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Settlement Behavior Characteristics of CFRD in Construction Period
- Case of Daegok Dam -

콘크리트 표면 차수벽형 석괴댐의 축조 중 침하거동 특성
- 대곡댐을 중심으로 -

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요 지

본 연구에서는 대곡댐의 계측자료에 의한 CFRD의 축조에 따른 거동분석을 통하여 댐체가 받는 하중의 변화에 따른 침하 변형 거동을 분석하였으며, 외국의 CFRD 계측 결과와 비교 분석하였다. 대곡댐의 깊이에 따른 침하량 분석 결과, 전체적인 거동양상이 일반적인 CFRD 거동과 잘 일치하는 것으로 평가되었다. 또한, 38개 CFRD의 계측자료 분석 결과 변형계수, 간극비, 형상계수 등은 댐체의 침하 거동을 예측하는데 중요한 인자임을 확인하였으며 최대 층별 침하량이 작을수록 간극비는 낮게 나타났다. 최대 층별 침하량과 댐 높이의 관계에서 0.001에서 0.01사이에 상관계수를 갖는 댐이 26개로서, 일반적인 CFRD는 대략적으로 평균하였을 경우 최대 층별 침하량과 댐 높이는 0.005의 상관계수를 갖는 것으로 나타났다. 간극비가 낮은 경우 변형계수가 높았으며 형상계수는 4 이하로 나타났고 간극비가 높은 경우 상대침하율이 상대적으로 컸으며 형상계수도 4 이상으로 나타났다.

Abstract

In this study, the deformation behavior of Daegok dam during the construction was analyzed based on the measurement data and a comparative analysis with foreign CFRD measurements was performed. From measuring settlements of Daegok dam with depth, overall behavior was evaluated to be consistent with measured data of other CFRD dams. In addition, construction modulus, void ratio and shape factor were also evaluated to be major factors in predicting the settlement behavior during construction of CFRD-typed dam from measured data of 38 CFRD-typed dams, and the maximum internal settlement is proportional to the void ratio. From the relationship between the maximum internal settlement and the height of a dam, 26 dams were assessed to have its relative modulus ranging between 0.001 and 0.01. In case of general CFRD, the average modulus of maximum internal settlement to the height of a dam is estimated to be 0.005. In case of a low void ratio, the construction modulus was high with its shape factor below 4. On the other hand, in case of a high void ratio, the relative settlement rate was high with its shape factor more than 4.

Keywords : Concrete faced rockfill dam, Settlement, Shape factor, Void ratio

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1. Introduction

In Korea, most dams built since 1990 or currently under design are more complicated in type, compared to existing old dams. CFRD (Concrete Faced Rockfill Dam) and RCD (Roller Compacted Concrete Dam) are good examples of these type. Especially, in case of CFRD, the number of its construction has been rapidly increasing. Eight large-scale dams that had been constructed after 1990 are in CFRD type. And, as of now, in the year of 2005, seven multipurpose and power-plant dams are being constructed in CFRD type. As the number of CFRD constructions increases, the necessity of an accurate assessment on its construction behavior also has been increasing accordingly (see Table 1). But, our domestic research on CFRD construction behavior has yet been insignificant.

Many CFRD designs that had overcome technical difficulties, such as dam construction on soft foundation, dam raising, and other problems, had been utilized for dam constructions in foreign nations. CFRD is the most preferred construction type for new dam constructions in overseas nations, such as Australia, Brazil, China, and etc. Australia already has produced a standard CFRD design guideline from its experience. China, a nation with strong ambition in CFRD, also has produced a CFRD Chinese Design Code and has utilized it in the

Table 1. The list of concrete faced rockfill dams in Korea

Name	Height (m)	Purpose	Year	Slope		Face Slab Thickness (m)	Reinforcement each way (%)	Plinth width(m)	Face Area $(10^3\ m^2)$	Rockfill Type	Rockfill Volume $(10^6\ m^3)$	Reservoir Capacity $(10^6\ m^3)$
				Upstream	Downstream							
Buan	50	W,F,P,I	1996	1.4	1.4	0.3+0.0034H	0.4	3	18.2	Rhyolite	614	41.5
Cheongsong (Lower)	54	P	2006	1.4	1.4	0.3+0.003H	0.4	4~6	19.6	Granite	782	9.29
Cheongsong (Upper)	97	P	2006	1.4	1.4	0.3+0.003H	0.4	4~6	34.4	Granite	2143	7.5
Daegok	52	W	2005	1.4	1.8	0.3	0.4	4~5	10	Gneiss, Shale	528	28.5
Dongbok	44.7	W	1985	1.5	1.5	0.3+0.008H	0.5	3~5	7	Andesite	420	99.5
Miryang	89	W,F,P,I	2001	1.4	1.4	0.3+0.003H	0.45	5~8	54	Andesite	3943	73.6
Namgang	34	W,R,P,I	1999	1.5	1.5	0.35	0.5	5	41.8	Gneiss	1280	309
Pyonghwa (1st stage)	80	F	1988	1.5	1.5	0.66~0.95	0.5	4.5~10	45.7	Gneiss	2413	590
Pyonghwa (2nd stage)	125	F	2005	1.4833	1.5	0.3	0.4	4~4.5	86.67	Gneiss	4705	2630
Sancheong (Lower)	70.9	P	2002	1.4	1.4	0.3+0.002H	H0.35, V0.48	4~7	31.7	Granite	1690	7.4
Sancheong (Upper)	86.9	P	2002	1.4	1.4	0.3+0.002H	H0.35, V0.48	4~7	23	Gneiss	2165	6.4
Tamjin	53	W,F,P,I	2005	1.4	1.8	0.3+0.003H	0.4	4~6	30	Tuff	1442	191
Yangyang	72	P	2005	1.4	1.4	0.3+0.003H	0.4	4~6	26	Gneiss	1265	5.2
Yongdam	70	W,F,P	2001	1.4	1.4	0.3+0.003H	0.5	5~8	43	Schist, Gneiss	2206	815
Hwabuk	45	W,F,P,I	2008	1.4	1.4	0.3	0.4	5.4	18.9	Tuff	877	48.7
Yecheon (Lower)	65	P	2010	1.4	1.4	0.3+0.003H	0.4	4~6	-	Granite	-	6.85
Yecheon (Upper)	75	P	2010	1.4	1.4	0.3+0.003H	0.4	4~6	-	Granite	-	8.96

ex) P=Hydro power, I=Irrigation, F=Flood control, W=Water supply, H=Horizontal, V=Vertical, H=Dam Height construction field. Many foreign nations have been performing active researches on CFRD.

