Evolution of CFRD Technology *in* Korea

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Contents

PART 1

CFRD ?

CFRD

Concrete Face Rockfill Dam

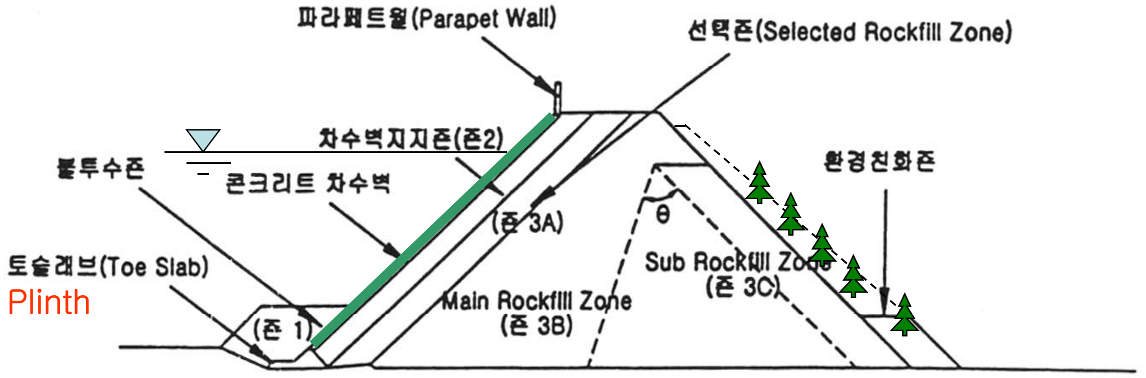
◆댐설계기준•해설 (2011, 국토해양부)

- **표면차수벽형석괴댐**

  제체의 상류면에 콘크리트 또는 아스팔트 등의 인공차수재료에 의한 차수벽을 설치하여 댐의 차수기능을 충족시키고, 그 배후에는 투수성 재료를 배치하여 제체의 안정성을 확보하는 댐

  – **콘크리트** 표면차수벽형 석괴댐
  – **아스팔트** 표면차수벽형 석괴댐

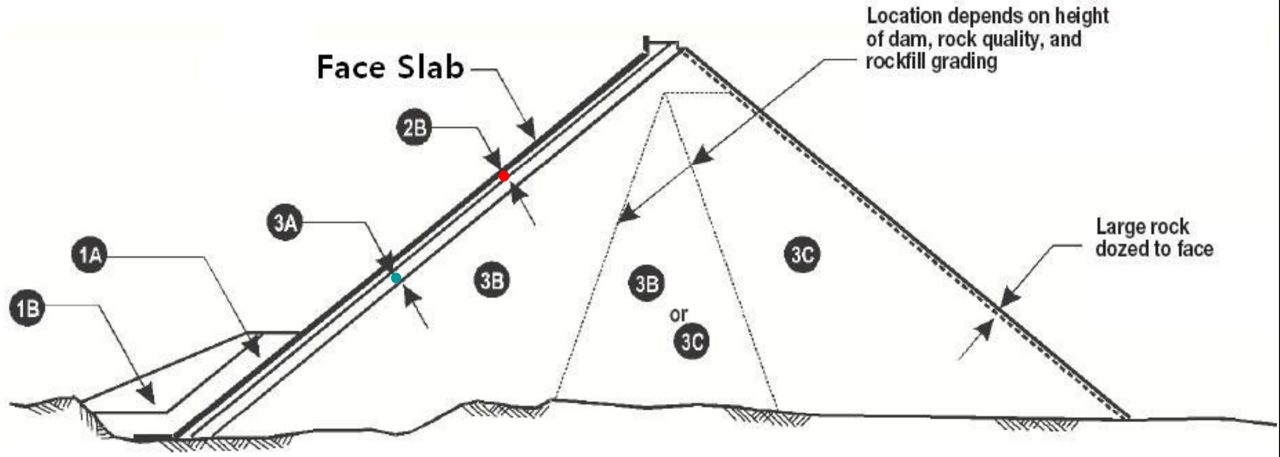
댐설계기준•해설 (2011, 국토해양부)



※ θ는 댐의 높이, 암석재료상태, 암석축조 등에 의존하는 값이다.

- ZONE-1 : upstream blanket zone
- ZONE-2 : Bedding Zone, d_{max}<75mm, #200:<5-15%
- ZONE-3A : Transition Zone, <150mm
- ZONE-3B : Main Rockfill Zone, <800mm
- ZONE-3C : Sub Rockfill Zone, <1500mm

ICOLD Bulletin 141



1A Cohesionless fine-grained soil
1B Random fill
2A Perimeter zone filter
2B Processed minus 75 mn
3A Selected rockfill – 0.4 m layers
3B Quarry run rockfill – 1 m layers
3C Quarry fun rockfill – 2 m layers

Zone	Material	Grading	Layer
2A	Filter	Minus 36 mn	0.4 m
2B	Crushed rock	Minus 75 mn	0.4 m
3A	Rockfill	Minus 0.4 m	0.4 m
3B	Rockfill	Minus 1.0 m	1.0 m
3C	Rockfill	Minus 2.0 m	2.0 m

