1974); these all involve immediate remedial measures and are differentiated by timing (i.e. during construction, during first filling or during operation) rather than severity of accident. It would therefore be expected that their figures for accidents are proportionally lower than UK incidents, as the Foster data appears to only include a Type 2 (serious) incident under the UK definition.

Table D.7 indicates that the failure rate for dams after 5 years of operation is typically about 10% of that during the first five years. Over the life of the dam the rate of accidents to failures varies with failure mode, typically between unity and four; although the ratio is 12 for piping from the embankment into the foundation. Unfortunately the accident rates after 5 years of operation are not differentiated from the average lifetime accident rate for each dam. They also note that the failure rate for dams prior to 1950 is about 7 times higher than for dams constructed after 1950.

Published predictions of the probability of failure of existing dams during operation are less common, with data identified by mode of failure being summarised in Table D.9. It can be seen that the predicted probabilities of failure in operation for US dams of 13 x 10^{-5}/annum are 50% higher than the world-wide historical value of 9 x 10^{-5}/annum (as given in Table D.7); whilst the predicted UK figure (Cullen, 1990) of 64 x 10^{-5}/a is approximately 7 times the historical value. These values are for observed performance over different time periods, and thus are not strictly comparable, as they should be adjusted for the upgrading of dams in recent years in reducing the probability of failure. A description of this early work by Cullen on risk based methods is given in Section E.7.2; the output being considered unreliable.

Data presented by threat is summarised in Table D.10. Attewill and Spasic-Gril (2001), in their study of Lake Sarez have assigned probabilities to a number of threats; external erosion, internal erosion and dam stability. The work accepted that all the probabilities were subjective. It was claimed that the probabilities of the separate hazards have been combined to derive the overall probability of failure by means of event trees. It was concluded the method of risk analysis used was of value in

- establishing the sensitivity of the overall risk to the variation in probability of the individual hazards
- ranking alternative structural measures to reduce risk

Funnemark et al, 2000 use event trees to assign probabilities to dam failure modes for the Valldalen dam in Norway. The dam is a 93m high rockfill dam with central moraine core, built in 1965. The low probability of failure by internal erosion is probably partly due to the inference that the use of modern concepts in the design of filters should reduce the risk of this mode of failure. The overall probability of failure appears to be a similar order of magnitude to the results from the ICOLD database given in Table D.7.

Table D.6 : Published information on relative annual probability of different failure modes for embankment dams based on historic performance (wear-in period and subsequently)

	Middlebrooks 1953	Charles & Boden 1985, (Table 2.5)	ICOLD Bulletin 99, 1995 (Fig 11 in Bulletin) Note : below only includes primary cause of failure			Laszlo, 2001
Location, number of dams, and period of sample	US dams, known failures	British dams, known failures	World-wide, 17,400 number, all known failures prior to 1995			Flood levees in Hungary
	%	%	No	Code	% of failures, exc. ‘unknown’	%
Mode of failure						
External erosion (Overtopping)	30	24	36	2.3.8	51%	19.5 overtopping + 0.6 wave scour
Rupture of upstream dam	Not differentiated		4	2.3.9	6%	
Internal erosion (dam body)	38	55	19	2.4.12	27%	1.3
Internal erosion (foundation)			12	2.1.5	17%	2.2
Shear failure	15	14	0	2.1.3, 2.1.17	0%	1.8
Appurtenant works	Not differentiated		Excluded			na
Other causes.	17	7				
Unknown cause	-	-	46			74.6
		Total	117			

Table D.7 : Published information on historic failure statistics of embankment dams, primarily from ICOLD database