A chronicle of modern rockfill dam design, including a description of the present practice of concrete faced rockfill dam design is presented by Cooke (1984). Clements (1984) has investigated the actual crest settlements and deformations of 68 Rockfill dams after construction and compared the measured values with the estimated values from empirical formulas. He pointed out that the values from the empirical formulas exhibit significant differences from the observed values. Fitzpatrick et al. (1985) have proposed a simple method to estimate the deformation moduli for CFRD rockfill materials. Liu et al. (1993) proposed a method to predict the settlements caused by impounding, based on the rockfill vertical strain, vertical stress, and modulus of compressibility at the end of dam construction. Giudici et al. (2000) have investigated the deformations of 13 CFRDs that had been designed and constructed in Australia, and suggested a research for investigating the effect of a shape of valley on the deformation modulus of CFRD before and after the construction. Hunter (2003) has explained the characteristics of Rockfill behavior from actual CFRD cases (Hunter and Fell, 2003). It is often necessary to rely on the historic performance data of other dams to estimate the dam properties. There is some published information to estimate the deformation of CFRD (e.g., Pinto et al., 1982; Clemants, 1984; Sherard and Cooke, 1987; Pinto and Marques, 1998; Giudici et al., 2000). However, these are based on limited data, and researchers often concentrated on only one or two factors which affect either the rockfill modulus or the measured deformation.

In this research, the measurement data of Daegok dam during its construction were collected and the deformation behavior was analyzed based on the data. Also, various problems that may occur during impounding were examined and a comparison analysis with foreign CFRD measurement data (height, shape factor, void ratio, settlement, settlement rate, and deformation modulus) was performed to provide a basic information that will be needed for domestic CFRD design, construction, and long-term maintenance.

2. Analysis of Measured Data at Daegok Dam

Daegok dam was constructed as the water supply mainly for Ulsan metropolitan area's water service. Daegok dam project was initiated as one of the Nakdong river water quality improvement project to provide clean and stable tab water to Ulsan area. This dam is located in the mid stream of Daegok river, the first water stream of Taehwa river water system, which is about 8.5 km away in the upper stream of Sayeon dam. This location of Ulju-Gun Dudong-Myun Cheonjun-Ri falls under the administrative district of Ulsan metropolitan city. The type of Daegok dam which is a mid sized dam of 52.0 m high and 190.0 m wide is CFRD.

Right underneath an concrete face, bedding and transition/filter are placed as a base of the concrete face.

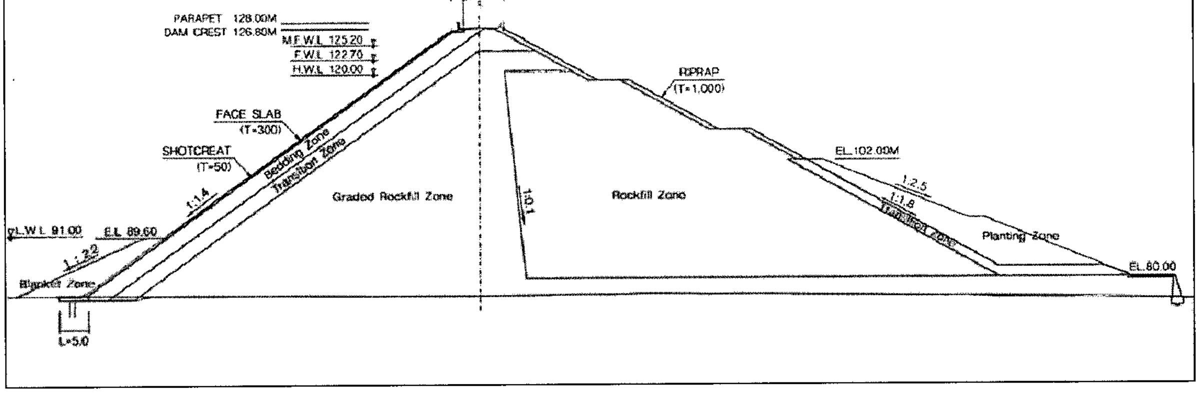


Fig. 1. Cross-section of Daegok dam (left : upstream & right : downstream)

It is designed to restraint the water from passing through the concrete face as much as possible after the completion of construction. Concrete face is 30 cm thick and has steel reinforcement ratio of 0.40%. The dam's upper stream has 1:1.4 slope, and its lower stream has 1:1.8. And, an environment friendly banking layer and leakage water collecting wall are installed up to EL.102.0 m on this dams lower stream slope (see Table 2).

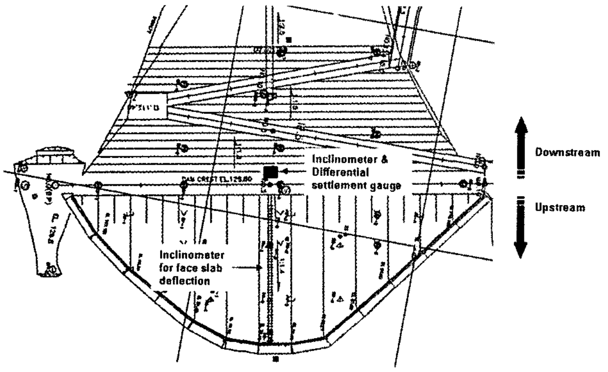


Fig. 2. Overall plan view of dam and locations of instrumentation equipments

The installation and measurements of instruments buried in Daegok dam, such as multi-layer settlement meter, face slope inclinometer, settlement cell, and piezometer, have been performed ever since the dam construction in 2001. And other instruments for leakage measuring device, and crest and slope settlement survey point have been installed and measured since 2004.