Advantages

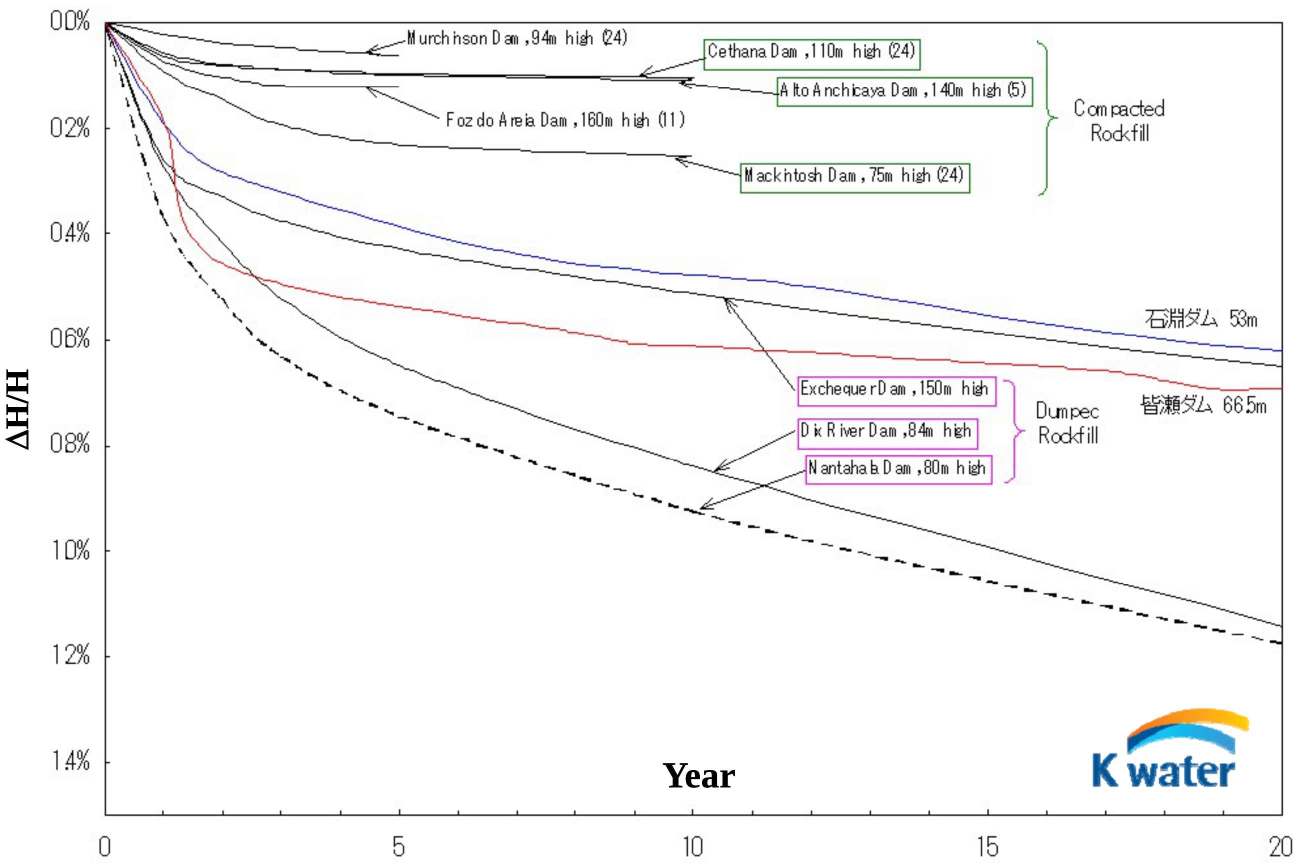
1. 안정성

① **사면안정성 :** 1:1.3~1.4 ☞ ϕ=40~50도 > 안식각

② **침투안정성 :** 조립의 배수재료, 간극수압=0

③ **내진성 :** 과잉간극수압=0, 지진파괴사례=0

④ **변형특성 :** 침하량=작음



Advantages

2. 경제성 (CFRD=1.0)/ 신속성

① 콘크리트댐 체적 : 1 / 2.7

② 아치댐 체적 : 1/10 ~ 1/14

③ 중심코아형석괴댐 : 약 40~50%

④ 아스팔트 페이스 콘크리트댐(AFRD) :
상류사면: CFRD=1:1.3-1.4, AFRD=1:1.7

Advantages

3. 적응성

① 지형, 지질, 기후의 영향 작음

② 기존댐의 숭상에 유리

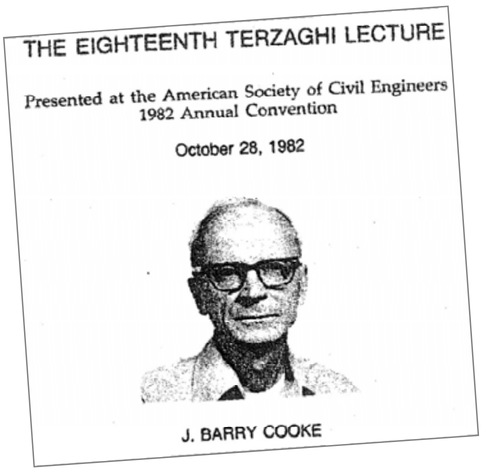
③ 분할시공 가능

PART 2

History of CFRD

Success & Failure

The 1st CFRD



THE EIGHTEENTH TERZAGHI LECTURE

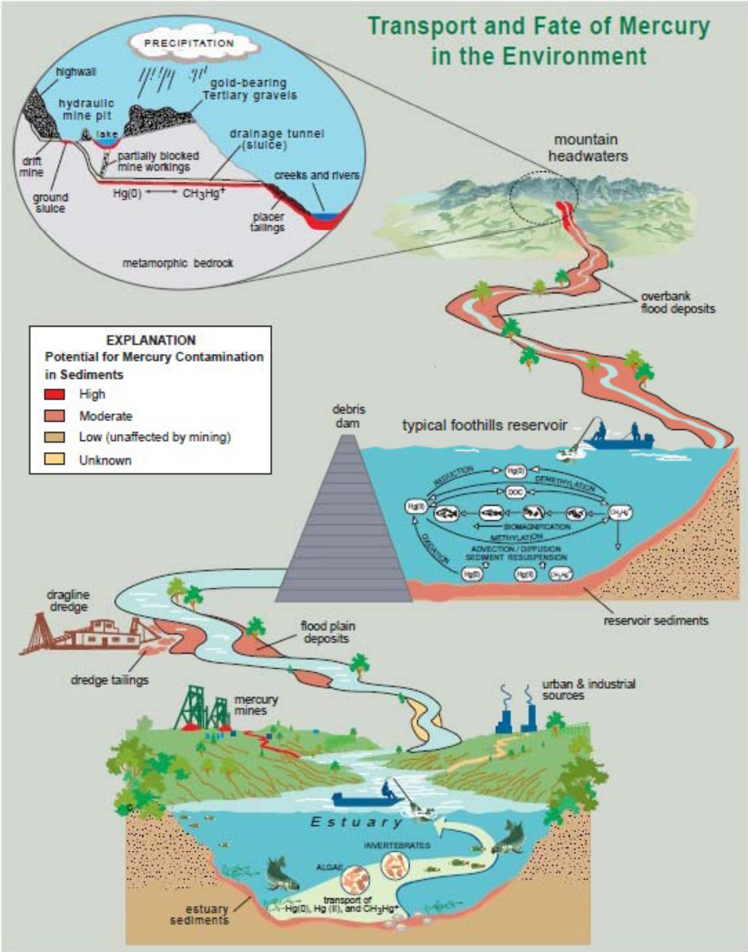
Presented at the American Society of Civil Engineers
1982 Annual Convention

October 28, 1982

J. BARRY COOKE

Figure 1. Monitors (water cannons) were used to break down the gold-bearing gravel deposits with tremendous volumes of water under high pressure. Some mines operated several monitors in the same pit. Malakoff Diggings, circa 1860.

"The concrete face rockfill dam, CFRD, had its origin in the mining region of the Sierra Nevada in California in the 1850s"



Leakages
&
Deformations

TABLE 1.—Summary History of Rockfill Dams

Periods in evolution of dam technology (1)	Concrete Face			Earth Core		
	Year (2)	Height, in feet (3)	Number or names (4)	Year (5)	Height, in feet (6)	Number or names (7)
Early period (1850–1940) Dumped rockfill	1850	75	Many timber face	1850 to 1940		No earth core
	1925	100	8 dams			
	1925	275	Dix River			
	1930	330	Salt Springs			
	1930–40	200	Many	1940		Begin earth core
Transition period (1940–1965) Dumped	1950–55	200	A number	1940		Begin
		200–300	PG&E dams	1950	250–400	Kenney, Watagua
	1955	370	Paradela	1955	250–420	30 dams
	1965	490	Exchequer	1960	510	Goschenen
Compacted	1955–65	200	Several	1955–65	300–400	Ambuklao, Brownlee, Lewis Smith
Modern period (1965–1984) Compacted rockfill	1965–70	200–300	Many	1965–84	300–600	Many major dams
	1971	320	Cethana		800	Oroville,[a]
						Mica,[a]
	1974	460	Anchicaya		850	Chivor
	1980	530	Areia		1,000	Chicoasen
						Nurek[a]

[a]Earth core gravel shell dams.

70년 경과된 Salt Springs댐

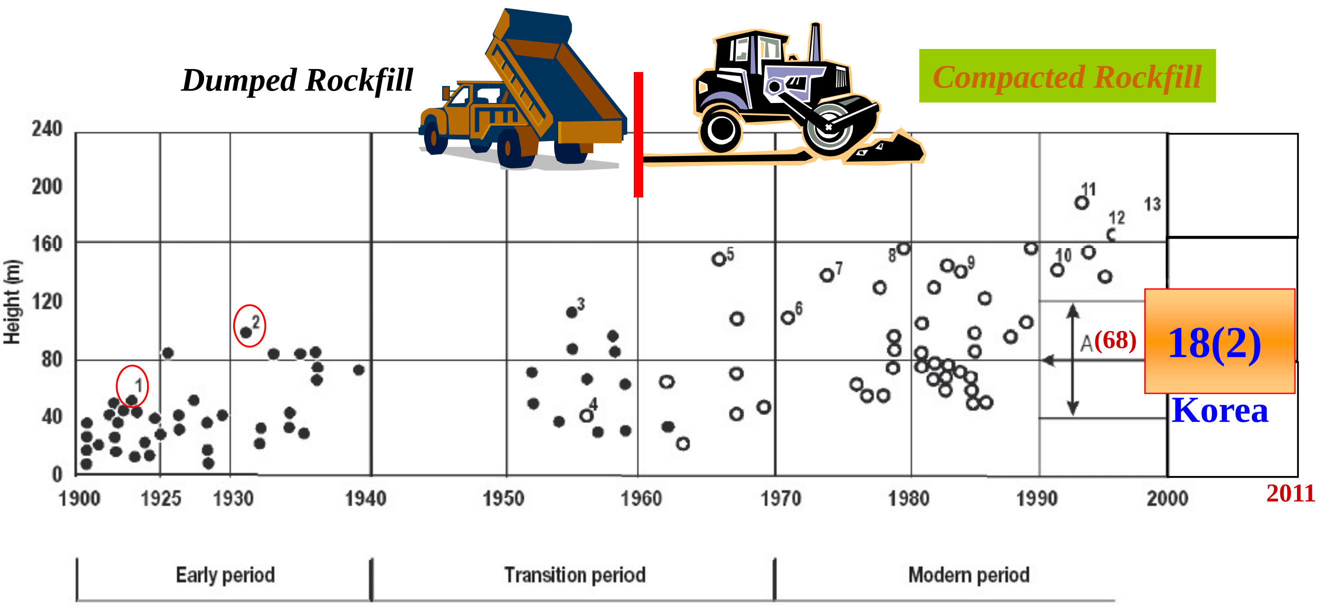
Figure 1: Typical section of the concrete face at Salt Springs dam after 70 years of service and repairs. The shotcrete overlay repairs can be seen in the background.

2005년 차수벽 보수 (Geomembrane)

Figure 4: The geomembrane installation at Salt Springs completed with a protection layer installed at the abutments and the reservoir rising in May 2005.