Mode of failure	Average Probability $x10^{-5}$ (i.e. over life of dam)			Proportions of all failure in operation	Ratio accidents/ failures (whole life)	Average annual probability $x10^{-5}$			
	Failure in operation	Failure (whole life)	Accident (whole life)			Failure in first five years	Failure after 5 years of operation	Table in	
Column	1	2	3	4	5	6	7	8	9
Source	Table 2 of Note 1 and Table 5.1 of Note 2		As Columns 8, 9	Col 1	Col.3/ Col. 2	As Columns 8, 9		Note 1	Note 2
External erosion (Overtopping)	490	550	?	44%	?	?	?	not given	not given
Internal erosion (dam body)	340	350	670	31%	1.9	45.3	5.6	5	6.3
Internal erosion (foundation)	160	170	620	14%	3.6	25.5	1.9	10[3]	7.2
Internal erosion (embankment into foundation)	18	18	210	2%	11.7	1.9	0.4	14	8.1
Shear failure	45	63	22	4%	0.3	4	1.5	17 + 20	9.1, 10.2
Other causes/ unknown.	57	69	?	5%	?	?	?	not given	not given
Total	1,110 (1.1%)	1220 (1.2%)	1,312		1.2	74 (148)[4]	9.4 (18)[4]		

1. Foster, Fell & Spangle, 2000. The statistics of embankment dam failures and accidents. . Population of 11,192 dams, up to 1986, of which after 5 years of operation there are 124 failures and 279 accidents
2. Foster , Fell & Spannagle, 1998. Report by Univ. New South Wales.
3. Typographic error in their Table 2.10, such that last two columns should be 10^{-6}, not 10^{-3}
4. Adjusted assuming overtopping and other causes have same percentages as column 4

Table D.8 : Average annual probability of failure due to piping through embankment dams by dam zoning category (as Table 5 of Foster, Fell & Spangle, 2000)

Zoning Category	No. of failures	No. of accidents	Average probability $(x10^{-5})$ (i.e. over whole life of dam)		Average annual probability of failure $(x10^{-5})$[1]		Probability of Failure after 5 years : Ratio of dam type to average
			Failure	Accident	First 5 years of operation	After 5 years of operation	
Homogenous earthfill	14	9	1600	920	209	19	3.4
Earthfill with filter	2	1	150	60	19	4	0.7
Earthfill with rock toe	5	5	890	800	116	16	2.8
Zoned earthfill	4	9	120	240	19	2.5	0.4
Zoned earth and rock fill	1	7	120	730	15	2.4	0.4
Central core earth and rockfill	0 (1)	19	(<110)[2]	2200	(<14)[2]	(<3.4)[2]	0.6
Concrete (or other) face earthfill	2	1	530	240	69	8	1.3
Concrete (or other) face rockfill	0	1(11)[3]	(<100)[4]	350	(<13)[4]	(<1.7)[4]	0.3
Puddle core earthfill	4	10	930	2070	121	4	0.6
Concrete corewall, earthfill	0	2	(<100)	810	(<13)	(<0.8)[4]	0.1
Concrete corewall, rockfill	0	2	(<100)[4]	2160	(<13)[4]	(<1.3)[4]	0.2
Hydraulic Fill	0	3	(<100)[4]	3240	(<13)[4]	(<0.5)[4]	0.08
Zoning type unknown	7	6					
All dams	39	75	350	670	45	5.6	

Notes

1. The percentages of failures by piping through the embankment occurring at the different times after construction are as follows: 49% during first filling, 16% during the first 5 years operation, and 35% after 5 years operation. Calculations of annual frequencies of failure are made as follows:
    - average annual probability of failure (all years) = (average annual probability of failure)/(average age);
    - annual probability of failure (first 5 years)) = (average annual probability of failure) x 0.65/ 5; and
    - annual probability of failure (after 5 years) = (average annual probability of failure)x 0.35/ (average age – 5).
2. Upper bound value of the average annual probability of failure determined by assuming one dam failure
3. Eleven accidents to concrete face rockfill dams involving leakages through the concrete face (not included in % statistics).
4. Assume average annual probability of failure of < 1 x 10^{-3}

Table D.9 : Published information on predicted annual probability of failure for dams in operation, by mode of failure

Mode of failure	Average annual probability x10^{-6}	
Dam	Typical US dam	UK (NWW) 'typical dam'
Ref.	Stanford University (as Table 3.6 in Cullen, 1990)	Table 3.5 of Cullen, 1990,
External erosion (Over topping)	?	210
Internal erosion (dam body)	65	70
Internal erosion (foundation)	?	21
Shear failure	11	?
Other causes/ unknown.	47	?
Total	130	640