Major measurements related to construction processes are shown in Table 2. Underground instrumentations on

Table 2. General features of Daegok dam

List	Unit	Contents			
Level of dam crest	EL. m	126.8 (including 1.2 m of parapet wall : 128.0 m)			
Height of dam	m	52			
Length of dam	m	190			
Width of dam	m	9.5			
Volume of dam	103m	470			
Angle of Slope	V:H	Upstream 1:1.4, Downstream 1:1.8			
Materials	Zone	C (t/m^2)	ϕ (°)	γ_d (t/m^3)	Max. size
Face bedding	2	0	45	2.27	< 75 mm
Transition	3A	0	45	2.15	< 150 mm
Graded Rockfill	3B	0	45	2.15	< 800 mm
Rockfill	3C	0	39	2.03	< 600 mm
Planting	4	0	30	1.8	general soil
Embankment method	Zone	Number of passes		Construction period	
Vibration Compaction (Roller weight ; 10 ton)	2	6		2001.09 ~ 2002.04 (8 months, 62 stages)	
	3A	6			
	3B	5			
	3C	4			

Table 3. Main construction process

Period	Explanation
2001. 9 ~ 2002. 4	Completion of dam embankment (52 m) for 8 months
2002. 4 ~ 2003. 3	Stabilizing period and shotcrete on upstream slope for 12 months
2003. 3 ~ 2003. 5	Construction of face slab for 3 months
2004.11 ~	Beginning of impoundment

Table 4. Instrumentations installed in CFRD and measured period

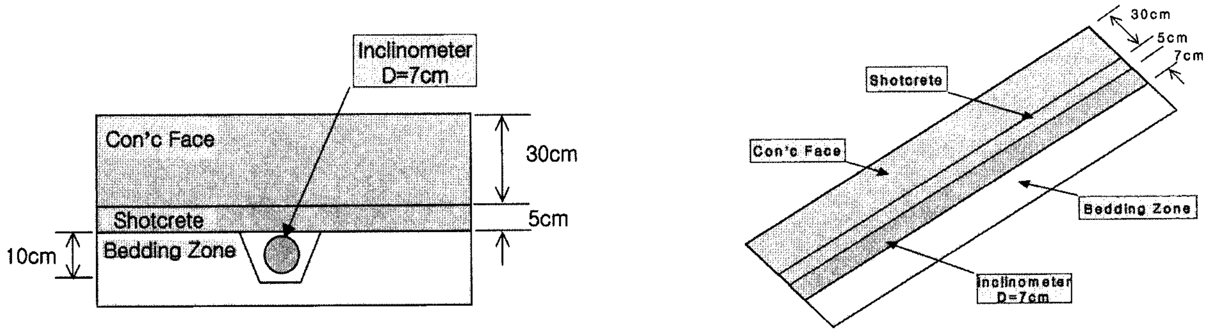
Instrumentation	Object	Unit	Elevation (m)	Position	Period
Inclinometer for face slab deflection	Measuring the deflection of concrete face slab	1	EL.78.0~126.8	Center of upstream slope	2003.9.04 ~2004.7.08
Differential settlement gauge	Measuring settlement of each layer vertically at center of dam	1	EL.76.0~126.8	Center of the crest	2001.9.26 ~2004.5.27
Inclinometer	Measuring the horizontal deflection at the center of dam	1	EL.76.0~126.8	Center of the crest	2001.9.28 ~2004.5.27
Settlement cell	Measuring differential settlement of inner position using difference of pressure	12	EL.95.0 (7 units), 110.0 (5 units)	Upstream (5 units), downstream (7 units)	2001.12.11 ~2004.5.27

Daegok dam are shown in Fig. 2. And the status of each installation and measurement period is shown in Table 3.

2.1 Face Slope Inclinometer for Face Slab Deflection

Daegok dam has a face slope inclinometer installed to monitor the deformation of the concrete face. But, unlike other dams, because of the difficulties in measuring actual horizontal displacements of dam body, such as the displacements caused by water pressure or other external forces and the horizontal displacements of bedding rock zone which is below the concrete face, the face slope inclinometer is installed in bedding zone in the lower part of concrete face (see Fig. 3 for details). The base of an 85 m-long face slope inclinometer is installed and fixed EL. 78.0 m from the bottom.

After the analysis of measurement records up to July



(a) Cross-sectional view (dam axis)

(b) View of perpendicular to dam axis

Fig. 3. Sectional view of face slope inclinometer for face slab deflection

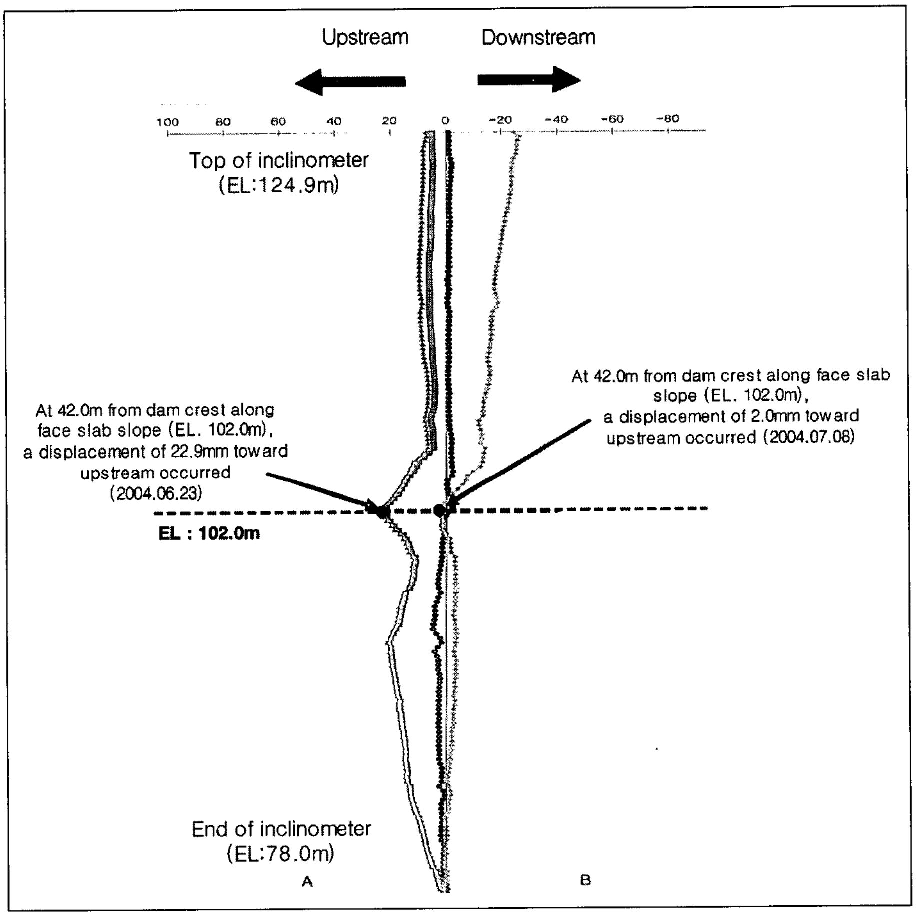


Fig. 4. Measuring results of face slope inclinometer for face slab deflection (up and downstream direction)