K water

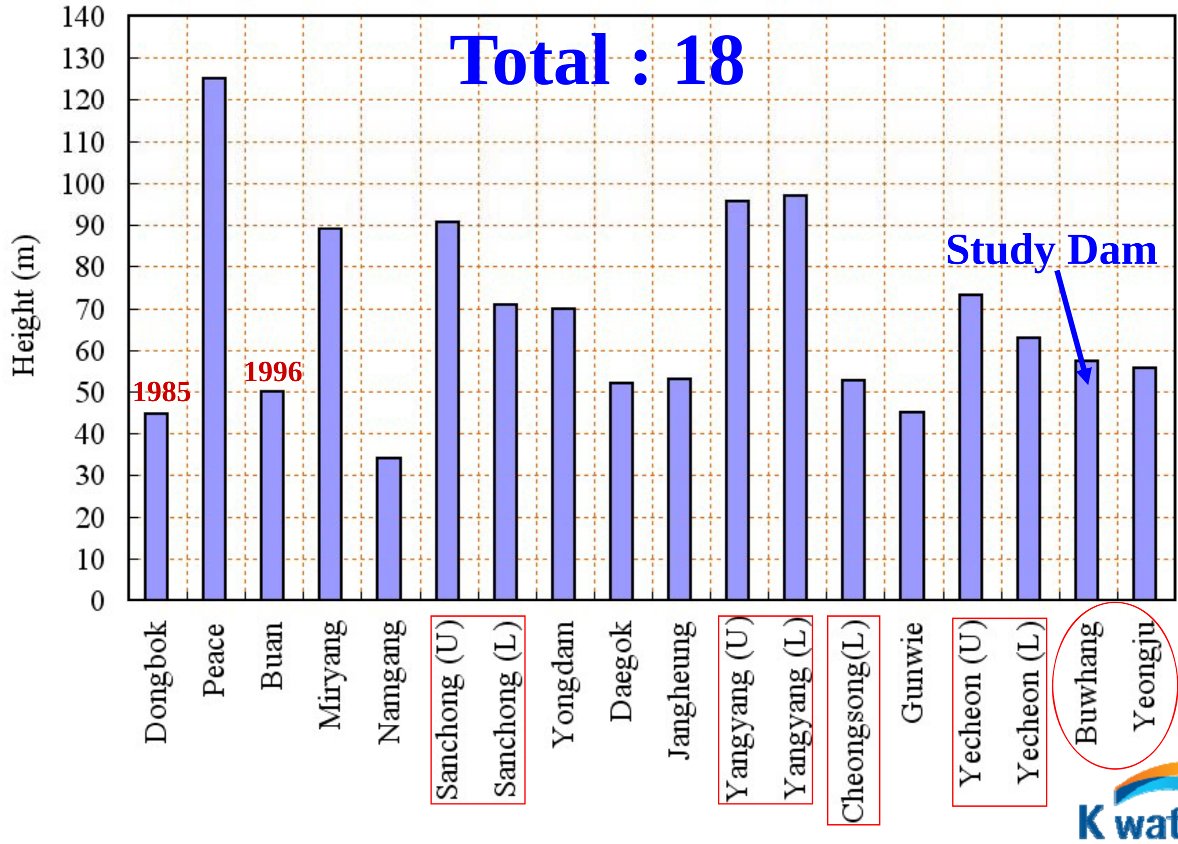
Construction of CFRDs



1. Strawberry Creek
2. Salt Springs Dam

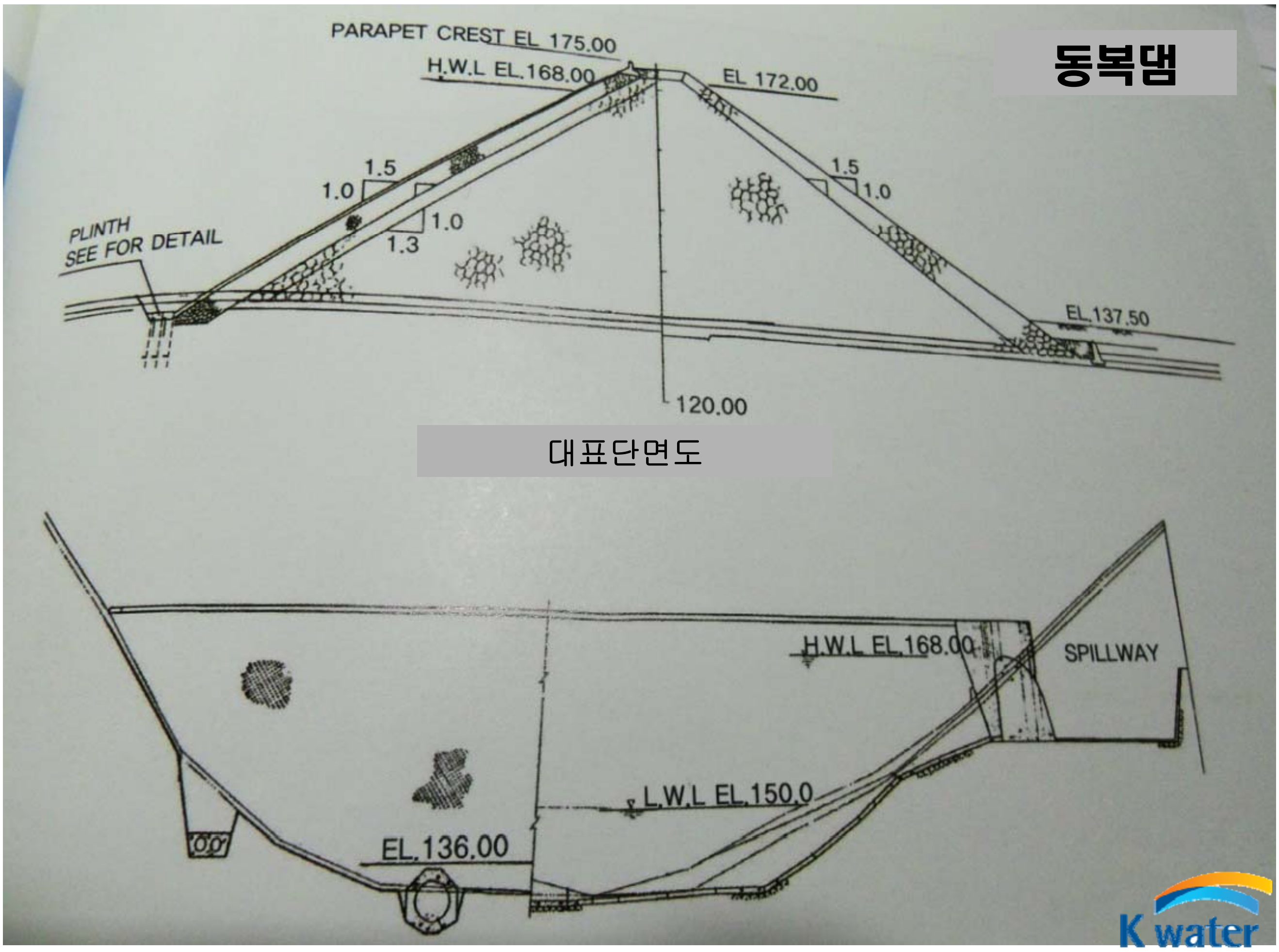
K water

CFRDs in Korea (1985-2011)