Table D.10 : Published information on predicted probability of failure, by threat

Threat	Average annual probability x10^{-6}			
dam	Lake Sarez natural landslide dam		Valldalen, Norway	Venemo, Norway
	Attewill and Spasic-Gril 2001		Funnemark et al, 2000, Table 10	Amdal & Riise, 2000
	Low range	High range		
Flood	160	360	54	7
Earthquake	270	2160	0.3	0.5
Internal geotechnical	Not incl.	Not incl.	3	Not incl.
Electromechanical	Not incl.	Not incl.	Not incl.	10
Sediment blockage	770	3120	Not incl.	Not incl.
Cascade failure of u-s dam	Not incl.	Not incl.	Not incl.	230
Other	Not incl.	Not incl.	Not incl.	Not incl.
Total	1,200	5,640	57	248

D.4.3 Concrete dams

Table D.11 summarises published information on the relative annual probability of the different failure modes, which includes failure both in the wear-in period and subsequently. It can be seen that overtopping, sliding, and internal erosion of the foundation are broadly similar in annual probability.

In parallel with the work on embankment dams there was research on historical performance on concrete dams, reported in a University of New South Wales research report (Douglas, Spannagle & Fell, 1998) and in summary form in Hydropower & dams (Douglas, Spannagle & Fell, 1999). However, this had a relatively limited population of 487 dams, comprising 46 failures, 176 accidents and 265 major repairs. The results of the statistical analysis are therefore considered less reliable than for embankment dams.

ICOLD Bulletin 109 (1997) notes in relation to concrete dams (pages 35 to 39)

a) "the safety record of gravity dams built before 1930 was in fact worse than for embankment dams. The probability of failure was similar, but for gravity dams sudden failures caused more victims
b) overturning of blocks or sliding on the foundation (was) the most frequent cause
c) forty per cent of failures occurred on first filling
d) masonry dams built since 1930 have displayed similar safety performance as concrete dams
e) although arch dam experience trails gravity dams by 50 years, today's safety appears equivalent,
f) buttress and multiple arch dams therefore appear to be less safe than gravity and arch dams"

Table D.11 : Published information on relative annual probability of different failure modes for concrete dams based on historic performance (wear-in period and subsequently)

	ICOLD Bulletin 99, 1995 (Fig 10 & 12 in Bulletin) Note : below only includes primary cause of failure			Douglas, Spannagle & Fell, 1999 (Table 4)
Location, number of dams, and period of sample	World-wide, 17,400 number, all known failures prior to 1995			world-wide, 487 number
	No	Code	% of failures, exc. 'unknown'	
Mode of failure				
External erosion (Overtopping)	8	1.3.7, 3.4.6	33%	32%
Rupture of upstream dam	-	not	differentiated	
Internal erosion (foundation)	7	1.1.5, 3.1.5	29%	19%
Shear failure – foundation	9	1.1.3, 1.3.2, 3.1.3, 3.4.2	38%	22%
shear failure – dam body				19%
Appurtenant works	Excluded			
Other causes.				16%
Unknown cause	5			
	29			

D.4.4 Service Reservoirs

Service Reservoirs are too small to come under the ICOLD definition of a "large dam" and are therefore not considered by ICOLD. This is therefore no data on historical performance from the ICOLD Bulletins. Although their safety is actively managed in Hong Kong, because of their proximity to potentially unstable slopes above dense concentrations of population, we have been unable to find any published information on the historical performance of service reservoirs.

D.4.5 Cascades

Amdal & Riise (2000) report an assessment of the overall probability of failure of a 64m high rockfill dam in Norway. The probability of failure of the subject dam resulting from a breach of an upstream dam was 2.3×10^{-4}/a, whilst the overall probability of failure of the subject dam due to all other causes was only 0.18×10^{-4}/a, showing the importance of considering cascade failure as a failure mode.