2004, the maximum displacement value of 22.9 mm was recorded at 42.0 m (EL.102.0 m) away from the dam crest towards the slope in June 2004 (see Fig. 4). The initial displacement was in a direction toward the upper stream. But, after the record, the displacement has changed its direction toward the lower stream. From a closer look on the measurement data, it can be seen that the magnitude of displacement varying with time is significant. It appears that the face slope inclinometer data do not fully reflect the actual displacements of the concrete face because it is installed in the bedding zone.

But, it is also found that a consistent maximum horizontal displacement was measured at EL.102.0 m. This measurement is very similar to the result of differential settlement guage: a maximum settlement of 105 mm at EL.106.0 m. In other words, because both measurement meters are showing its maximum value at a similar position, it can be said that the maximum displacement occurs at EL.102.0~EL.106.0 m. This tendency matches well with the result of a limit element analysis on model diagram. After the analysis on the measurement data, as impounding proceeds after the construction, a regular 8.7 cm displacement in upper stream direction is measured from a survey point 43.0 m away from the slope (EL.101.0 m). In conclusion, this part of the dam structure is expected to have a greater displacement than other parts. A continuous observation is required.

2.2 Multi-layer Settlement Meter

In case of the Daegok dam, to measure the vertical settlement during the construction, the multi-layer settlement meter was installed at the same position with a inclinometer (see Fig. 5).

As a result, it is shown that almost all the settlement data were being stable, and in Fig. 6, the largest amount of vertical displacement was 10.7 cm at the EL, 106.0 m, that was 6 m away from the center of dam. And the overall movement phase was confirmed with a general behavior of CFRD.

The maximum settlement occurring during construction was 10.7 cm and this amount was 0.21% of the dam height. Comparing with other dams, this data was smaller than that of other dam. For instance, the maximum relative settlement rate of Miryang dam was 0.48%. However, because the settlement kept occurring after 2 years due to dam stabilization process, a continual observation is required.

Furthermore, since April 2004, although it was not bigger enough, the survey points, M-5 (EL.97.8 m), M-6

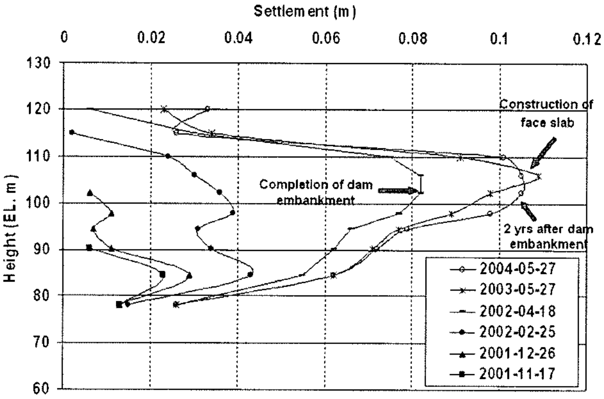
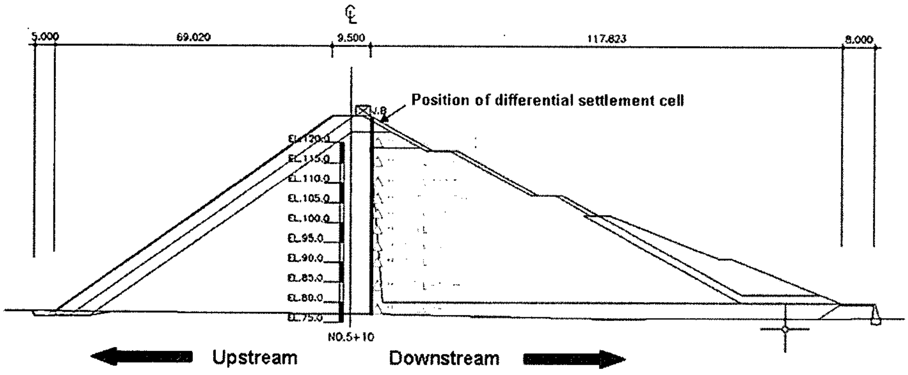


Fig. 6. Height vs. settlement due to construction period



No.	Location (EL. m)
M-10	120.1
M-9	115.0
M-8	110.0
M-7	106.0
M-6	102.2
M-5	97.8
M-4	94.4
M-3	90.1
M-2	84.4
M-1	78.1

Fig. 5. Position of multi-layer settlement meter (M-1~M-10)

(EL.102.2 m), M-8 (EL.110.0 m) have given a large displacement (more than 5 mm) than other survey points. It is thought that it is a temporary variation due to constructions such as a leveling of dam crest and also requires continual observation.

2.3 Inclinometer

A inclinometer was installed at the center of the dam, and a horizontal displacement occurring from the center of the dam was measured. The lower side of the inclinometer was fixed at the EL.74.4 m, and was installed 6m to the downstream slope in the same way as with the differential settlement gauge. Fig. 7 shows the horizontal displacements that were measured after completion of dam construction, concrete face slab installation, and 2 years after completion of dam construction, respectively.

After face slab installation, about 8.3 mm of displacement from the top of dam to the downstream, and 8.6 mm of maximum displacement at 36 m from the dam crest (EL.91.0 m) occurred. In addition, 2 years after completion (May 2004), 21.3 mm to the downstream at the dam crest, 10 mm at the upstream at 35m from the crest (EL.90.0 m), and 7 mm of displacement at EL.100.0 m (25 m from the crest) were measured, respectively.

Furthermore, during the stabilization period, 2.0 cm of displacement occurred at the top of dam to the downstream. This was not observed in the traditional dams. Even though it is thought that it happened because the inclinometer was installed not to the center but slightly to the downstream, and further observations are needed in the future.