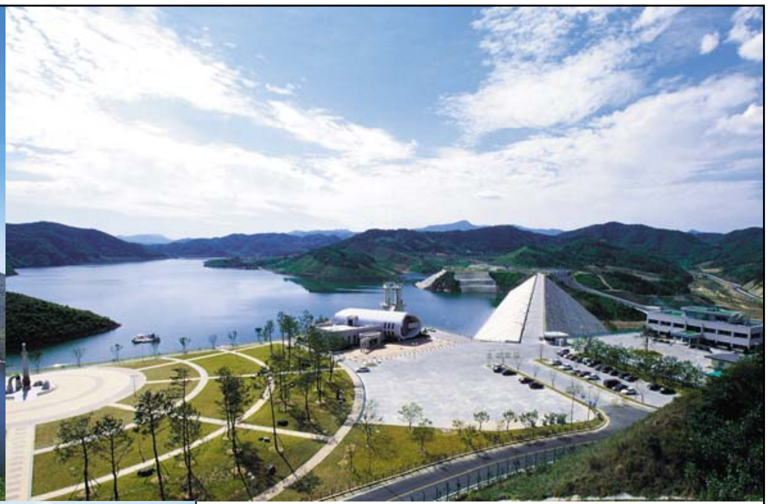
Dongbok(東福) Dam

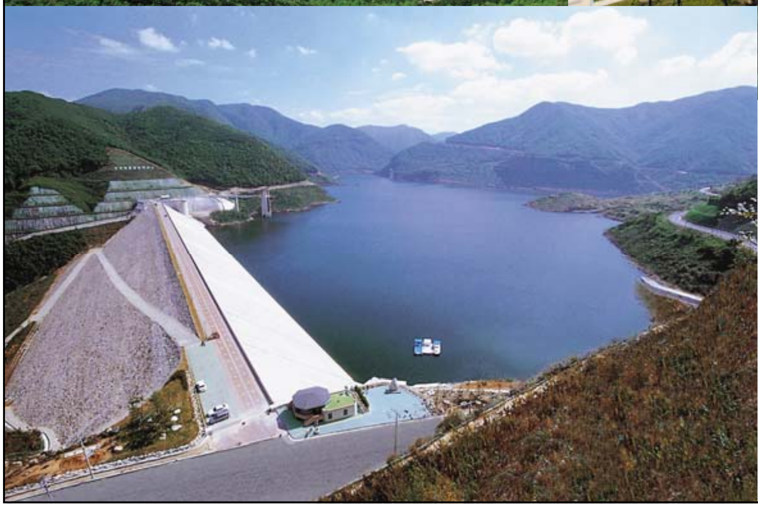
동복댐



대표단면도

남강다목적댐





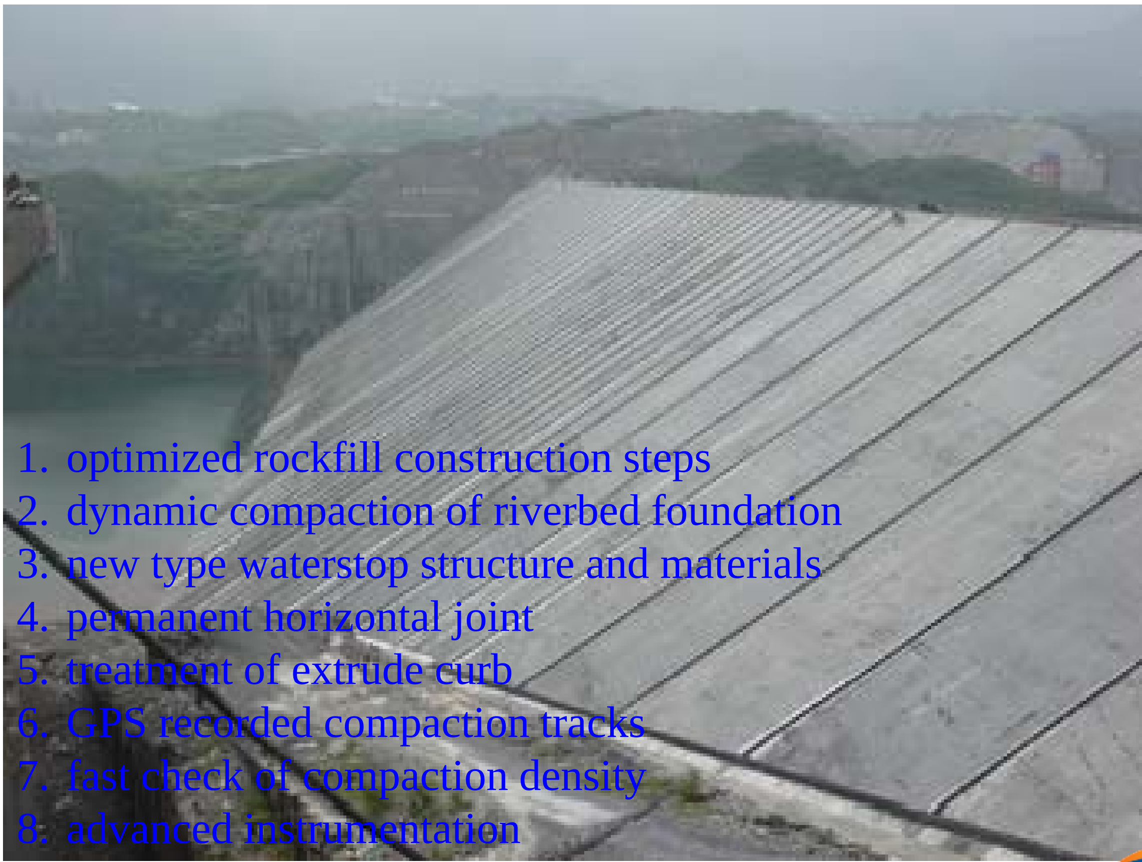
부안댐 용담댐

밀양댐

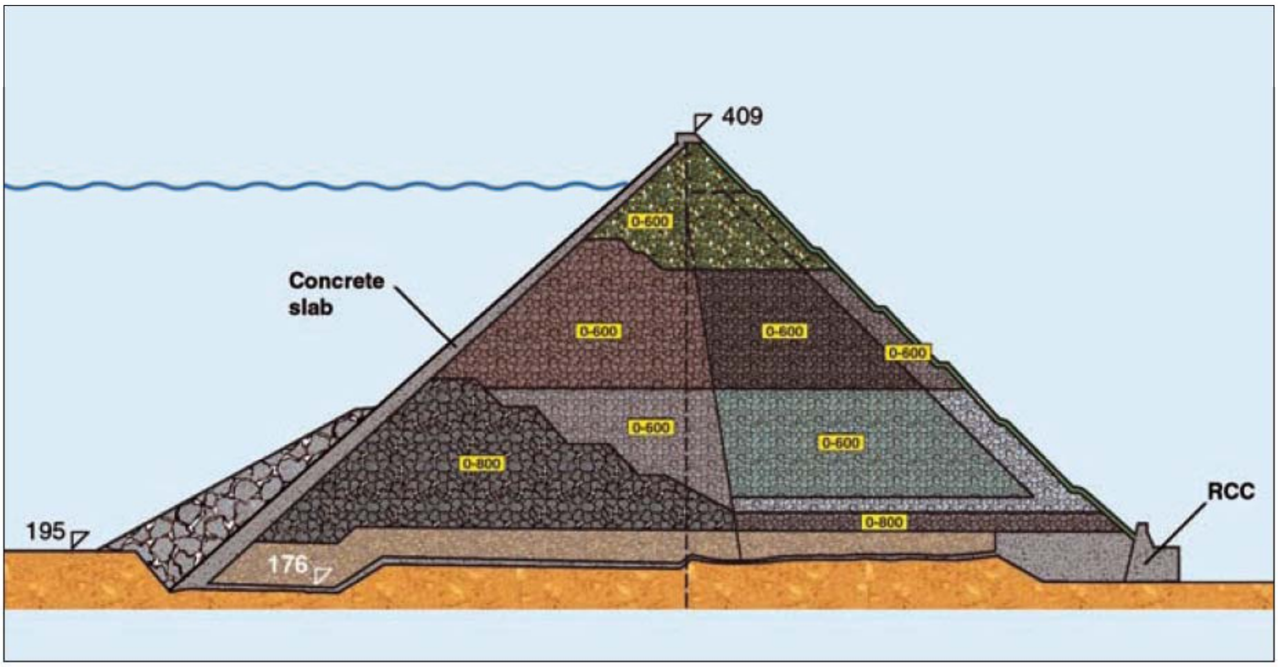
High CFRDs

Shuibuya댐(중국)

공사기간 : 2002-2008
목　　적 : 수력발전+홍수조절
높　　이 : 223m (세계 1위)
저수용량 : 45억m^3



1. optimized rockfill construction steps
2. dynamic compaction of riverbed foundation
3. new type waterstop structure and materials
4. permanent horizontal joint
5. treatment of extrude curb
6. GPS recorded compaction tracks
7. fast check of compaction density
8. advanced instrumentation



Bakun댐(말레이시아)

공사기간 : 2002-2011
목　　적 : 수력발전
높　　이 : 207m (세계 2위)

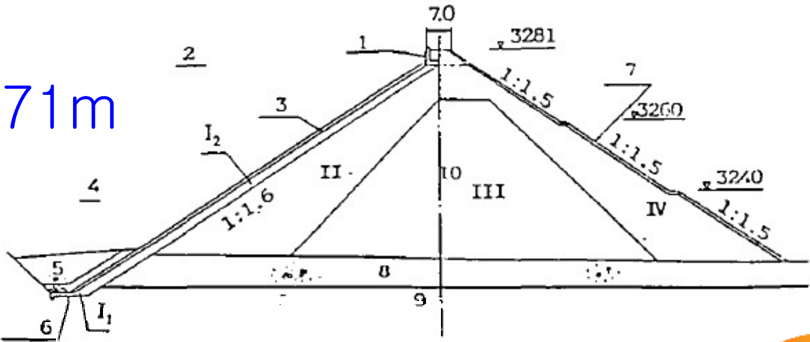
Accidents

Gouhou 댐 붕괴사고 : CFGD
1993. 8.27

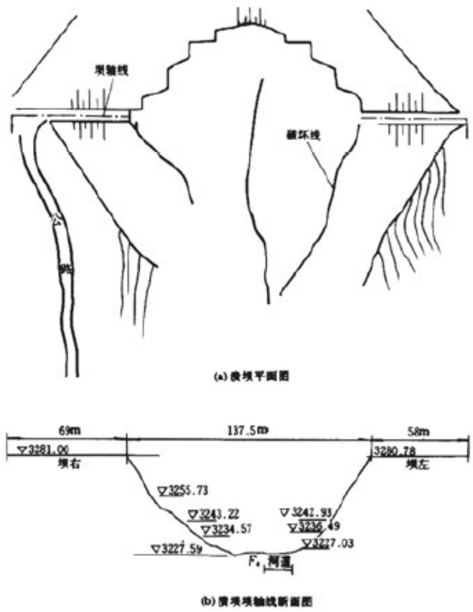
Qinghai Province

원인 : Zoning불량, 축조재료의 배수불량

H=71m



Gouhou댐 붕괴(1993, 중국)



발생 : 1993. 8. 27

피해 : 340명 사망

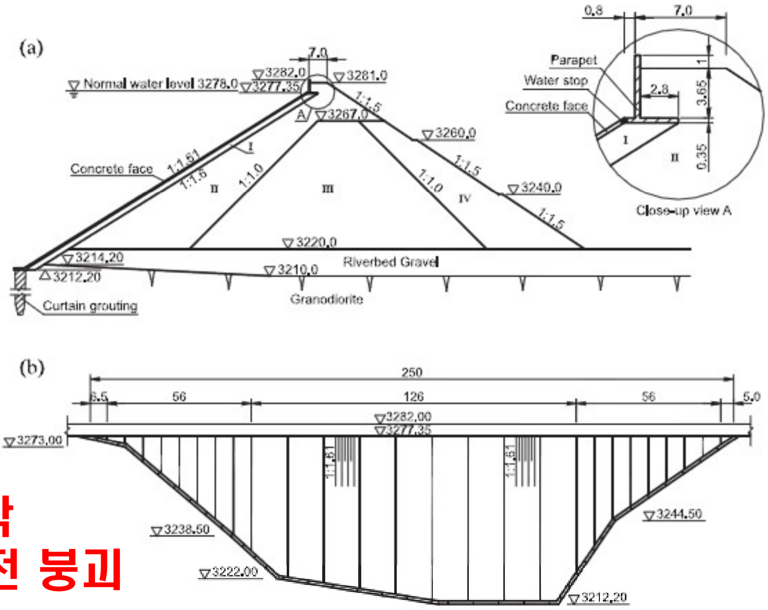
<사고경위>

1985.8 공사착수

1990.10 공사준공

1992.9 담수시작

1993.8.27 20:00붕괴 시작
3시간만에 완전 붕괴



K water

Fig. 13. Pore-water pressure contours (kPa) within the cross section at z = 150 m at different times for case II (sandwich layer): (*a*) t = 0.04 days; (*b*) t = 0.1 days; (*c*) t = 0.2 days; (*d*) t = 0.4 days.

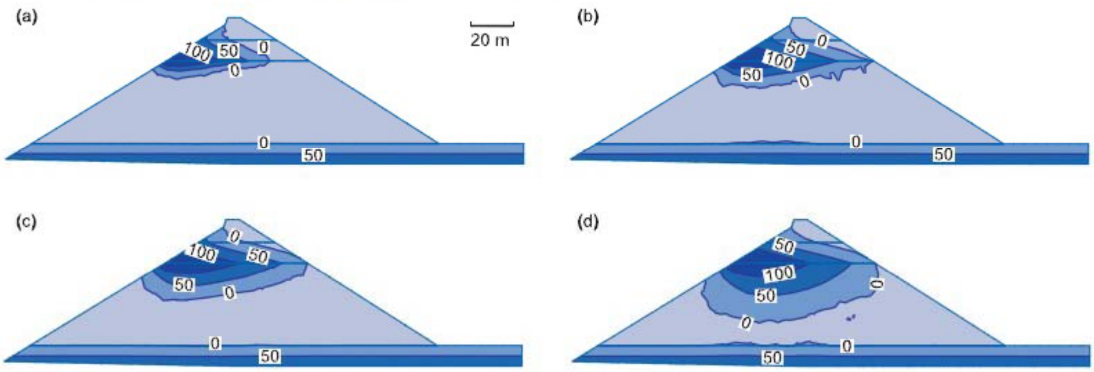
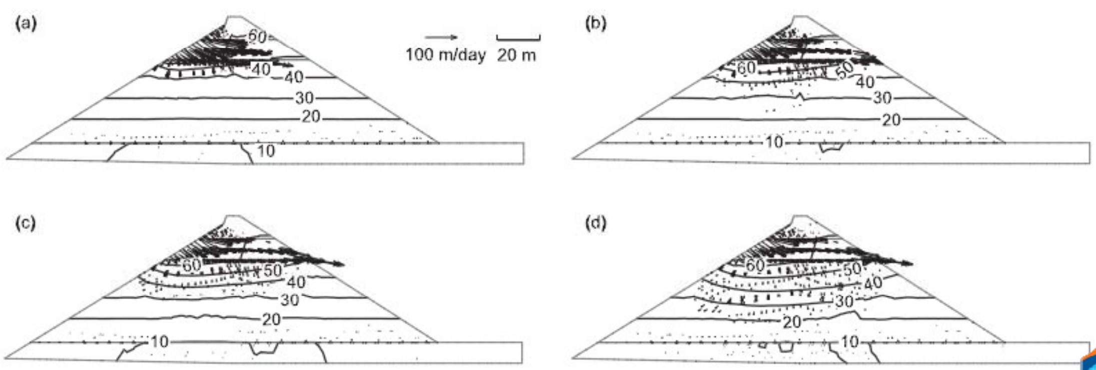
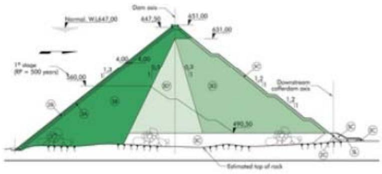


Fig. 14. Total head contours (m) and velocity vectors within the cross section at z = 150 m at different times for case II (sandwich layer): (*a*) t = 0.04 days; (*b*) t = 0.1 days; (*c*) t = 0.2 days; (*d*) t = 0.4 days.



K water

- 댐명 : Barra Grande댐
- 위 치 : 브라질
- 누수량 : 850 *l/sec*
- 높 이 185m
- 사고발생일 : 2005년 9월 22일
- 2006년 9월 차수벽 손상 확인



Barra Grande dam(브라질)의 단면

Barra Grande dam 차수벽의 파괴

Mohale dam(Lesoto, South Africa)

Mohale dam의 차수벽 콘크리트의 전단파괴

- 댐명 : Mohale댐
- 위 치 : Lesoto(South Africa)
- 누수량 : 600 *l/sec*
- 높 이 : 145m
- 사고발생일 : 2006년 2월 15
- 2000년 완공된 이 댐은 2006년 많은 비가 내리면서 수위가 올라가고 이로 인하여 하류방향 및 계곡을 따라 변형이 발생하였다. 이로 인해 댐 중앙부의 차수벽에 압축응력이 발생하여 파괴.