D.4.6 Miscellaneous threats

The probability of an aircraft strike is given by Smith (1988) as follows:

		Crash rate x 10^{-5} years per square mile
Background, randomly distributed across the UK	Private aircraft	7.5
	Helicopters	2.5
	Small transport	0.25
	Airline transport	1.3
	Combat military	3.8
	Total (all aircraft)	15.0
Additional where close to Airfield r – distance in miles to runway, t is the angle in degrees	Take-off	$0.22/r\ e^{-r/2}\ e^{-t/80}$
	Landing	$0.31/r\ e^{-r/2.5}\ e^{-t/43}$

For the critical element of a dam having a footprint of 100m by 20m and no nearby airfield, this would give a probability of 1×10^{-7}/annum. This may be compared with the figures quoted by Thompson et al (2001) for the probability for an individual of death due to impact from a crashing aeroplane of 1.2×10^{-8}/ annum.

The failure of gates and valves is discussed by Pohl (2000), who carried out a questionnaire survey in Germany, Austria and Switzerland. Based on this data he concluded that the average annual probability of total failure to open was 0.3% of the times it was used. This seems relatively high, for a well maintained regularly used gate or valve, and presumably reflects the preponderance of gates and valves that were used infrequently. No data is given on the effect on dam safety.

D.4.7 Summary

This published data indicates that

- the likelihood of failure reduces significantly after the first few years of operation
- the probability of an accident/incident is greater than a failure (incidents could be used as a measure of the likelihood of failure, similar to near miss reporting in H&S)
- internal erosion is broadly similar to overtopping in terms of annual probability of failure, with sliding much less common and electromechanical failure rarely differentiated as a separate failure mode.

D.4.8 Other types of installations

It is of interest to compare the probabilities of failure of dams with failures of other types of earthworks, available data being summarised in Table D.12. It can be seen that the failure rate is much higher than for dams.

Table D.12 : Published values of probability of failure for installations other than dams

	Probability of failure	Remarks
Infrastructure embankments (CIRIA, 2001, Section 3.5.2)		
Rail embankment (LUL)	0.5 failures/ annum	
Motorway embankment	3% had failed to 1989	Annual probability/ year varied from 0.1% to 8.3%

Research is ongoing in relation to other types of installation. An example is work on the probability of failure of flood dikes in Holland. An unsuccessful attempt was made to obtain information on this; through Prof. Vrijling who is chairman of a state committee that works on these problems, devises new methods, supervises the (trial) applications etc.

D.5 Materials used in dams

D.5.1 General

It is important to realise that as 50% of UK dams are over 100 years old, the materials likely to have been used in the construction of these dams would have been very different from those used today. This section therefore summarises briefly how the materials likely to have been used in dam construction in the UK will have changed with time.

D.5.2 Impervious elements

Description of the historical development of impervious elements in UK embankment dams are given in Binnie (1981, 1987), Johnston (1999), and Skempton (1989).

D.5.3 Outlet works

Table D.13 gives a description of the chronological introduction of materials likely to have been used on outlet works construction, taken from Brown (1996).

Table D.13 : Dates of introduction of materials likely to have been used in dam construction

Date	Material	Remarks
1200BC	Iron	Took over from copper
1783 AD	Puddling process to produce Wrought Iron	Wrought iron originally produced by removing carbon and other impurities from cast (pig) iron by repeated hammering; however Henry Cort patented puddling process which heated the pig-iron with haematite whilst stirring (puddling) with long iron rods
1824	Portland cement	Joseph Aspdin patented process for making cement by heating powered limestone with selected clays
1850's	Steel	Lower iron carbon content of pig iron to below 1.5% and controlling other impurities. Bessemer process invented. Replaced in mid 1950's by oxygen process. Carbon content of mild steels 0.1 to 0.25%, medium (0.25 to 0.6%) and hard steels (0.6 to 1.5%).
1854	Reinforced concrete	Patent by Wilkinson recognising use of iron in concrete (Bussel, 1996). However, wide use only started in 1892 with Hennebique system. See also other papers on the Special Issue : Historic concrete in Proc ICE Structs & Buildings Aug/Nov 1996.
	Precast Concrete pipes	Date of introduction not available
1920's	Spun grey iron pipes	see Reader et al, 1997, Section 2.4
1960's	Ductile iron pipes	