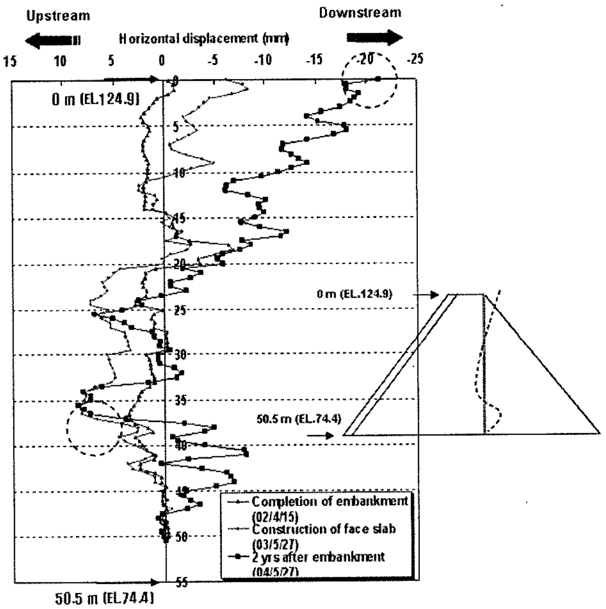
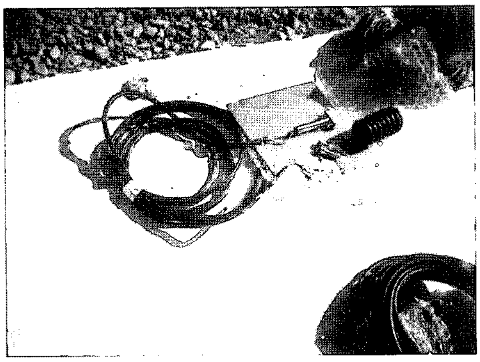


Fig. 7. Horizontal displacement after construction

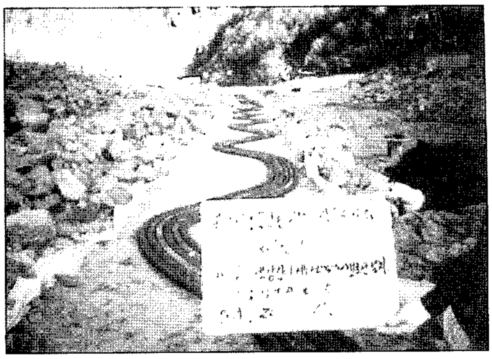
2.4 Settlement Cell

To measure the settlement and differential settlement inside the dam, at EL.94.0 m, and EL.110.0 m, 7 and 5 units of settlement cell respectively were installed. A settlement cell is an instrument that is able to compare the differential settlements of other same height zones. The photograph of settlement cell that was installed in the Daegok dam is shown in the Fig. 8, and the data in the Fig. 9.

As shown in Fig. 9, the data from the SC-1, SC-7 and SC-9 ~ SC-12 could not be obtained due to instrumental error. From the data at the EL.94.0 m, 6 settlement cell except SC-1 shows that there have been 0.93 cm to 6.57



(a) settlement cell sensor



(b) Installation of settlement cell

Fig. 8. The photograph of settlement cell

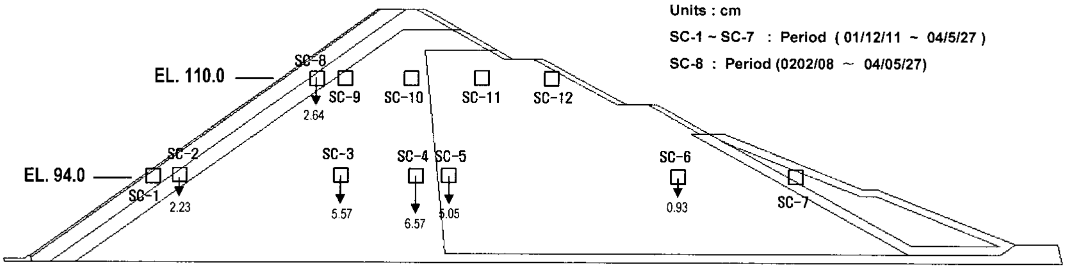


Fig. 9. Measured results of settlement cell (SC-1~SC-12)

cm of settlement. And the settlement data at the SC-4 (6.57 cm) is confirmed with one (7.9 cm) of the differential settlement gauge (M-4, EL.94.4 m) that was installed near.

Most of liquid settlement cells installed at EL.110 m survey point were out of order, and similar trends were also observed in other dams. Therefore, even though a liquid settlement cell is cheap and easy to be used when measuring the settlement inside a dam, it is required to handle with care in the future.

3. The Behavior Characteristics of Daegok Dam Compared with Other CFRDs

The concrete face rockfill dam, CFRD, has become popular in the last 40 years as a result of their good performance and low cost compared with earth dams. Experience up to 1960 using dumped rockfill, demonstrated the CFRD to be a safe and economical type of dam, but is subject to concrete face damage and leakage caused by the high compressibility of the segregated dumped rockfill.

As a result, the CFRD became unpopular, although rockfill had been demonstrated to be a high strength and economical dam building material. With the advent of vibratory-roller compacted rockfill in the 1950s, the development of the CFRD resumed so that the CFRD became a major dam type today. Fig. 10 illustrates the trends in the height of the CFRD up to the year 2005. Table 5 shows the construction and behavior parameters of some CFRDs.

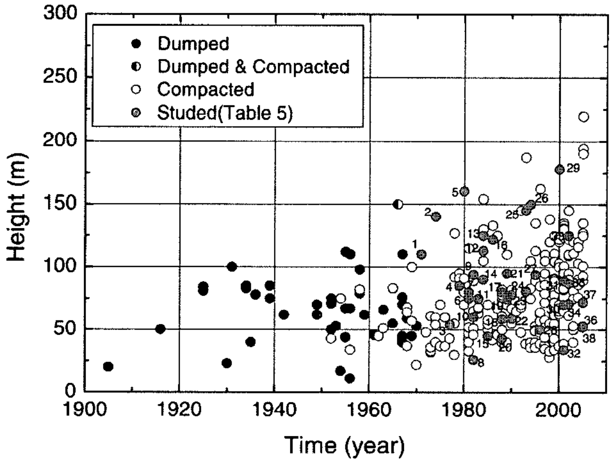


Fig. 10 Trends in the height of the CFRD with time

The construction modulus varies widely depending on the void ratio of the rockfill and the parent rock material. The moduli are derived from measurements of vertical settlement during construction and the calculated vertical fill load above the settlement gage, as follows (Pinto and Marques, 1998):

$$E_v = H \times Yr \times h \ / \ (1000 \times s) \qquad (1)$$

Where: E_v = Vertical deformation modulus (construction modulus), MPa
H = Vertical depth of rockfill above the settlement gage, m
Yr = Unit weight of rockfill, kN/m^3
h = Column of rockfill below the settlement gage, m
s = Settlement of the gage, m

Theoretically, a construction modulus (E_V) gradually decreases as the height of a dam increases. However, in reality, this does not apply to all cases. Rockfill materials from an initial quarrying tend to have a lower quality than materials from later quarring. Therefore, in general, lower quality materials are used to fill the lower portion of a dam construction (Fitzpatrick et al., 1973, Fitzpatrick et al., 1985).