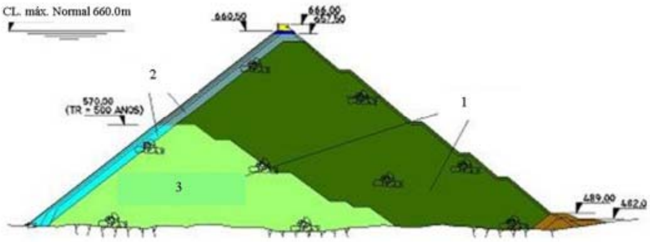
전단된 콘크리트를 제거한 후의 Mohale CFRD slab joint

파괴 분포(Mohale dam)

그림 3.3 Barra Grande dam과 Mohale dam의 차수벽 손상 사례

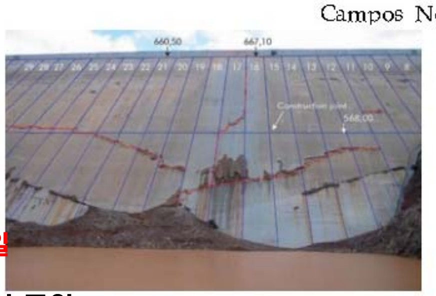
K water

Campos Novos Dam
- 위 치 : 브라질
- 준공연도 : 2005년
- 댐 높이 : 202m
- 댐 길이 592m
- 저수용량 : 12억m^3

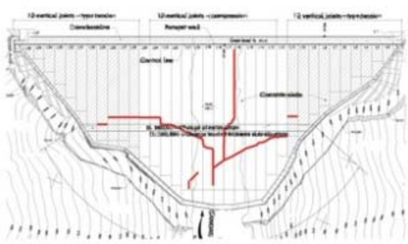


Campos Novos 댐 단면

- 누수량 : 1200
- 담수시작 : 2005년 10월
- 사고발생일 : 2005년 10월 19일
- 공 법 : compacted rockfill
- 현 황 : 계곡형상, 댐높, 재료특성 등의 복합적 요인에 의한 댐의 Abut에서 중앙으로의 변형이 발생하면서 댐 길이방향의 압축응력이 발생하여 콘크리트 차수벽 파괴



파괴 분포



파괴 분포

Abutment 부근의 파괴

전단된 철근

그림 3.2 Campos Novos Dam의 차수벽 손상 사례

K water

CFRD 기술발전 ?!?

TABLE 2.—Partial List of CFRD Dams over 50 Meters High with Design Data

Name (1)	Height, in meters (2)	Location (3)	Year completed (4)	Slopes US (5)	Slopes DS (6)	Fill-rock type (7)	Face area, in square meters (8)	Slab equation m + CH (9)	Reinforced each way, as a percentage (10)	Toe slab width, in meters (11)	Zone 1, in meters (horizontal) (12)
Morena	54	California	1895	0.5–0.9	1.3	DR-Granite		0.23 + 0.003H	0.5	Trench	
Strawberry	50	California	1916	1.2	1.3	DR-Granite		0.23 + 0.003H	0.5	Trench	
Dix River	84	Kentucky	1925	1.0–1.2	1.4	DR-Limestone			0.5	Trench	
Salt Springs	100	California	1931	1.1–1.4	1.4	DR-Granite	10,900	0.3 + 0.0067H	0.5	Trench	
Cogswell	85	California	1934	1.35	1.6	DR					
Malpaso	78	Peru	1936	0.5	1.33	PR & DR					
Cogoti	75	Chile	1939	1.6	1.8	DR-Gravel					
Lower Bear Number 1	71	California	1952	1.3	1.4	DR-Granite	5,800	0.3 + 0.0067H	0.5	Trench	
Lower Bear Number 2	50	California	1952	1.0	1.4		2,800	0.3 + 0.0067H	0.5	Trench	
Paradela	112	Portugal	1955	1.3	1.3	DR-Granite	55,000	0.3 + 0.00735H	0.5	Trench	
La Joie	87	Canada	1955	1.1	1.5	DR		Shotcrete		Trench	
Pinzanes	67	Mexico	1956	1.2	1.3	DR					
Courtright	98	California	1958	1.0–1.3	1.3	DR-Granite	6,700	0.3 + 0.0067H	0.5	Trench	
Wishon	82	California	1958	1.0–1.3	1.4	DR-Granite	20,000	0.3 + 0.0067H	0.5	Trench	
San Idelfonso	62	Mexico	1959	1.4	1.4	CR-DR					
New Exchequer	150	California	1966	1.4	1.4	Main DR-Meta Andesite Supporting Zone-CR		0.3 + 0.0067H	0.5		
Cabin Creek	76	Colorado	1967	1.3	1.3	CR			0.5		
Fades	70	France	1967	1.3	1.3	CR-Granite	16,500	0.35 + 0.0042H	0.5	4.0	
Rama	110	Yugoslavia	1967	1.3	1.3	CR					
Kangaroo Creek	59	Australia	1968	1.3	1.4	CR-Schist	8,000	0.3 + 0.005H	0.5	3.7	3.6
Pindari	45	Australia	1969	1.3	1.3	CR-Rhyolite	16,400	0.48 + 0.002H	0.81	3.0 minimum (2.6 × 0.085H)	4.5
Pindari Raised	75	Australia	P	1.3	1.3	CR-Rhyolite					
Cethana	110	Australia	1971	1.3	1.3	CR-Quartzite	23,700	0.3 + 0.002H	0.5[a]	3–5.36	3 + 3
Alto Anchicaya	140	Colombia	1974	1.4	1.4	CR-Hornfeld	22,300	0.3 + 0.003H	1 + 0.5	7.0	Varies-10 (toe)
Le Rouchain	60	France	1976	1.4	1.4	CR-Granite	16,000	0.35 + 0.0042H	0.5	4.0	
Little Para	54	Australia	1977	1.3	1.4	CR-Shaley Dolomite	10,200	0.3 + 0.0029H	0.5	4.0	4.0
Golillas (Chuza)	130	Colombia	1978	1.6	1.6	CG-Gravel	14,300	0.3 + 0.0037H	0.4	3.0	4.0
Outardes 2	55	Canada	1978	1.4	1.4	CR-Gneiss	8,375	0.3	0.45	3.05	
Winneke (Sugarloaf)	85	Australia	1979	1.5	2.2	CR-Sandstone	82,500	0.3 + 0.002H	0.5	0.1H minimum 6 m	5.0
Bailey, R.D.	95	W.Va., USA	1979	2.0	2.0	CR-Sandstone	65,000	0.3 + 0.003H	0.5	3.05 + 0.019H	4.3
Areia	160	Brazil	1980	1.4	1.4	CR-Basalt	139,000	0.3 + 0.0034H	0.4	4, 5.5, 7.5	5.0–7.10
Neveri-Turimiquire	115	Venezuela	1981	1.4	1.5	CR-Limestone	53,000	0.3 + 0.002H	0.5	3.5–7.50	5.0
Mackintosh	75	Australia	1981	1.3	1.3	CR-Greywacke	27,100	0.25	0.5[a]	3.0–3.86	3 + 3

TABLE 2.—Continued

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Mangrove Creek	80	Australia	1981	1.5	1.6	CR-Siltstone and Sandstone	29,100	0.375 + 0.003H	0.35	3, 4, 5	4.0
Mangrove Creek Raised	105	Australia	P	1.5	1.6	CR-Siltstone and Sandstone	33,400	0.3 + 0.003H	0.35	3, 4, 5	4.0
Shiroro	130	Nigeria	1982	1.3	1.3	CR	150,000	0.3 + 0.003H	0.4	6.0	7.0
Yacambu	150	Venezuela	1982	1.5	1.5	CG-Gravel	13,000		0.4		
Murchison	89	Australia	1982	1.3	1.3	CR-Rhyolite	16,200	0.3	0.5[a]	3–4.6	1 + 5
Awonga	47	Australia	1982	1.3	1.3	CR-Meta Sediments (Siltstone-Sandstone)	30,000	0.3 + 0.002H	0.55[b]	Existing concrete dam	3.0
Awonga, Raised	63	Australia	P								
Fortuna	65	Panama	1982	1.3	1.4	CR-Andesite	22,000	0.411 + 0.003H	0.5	4.0	5 + 0.02H
Fortuna, Raised	105	Panama	1983	1.3	1.4	CR-Andesite		0.411 + 0.003H	0.5	4.0	5 + 0.02H
Glennies Creek	67	Australia	1983	1.3	1.3	CR-Welded Tuff	24,500	0.3	0.43	3–4	4.0
Salvajina	145	Colombia	1983	1.5	1.5	CR-Dredger Tailings	50,000	0.3 + 0.0031H	0.4	4.0–8.0	5.0
Bastayan	75	Australia	1983	1.3	1.3	CR-Rhyolite	18,600	0.25	0.5[a]	3–3.8	3 + 3
Boondooma, Stage I	63	Australia	1983	1.3	1.3	CR-Rhyolite	25,000	0.3	0.4	3.5–5.5	3.5
Boondooma, Stage II	73	Australia	P								
Khao Laem	105	Thailand	1984	1.4	1.4	CR-Limestone Karstic	140,000	0.3 + 0.003H	0.5	4.6 (Gallery)	3.5
Bejar	71	Spain	1984	1.3	1.3	CR-Granite	19,140	0.35 + 0.003H	0.4	3-H/15	4
Terror Lake	58	Alaska	1985	1.5	1.4	CR-Greywacke Argillite		0.3 + 0.003H	0.4		
Alsasua	50	Spain	1985	1.3	1.4	CR-Limestone	13,850	0.3 + 0.003H	0.4	4.5 (Gallery)	3
Kotmale	97	Sri Lanka	1985	1.4	1.45	CR-Charnockite	60,000	0.3 + 0.002H	0.5[a]	3–8	3 + 3
Batang A1 (Main Dam)	85	Sarawak	1985	1.4	1.4	CR-Dolerite	65,000	0.3	0.5	4.6	3.5
Batang A1 (Lima Saddle)	60	Sarawak	1985	1.4	1.4	CR-Dolerite	15,000	0.3	0.5	4.6	3.5
Batang A1 (Bekatan Saddle)	70	Sarawak	1985	1.4	1.4	CR-Dolerite	42,500	0.3	0.5	4.6	3.5
Lower Pieman	122	Australia	1986	1.3	1.3–1.5	CR-Dolerite	35,000	0.3 + 0.001H	0.5[a]	3–9.0	3 + 3
Iruru	50	Peru	1986								
Ita	123	Brazil	UD	1.3	1.3	Basalt	110,000	0.3 + 0.00334H	0.4		3.0–6.0
Cirita	85	Indonesia	UD	1.3	1.4	CR-Breccia, Andesite		0.3 + 0.003H	0.4	4, 5, and 7	5–9
Segredo	145	Brazil	UD	1.3	1.3	CR-Basalt					
Acena	65	Spain	UD	1.3	1.3	CR-Gneiss	21,800	0.3 + 0.003H	0.4	3-H/15	3
Kaliwa	100	Philippines	UD								
Machadinho	124	Brazil	UD	1.3	1.3	Basalt	100,000	0.3 + 0.00334H	0.4		3.0–6.0
Split-Rock	67	Australia	UD	1.3	1.3	CR-Greywacke Gravel Breccia, Siltstone		0.3	0.35		4.0
La Miel	180	Colombia	UD	1.5	1.5	CR-Diorite		0.3 + 0.003H			
Dinkey Creek	115	California	P								