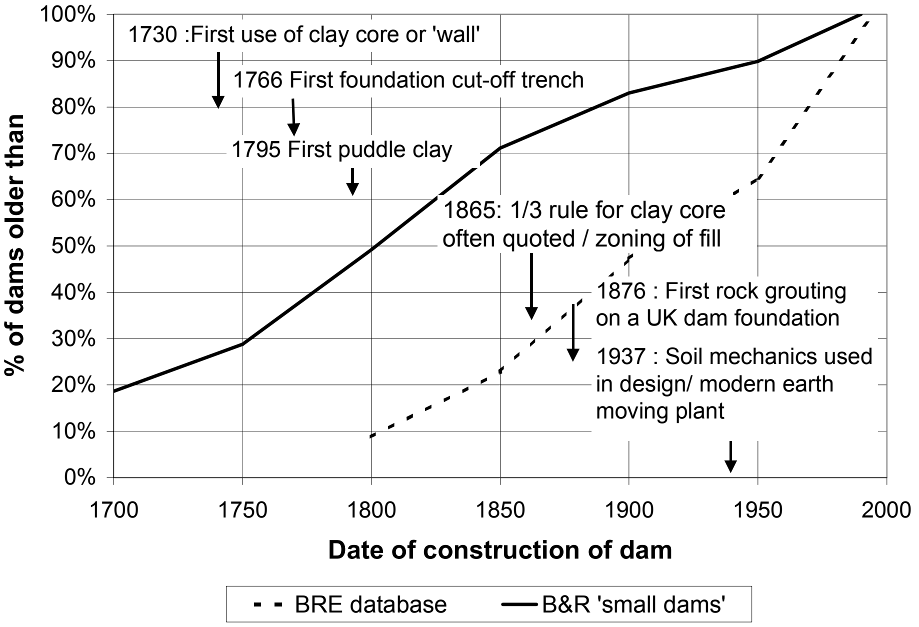


Figure D.1: Distribution of Date Completed for Dams in BRE Register

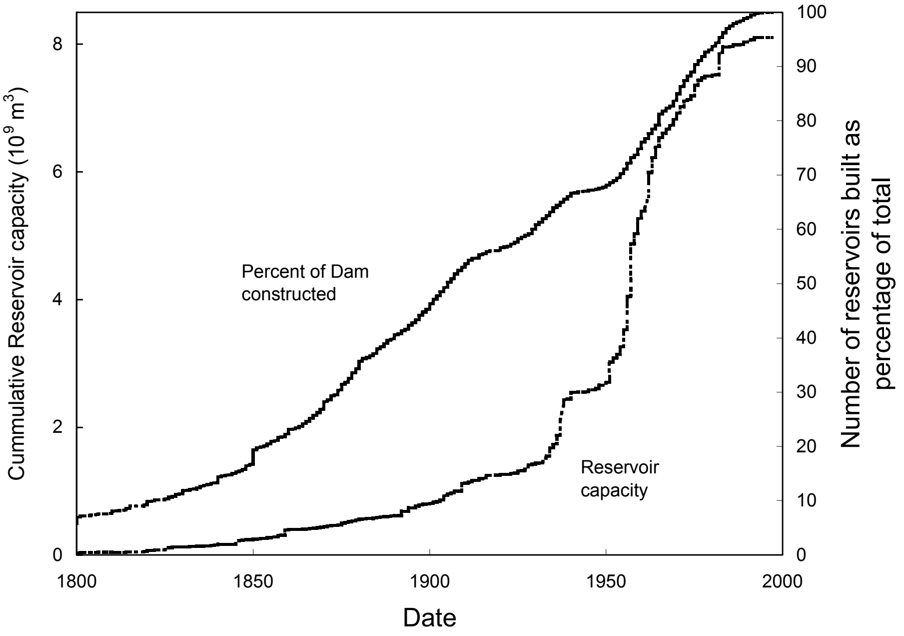