Fig. 11 shows a relationship between the height of

Table 5. Construction and behavior parameters of some CFRDs

No.	Dam	Country	Year	Height (m)	Length (m)	Face Area (10^3 m^2)	Shape Factor (A/H^2)	Slopes	Rock Type	Reference
1	Cethana	Australia	1971	110	215	30	2.5	1.3, 1.3	Quartzite	3, 28
2	Alto Anchicaya	Colombia	1974	140	260	22.3	1.1	1.4, 1.4	Hornfels	3
3	Little Para	Australia	1977	54	–	10	3.4	1.3, 1.4	Shale	11
4	Sugaroaf	Australia	1979	85	1050	83	11.5	1.3, 1.4	Siltstone	11
5	Foz do Areia	Brazil	1980	160	828	139	5.4	1.4, 1.4	Basalt	3
6	Mackintosh	Australia	1981	75	465	27.5	4.9	1.3, 1.3	Greywacke	10
7	Mangrove creek	Australia	1981	80	384	29	4.5	1.5, 1.6	Siltstone	19
8	Tullabardine	Australia	1982	26	200	5.5	8.1	1.3, 1.3	Greywacke	11
9	Murchison	Australia	1982	94	200	17	1.9	1.3, 1.3	Rhyolite	15
10	Fortuna 1st	Panama	1982	60	1056	22	6.1	1.3, 1.4	Andesite	21
11	Bastyan	Australia	1983	75	430	19	3.4	1.3, 1.3	Rhyolite	15
12	Khao Laem	Thailand	1984	130	1000	140	8.3	1.4, 1.4	Limestone	20
13	Shiroro	Nigeria	1984	125	560	65	4.2	1.3, 1.3	Granite	25
14	Kotmale	Sri Langka	1984	97	620	60	6.4	1.4, 1.45	Gneiss	7
15	Dongbok	Korea	1985	44.7	188.1	7	3.5	1.5, 1.5	Andesite	15
16	Lower Pieman	Australia	1986	122	360	37.8	2.5	1.3, 1.3~1.5	Dolerite	15
17	Pyonghwa(1st)	Korea	1988	80	410	45.7	7.1	1.5, 1.5	Gneiss	17
18	Guanmenshan	China	1988	58.5	183.6	8.2	2.4	1.4, 1.59	Andesite	8
19	Chengbing	China	1989	74.6	232	15.8	2.8	1.3, 1.3	Tuff	30
20	White Spur	Australia	1989	43	146	4.3	2.3	1.3, 1.3	Tuff	11
21	Xibeikou	China	1989	95	222	29.3	3.3	1.4, 1.4	Limestone	6
22	Longxi	China	1990	58.9	140.5	7.07	2.0	1.3, 1.3	Tuff	31
23	Zhushuqiao	China	1990	78	245	23	3.8	1.4, 1.7	Limestone	13
24	Huashan	China	1993	80.8	160.4	13.03	2.0	1.4, 1.4	Granite	32
25	Segredo	Brazil	1993	145	705	86	4.1	1.3, 1.2~1.4	Basalt	22
26	Xingo	Brazil	1994	150	850	135	6.0	1.4, 1.3	Granite	27
27	Wananxi	China	1995	93.8	210	18	2.0	1.4, 1.4	Granite	25
28	Buan	Korea	1996	50	282	18.2	7.3	1.4, 1.4	Rhyolite	17
29	Tianshenqiao	China	2000	178	1168	156	4.9	1.4, 1.25	Limestone	29
30	Yongdam	Korea	2001	70	498	43	8.8	1.4, 1.4	Schist	17
31	Miryang	Korea	2001	89	535	54	6.8	1.4, 1.4	Granite	17
32	Namgang	Korea	2001	34	1126	41.8	36.2	1.5, 1.5	Gneiss	17
33	Machadinho	Brazil	2002	125	700	77.3	5.0	1.3, 1.2	Basalt	10
34	Sancheong(L)	Korea	2002	70.9	286.1	31.7	6.3	1.4, 1.4	Granite	16
35	Sancheong(U)	Korea	2002	86.9	360	23	3.1	1.4, 1.4	Gneiss	16
36	Tamjin	Korea	2005	53	403	30	10.7	1.4, 1.8	Tuff	17
37	Yangyang	Korea	2005	72	347	26	5.0	1.4, 1.4	Gneiss	17
38	Daegok	Korea	2005	52	190	10	3.7	1.4, 1.8	Gneiss	17

CFRD and the maximum internal settlement. Fig. 11 (a) shows a proportional relationship on a semi-log graph. And, its equation format is equal to equation (2).

$$y = 112 + 61 \log(x), \quad R = 0.765 \qquad (2)$$

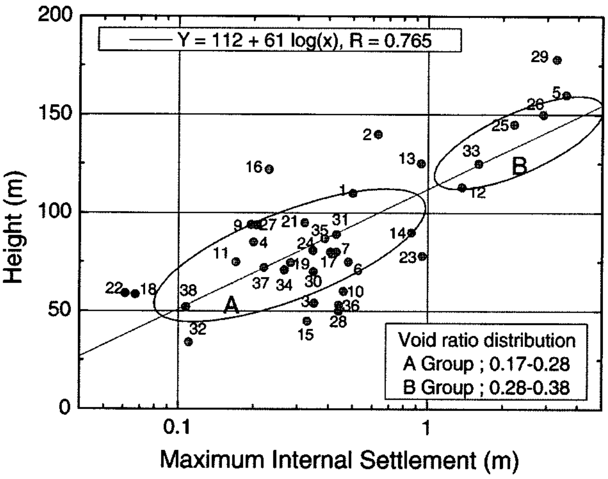
where, y is CFRD height, x is maximum internal settlement and R is coefficient of correction.