PART 3

Current CFRD Technologies in Korea

CFRD기술

A. 조사 기술

B. 설계 기술

C. 시공 기술

D. 유지관리 기술

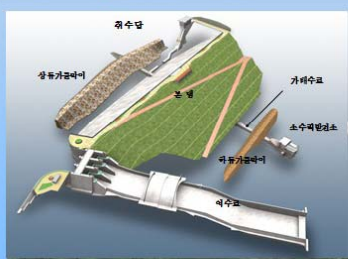
군위 다목적 댐

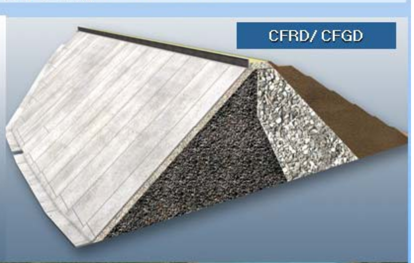
Purpose

- 경북 중부지역(군위, 의성, 칠곡)의 안정적인 용수공급
- 댐 하류 낙동강 유역의 홍수피해 저감
- 소수력 발전을 통한 청정에너지 개발

Dimensions

- 수 계 : 낙동강 위천
- 최 고 수 위 : EL. 207.5m
- 상 시 만 수 위 : EL. 204.0m
- 저수면적 : 2.65㎢(상시만수위 기준)
- 유효저수용량 : 40.1 × 106㎥
- 유 역 면 적 : 87.5㎢
- 계획홍수위 : EL. 205.1m
- 저 수 위 : EL. 181.0m
- 총저수용량 : 48.7 × 106㎥
- 홍수조절량 : 3.1 × 106㎥





TYPE	DIMENSION	VOLUME	GATE	SPILLWAY
Concrete Faced Gravel-fill Dam	H = 45.0m L= 330.0m	877,000㎥	High-Pressure Slide Gate (B : 5.0 m × H : 5.0m × 1EA)	Radial Gate(Gate Control Type) (B : 9.1m × H : 9.4m × 3EA)

부항 다목적 댐

Purpose

- 기상이변에 대비한 감천유역의 홍수피해 경감
- 경북 서북부 지역(김천, 구미)의 안정적 용수공급 도모
- 친수 환경 및 공원조성을 통한 지역경제 활성화

Dimensions

- 수 계:낙동강-감천-부항천
- 유 역 면 적:82.0㎢
- 유 로 연 장:17.4㎞
- 유역평균폭:4.63㎞
- 연평균강우량:1,127㎜
- 연평균유출량:1.65㎥/s
- 계획홍수위(F.W.L):EL.198.6m(200년빈도)
- 상시만수위(N.H.W.L):EL.195.0m
- 저수위(L.W.L):EL.165.0m
- 저 수 면 적:2.57㎢
- 총저수용량:54.3백만㎥
- 유 효 저 수 용 량:42.6백만㎥

TYPE	DIMENSION	VOLUME	SPILLWAY	Generator Equipment
Concrete Faced Gravel-fill Dam	H = 64.0m L= 472.0m	2,189,000㎥	Radial Gate (Over-Topping ype) (B : 7.6m × H : 9.87m × 3EA)	3,310MWh/Year(Volume : 600kW)

영주 다목적 댐

Purpose

- 낙동강 중.하류지역의 수질개선을 위한 하천유지용수 공급
- 최근 이상기후에 의한 낙동강 및 내성천 유역의 홍수피해 경감
- 경상북도 북부지역(영주시, 상주시)의 장래 안정적인 용수공급

Dimensions

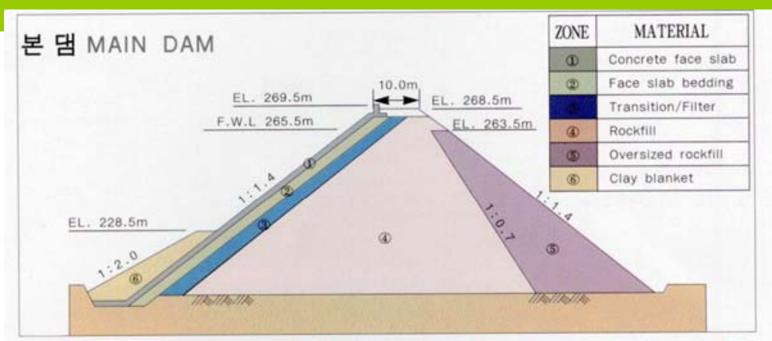
- 수 계 : 낙동강 제1지류 내성천
- 총 저수 용량 : 181.1백만㎥
- 유 역 면 적 : 500.0 ㎢
- 유효저수용량 : 160.4백만㎥
- 계획 홍수위 : EL. 164.0 m
- 년 평균 유입량 : 316.6백만㎥(10.04 CMS)

TYPE	DIMENSION	VOLUME	SPILLWAY	GENERATOR
Concrete Faced Rockfill Dam + Concrete Gravity Dam	H = 55.5m L= 330.0m	1,012,000㎥	Radial Gate (Gate Control Type) (B : 10.4m × H : 13.67m × 5EA)	16.3 GWh/Year(Volume : 5,000kW)