Figure D.2: Distribution of Age and Reservoir Capacity of British Reservoirs

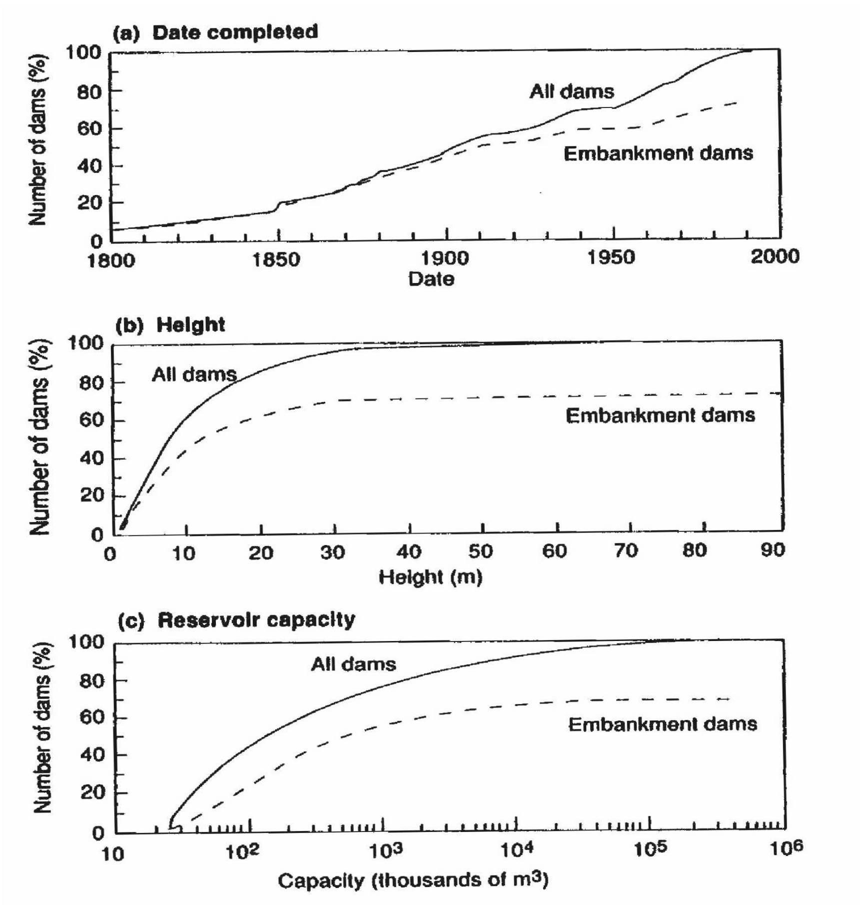


Figure D.3 : Distribution of Date Completed, Height and Reservoir Capacity for UK Dams