As can be seen in Fig. 11, the maximum internal settlement is proportional to the height of a dam. Fig. 11 (b) shows the relationship between the maximum internal vertical movement measured and the final height of the embankment. The data collected from the rockfill zone leads to Equation (3). Coefficients vary widely, but range from 0.001 to 0.0229.

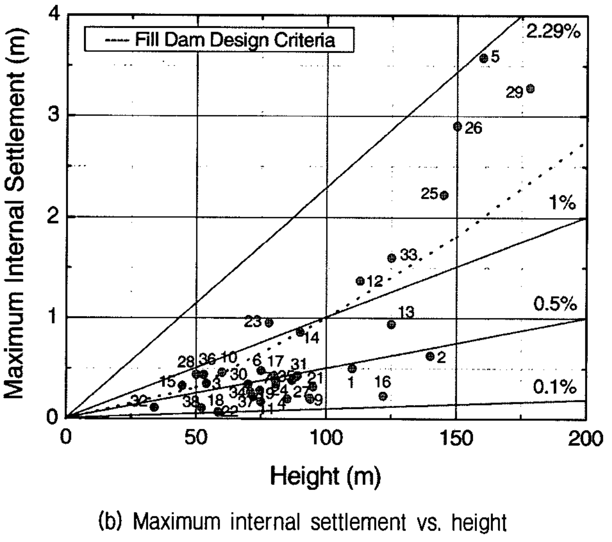
$$\text{Maximum Internal Settlement} = \alpha \times \text{Height} \quad (3)$$

where, α is 0.01 ~ 0.0229 for relatively high dam, α is 0.005 ~ 0.01 for relative medium dam, and α is 0.001 ~ 0.005 for relatively small dam.

Six dams that have comparatively higher void ratio than other CFRD: Segredo (Void ratio : 0.38), Foz do Areia (0.33), Tianshenquio (0.31), Khao Laem (0.29), Machadinho (none data), Xingo (0.28), appear to have a relatively steep slope with its correlation coefficient in between 0.01 and 0.0229. Among other CFRD, there are 7 dams with its correlation coefficient in between 0.005 and 0.01, and 19 dams in between 0.001 and 0.005. On the average, it appears that the maximum internal settlement and the height of a dam have a correlation coefficient of 0.005 (it means 0.5% of dam height). The height of Daegok dam is relatively small with 52 m, and its maximum internal settlement is also relatively small with 0.107 m. Daegok dam is showing a similar behavior pattern to other CFRD constructions.



(a) Height vs. maximum internal settlement



(b) Maximum internal settlement vs. height

Fig. 11. Relationship between height and maximum internal settlement

Fig. 12 shows a relationship between a construction modulus and a settlement rate in an algebraic graph. The construction modulus is inversely proportional to the relative settlement rate, and it is shown in equation (4).

$$\log(y) = 1.66 - 0.635 \log(x), \quad |R| = 0.768 \quad (4)$$

where, y is construction modulus, x is relative settlement rate and |R| is coefficient of correction.

Also, A group with low void ratio had a high construction modulus, and its shape factor was below 4. On the other hand, B group with high void ratio had a high settlement rate, and its shape factor was above 4. Here, the shape factor is defined as the area, A, of the concrete face in m^2 divided by the maximum height of the dam, H, squared. For narrow canyons with shape factor, A/H^2, equal to four or less, the indicated moduli of deformation are larger.

In general, there are many parameters that decide the

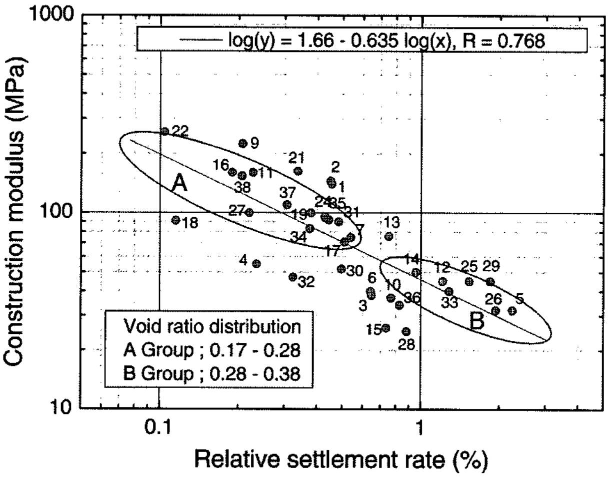


Fig. 12. Construction modulus vs. settlement rate

deformation characteristics of rockfill materials. Especially, the strength of a rock is the most important, but yet, not a dominant factor because in even weaker rocks the deformation can be smaller by flatter slopes and better compaction. Pinto and Marques (1998) suggested calculating the void ratio of a body in order to measure its degree of compaction. In this study, it was examined that the deformation rate can be predicted with the void ratio by comparing the relationship between the void ratio and a construction modulus. As can be seen in Fig. 12, Daegok dam is showing a similar behavior to equation (4). It can be said that the relationship between the settlement during construction and its deformation is similar to a general CFRD type.

Fig. 13 shows a relationship between a construction modulus and a void ratio. It is divided into two groups in accordance with whether its shape factor is higher than 4 or not. Its each relationship can be expressed with equation (5) and equation (6).

$$y_1 = 404.5 - 1051.4\ x, \quad |R| = 0.90 \qquad (5)$$

$$y_2 = 103.9 - 194.30\ x, \quad |R| = 0.50 \qquad (6)$$

where, y_1 and y_2 are construction modulus, x is void ratio and |R| is coefficient of correction.

In Fig. 13, Tamjin dam falls into group B with its relatively high void ratio and a shape factor of 10.7. Daegok dam with a shape factor of 3.7 falls into group A, a group where a void ratio in close relationship with a degree of compaction sensitively reacts to construction modulus changes. In Fig. 13, it is seen that Daegok dam is showing general aspects of a dam that has a comparatively lower void ratio than other CFRD.