K water

CFRD 설계 단면

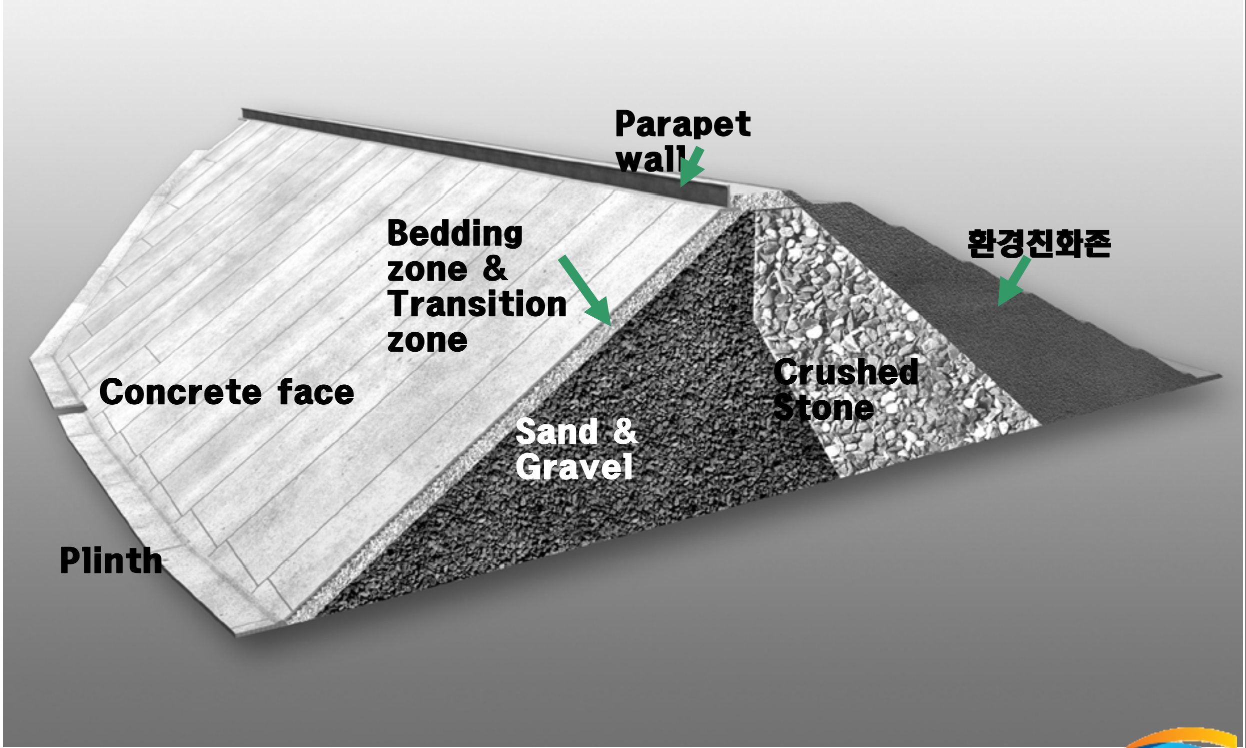
종래의 CFRD 단면



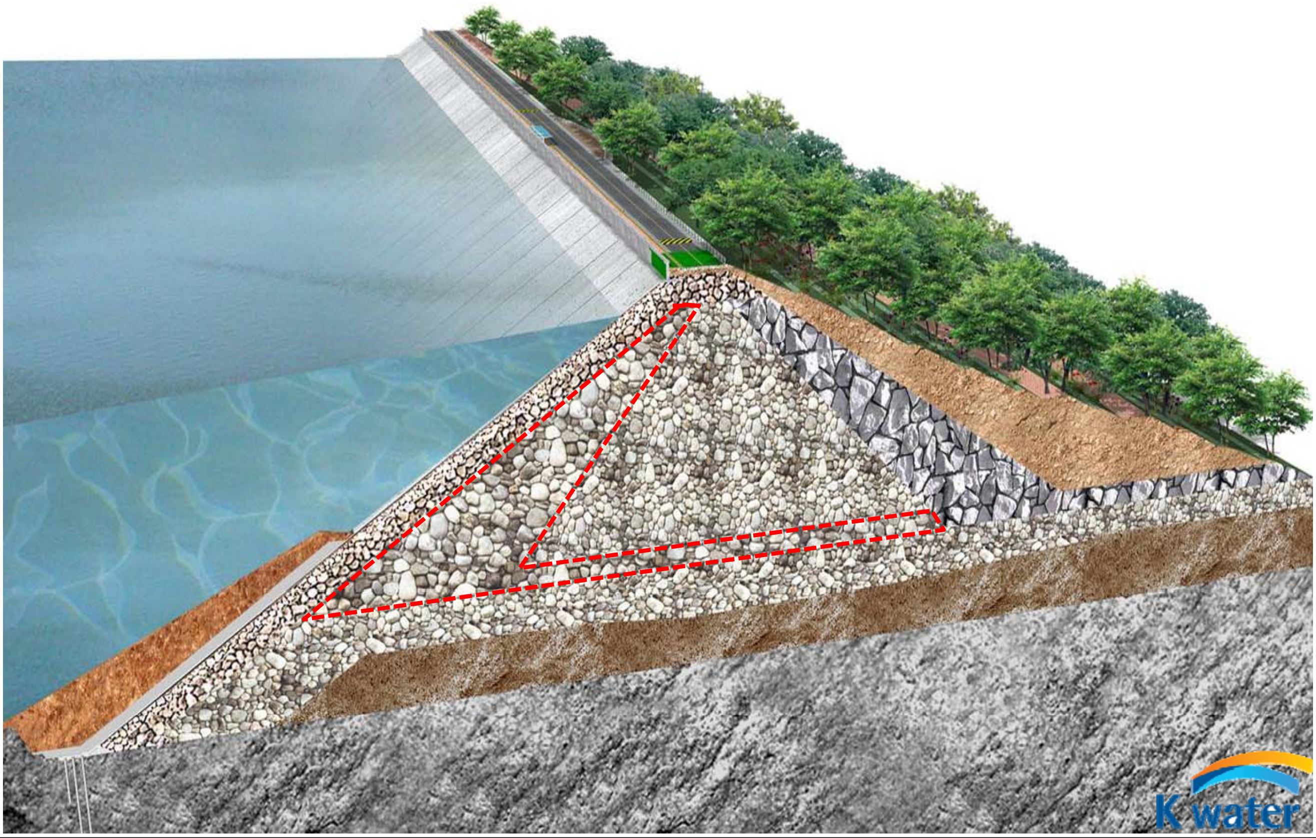
구분		최대치수 (mm)	재료	포설두께 (cm)	살수량	다짐장비	다짐 장비
②	BEDDING Zone	75	하상모래 및 **쇄석재**	40	O.M.C +3.0%~ -2.5%	10TON VIB. ROLLER	6회
③	TRANSITION Zone	150	하상사력 및 **쇄석재**	50	-	10TON VIB. ROLLER	6회
③	GRADED ROCKFILL	800	**발파암**	100	체적의 20%	10TON VIB. ROLLER	4회
⑤	ROCKFILL	1500	**발파암**	160	체적의 20%	10TON VIB. ROLLER	4회
⑥	UPSTREAM BLANET	150	점토	30	O.M.C +3.0%~ -2.5%	30TON Tamping Foot Compactor	6회

K water

최근의 경향 : CFRD=> CFGD



부항댐 입체도



첨단기술의 활용

댐 축조재료의 전단시험

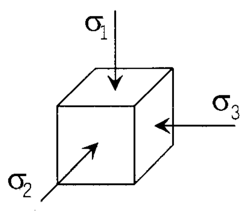
◆ **대형직접전단시험**

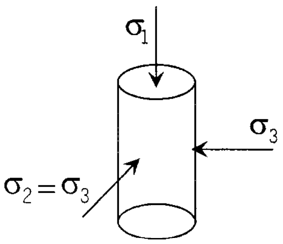
- 실내
- 현장

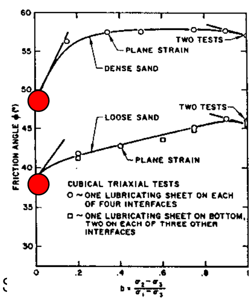
◆ **대형삼축압축시험 (Triaxial Tests)** : $\sigma_1 \neq \sigma_2 = \sigma_3$

- 정적 : 강도, 변형특성 (CU, CU',CD)
- 동적(반복재하) : 액상화, 변형특성시험

◆ 대형 입방체 시험 (Cubical Tests) : $\sigma_1 \neq \sigma_2 \neq \sigma_3$







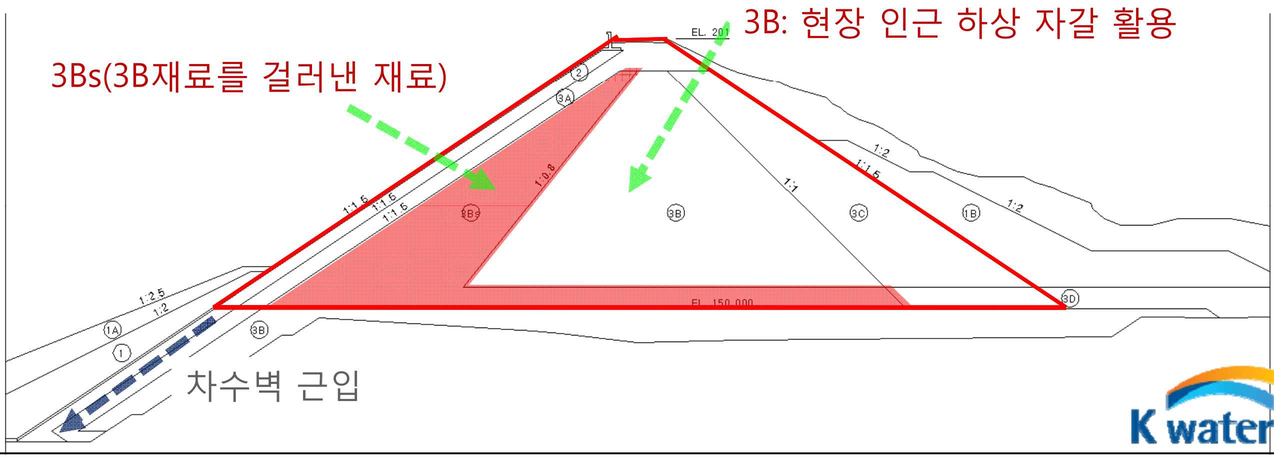
부항댐 원심모형실험

- 구조적 결함, 노후화, 지진 등으로 차수벽 균열 통한 침투수
  - 하상사력재 주축조재료 ⇒낮은 투수성 , 자유 배수 어려움
  - 배수를 위한 선별존 (Zone 3Bs) 도입

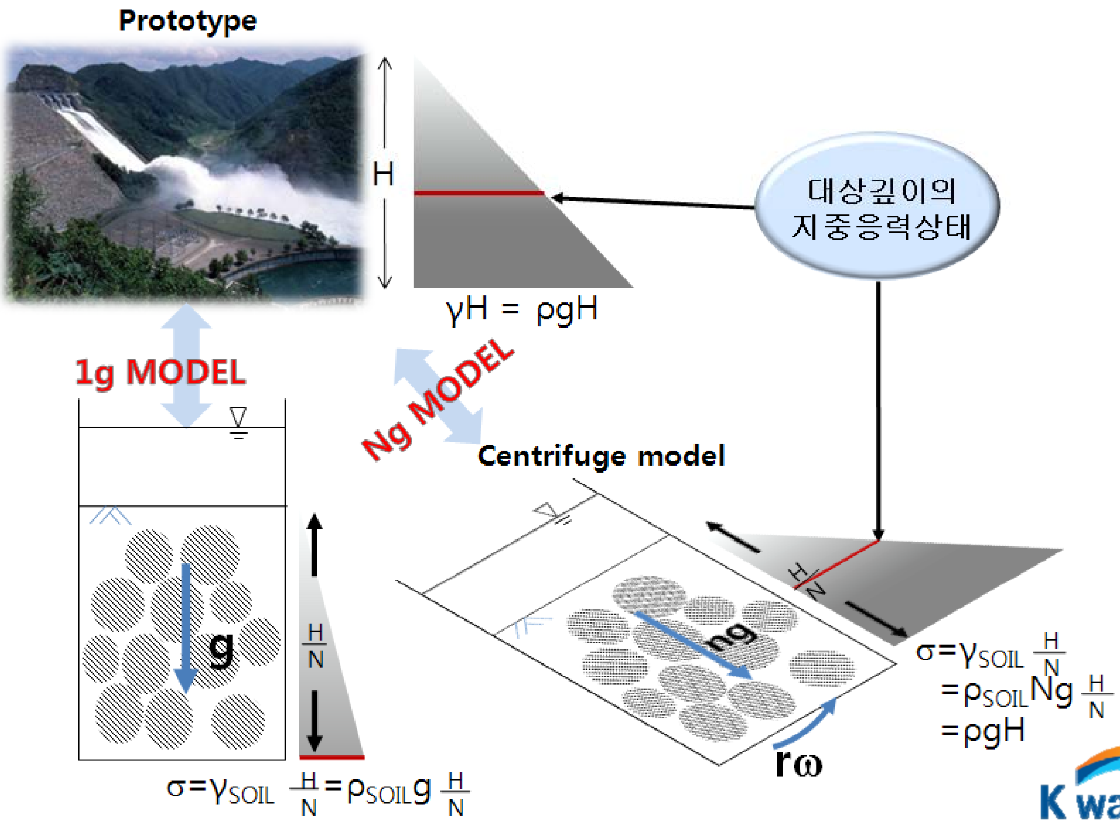
목표 1 : Zone 3Bs(선별존)의 역할 검증

- 특정위치에 깊은 풍화암대 발달로 인한 프린스의 근입

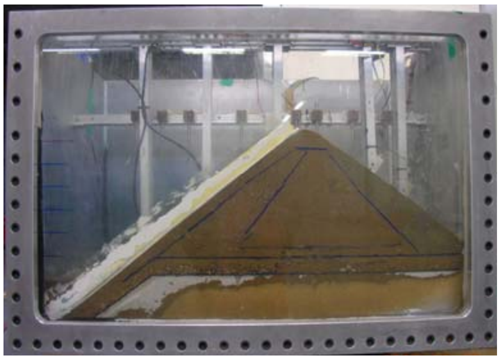
목표 2 : 담수시 차수벽 변형 평가 필요

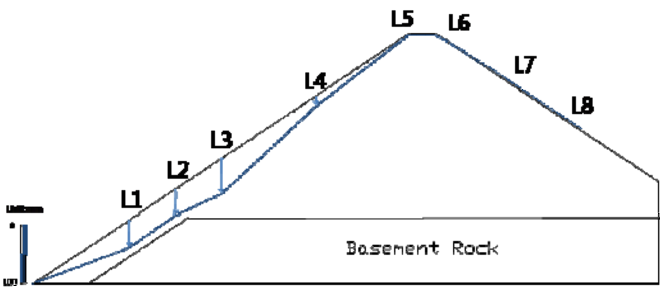


원심모형실험의 원리

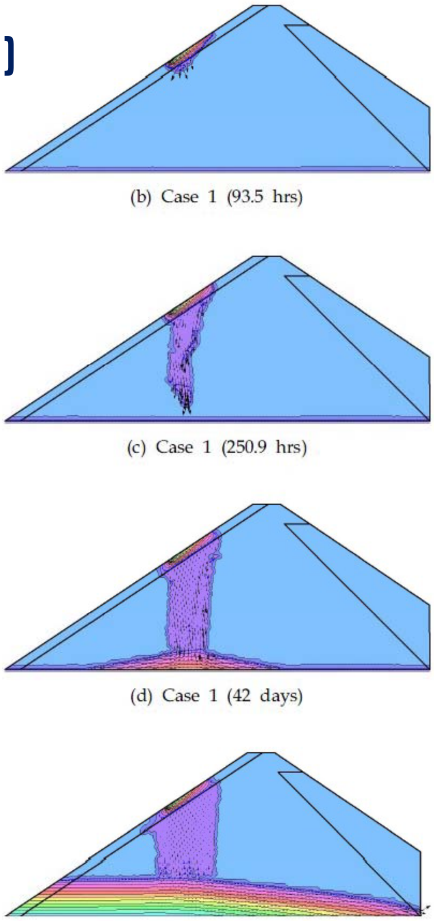


KAIST의 Geo-Centrifuge





3Bs(선별존) 없을 때



(b) Case 1 (93.5 hrs)