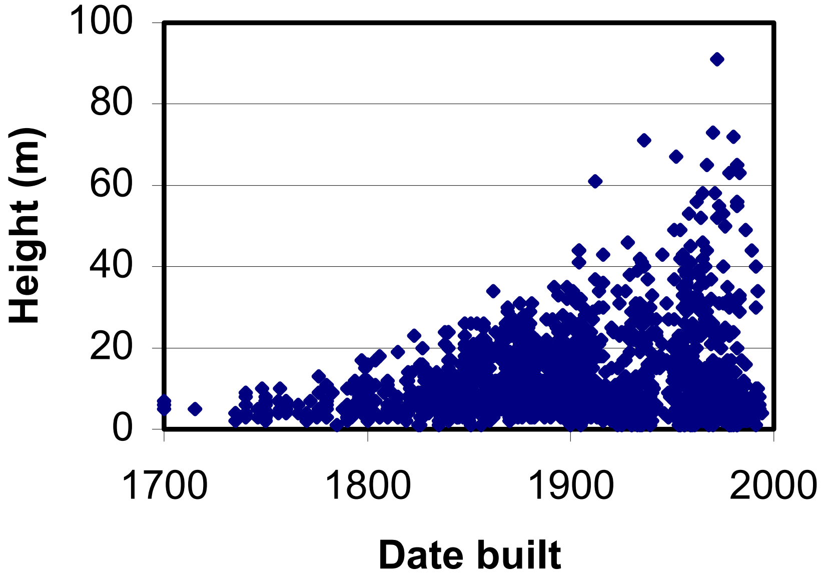
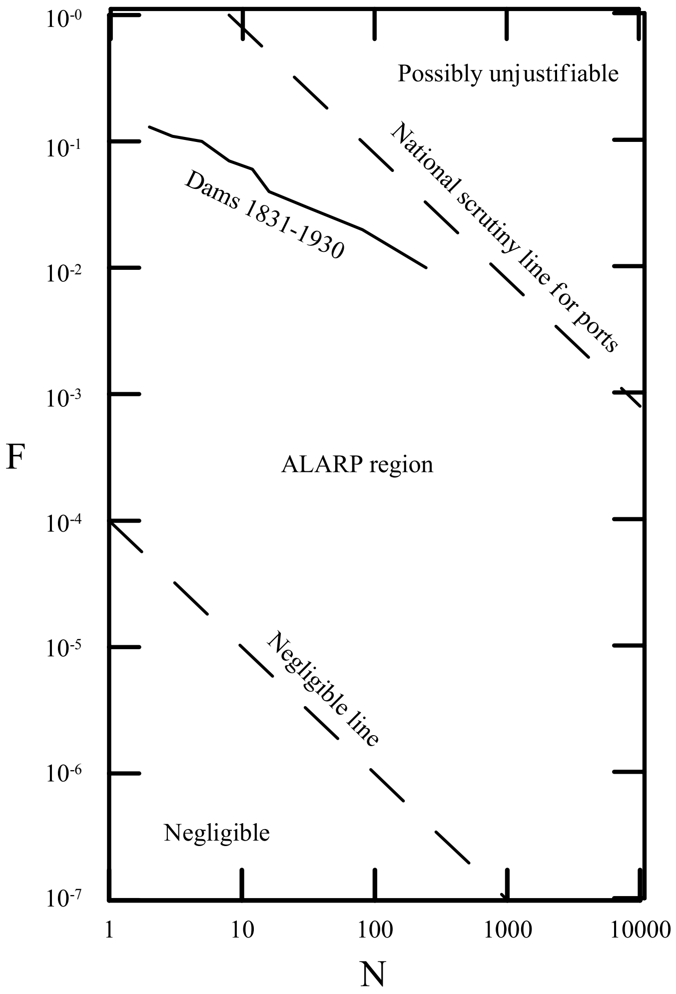


Figure D.4: Distribution of Dam Height with Date Built



F = frequency of N or more fatalities

N = number of fatalities

ALARP = as low as reasonably practicable

Figure D.5: Comparison of British Dam Failures During the Period 1831-1930 with Risk Tolerability for Ports as Given by HSC Advisory Committee on Dangerous Substances (after Charles 1997)

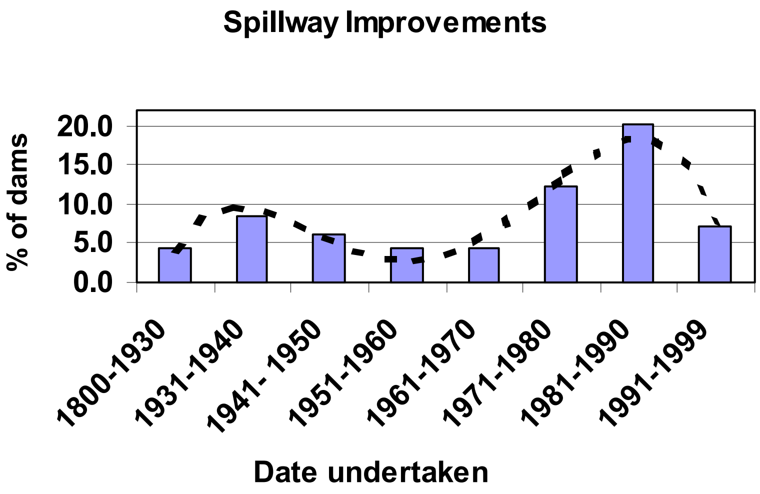


Figure D.6: Upgrading of Spillways with Time