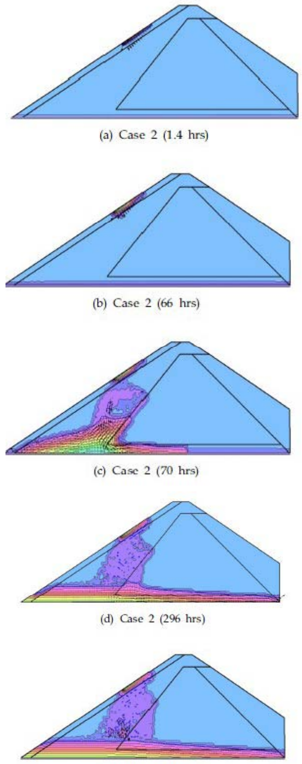
(c) Case 1 (250.9 hrs)

(d) Case 1 (42 days)

(e) Case 1 (300 days)

그림 5.10 시간에 따른 침투거동 (Case1)

3Bs(선별존) 있을 때



(a) Case 2 (1.4 hrs)

(b) Case 2 (66 hrs)

(c) Case 2 (70 hrs)

(d) Case 2 (296 hrs)

(e) Case 2 (497 hrs)

그림 5.13 시간에 따른 침투거동(Case 2)

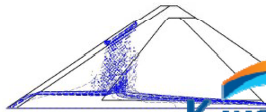
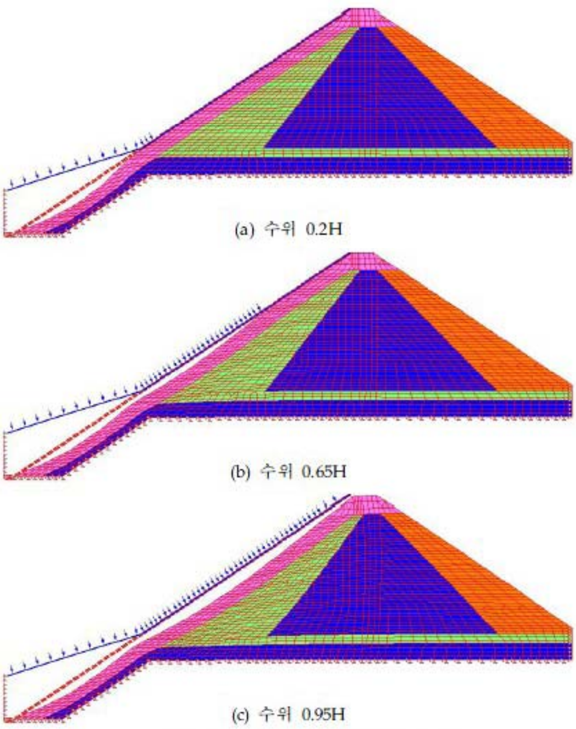


그림 5.14 시간에 따른 침윤선의

K water

변형해석 결과

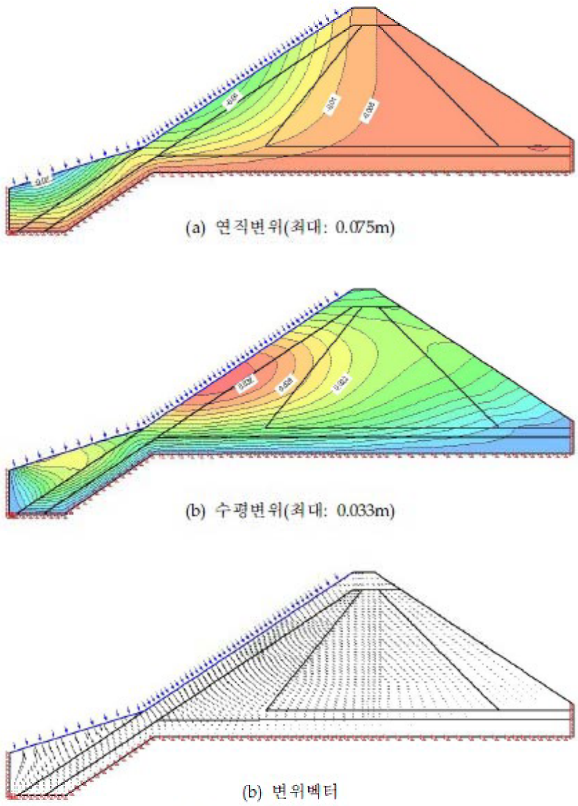


(a) 수위 0.2H

(b) 수위 0.65H

(c) 수위 0.95H

그림 5.17 담수에 의한 차수벽의 변형



(a) 연직변위(최대: 0.075m)

(b) 수평변위(최대: 0.033m)

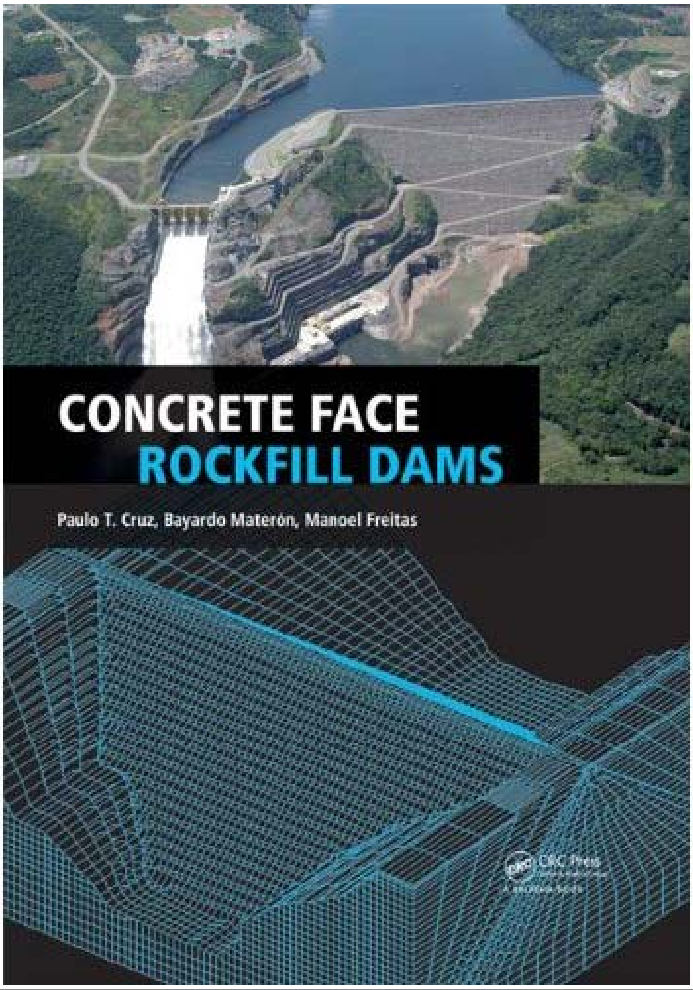
(b) 변위벡터

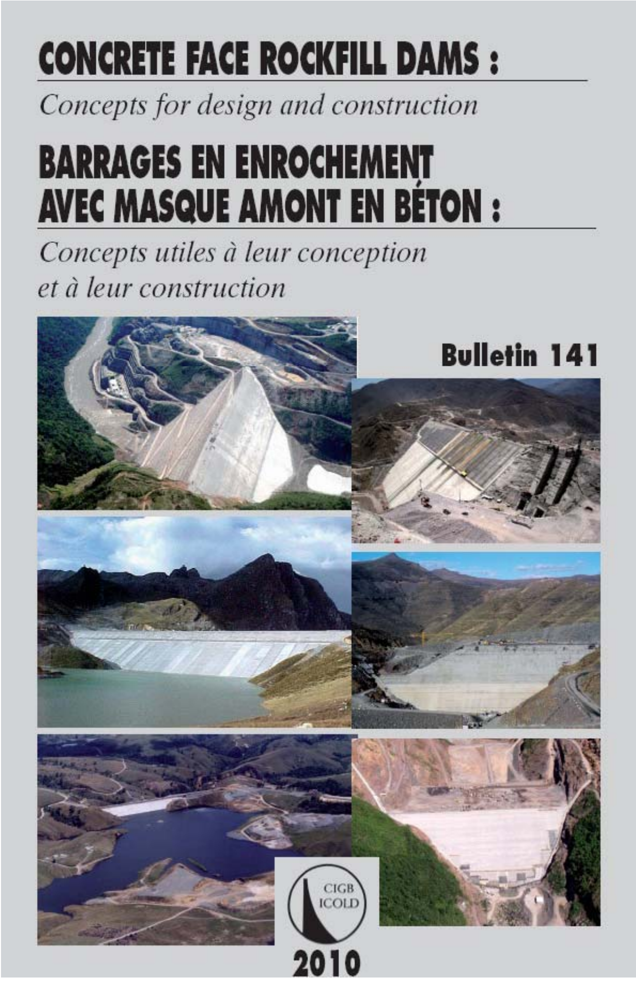
그림 5.19 담수시 해석결과(수압에 의한 변형 증분)

K water

Suggestions !

2010. 9 발간





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