In Fig. 13, two groups are formed according to its shape modulus. A steeper straight line in upper area represents a dam with a narrow valley and its shape modulus below 4. A dam with a bigger valley has a line with a much gentle slope. But, still, this data has some degree of dispersions, meaning that the shape factor is not the only decision element. Nevertheless, this valley shape factor is a very useful parameter used for settlement analysis.

Fig. 14 is a relationship between a construction modulus and a shape factor. According to its algebraic graph, the construction modulus is inversely proportional to the shape factor. Its relationship is shown in equation (7).

$$Y = 172.2 - 126.5 \log(x), \quad |R| = 0.615 \qquad (7)$$

where, y is construction modulus, x is shape factor and |R| is coefficient of correction.

A group, including Daegok dam, has relatively lower void ratio and higher construction modulus. On the other hand, group B has relatively higher void ratio and lower construction modulus. Fig. 14 shows that shape factor 4 is the boundary of these two groups.

From this study, it is now clearly seen that rockfill's

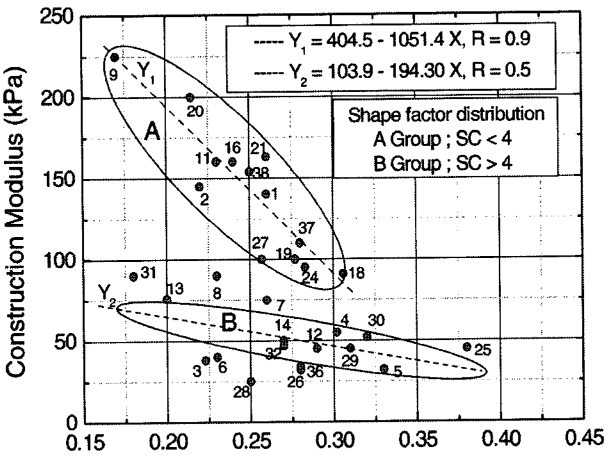


Fig. 13. Construction modulus vs. void ratio

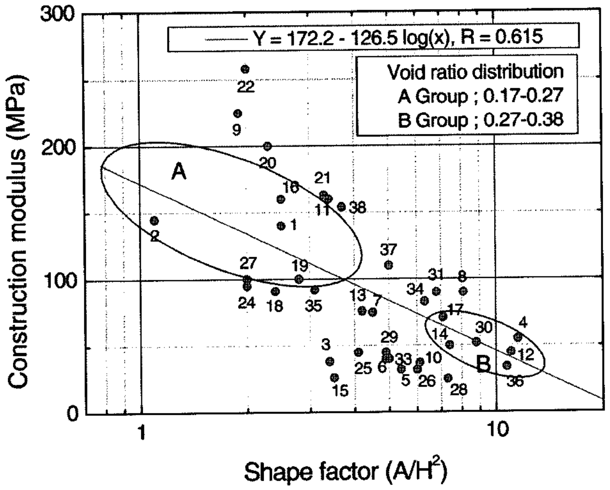
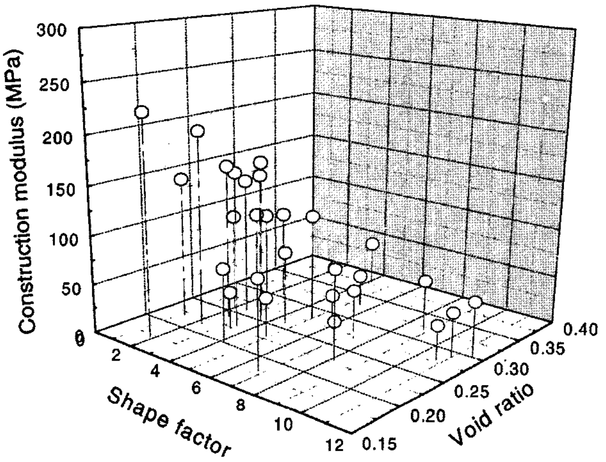
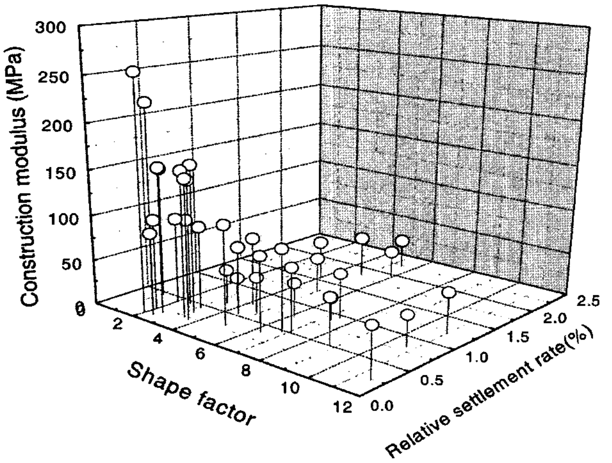


Fig. 14. Construction modulus vs. shape factor (A/H²)

void ratio has an effect on deformation. A dense dam body may have greater deformation modulus, but it is still under an influence of the shape of valley. A dam with a valley that has a shape factor below 4 will have a deformation modulus of 91 MPa and above (except Dongbok dam, 26 MPa). A dam with a bigger valley that has a shape factor 4 and above will have a deformation modulus in between 25~90 MPa (except Yangyang dam, 110 MPa). Tamjin, Namgang, Yongdam, and Foz do Areia were constructed across relatively wide valley, whereas Daegok, Wananxi, Lower Pieman, Bastyan, Murchison, Alto Anchicaya and Cethana were all constructed across a very steep, V-shaped valley. It therefore seems that valley shape may have a considerable influence on the construction modulus of compacted rockfill due to redistribution of load by arching between the abutments.



(a) Construction modulus - void ratio - shape factor relationship



(b) Construction modulus - shape factor - relative settlement rate relationship

Fig. 15. Behavior characteristics of CFRD

As can be seen in Fig. 15, high construction moduli in the 90~258 MPa range are clearly the results of arching effects in narrow valleys (low shape factor) with small settlement and void ratio. The higher construction modulus in narrow valleys is caused by the wall effect of the steep abutments. Arching of the rockfill results in a reduction of the vertical load on the lower central section of the dam, and consequently in smaller settlement.

Fig. 16 represents a relationship between the dam heights and its internal settlement that is measured from Miryang (Korea), Tamjin (Korea), and Daegok dam (Korea). It can be seen that the internal settlement has a maximum measurement at the middle of the dam height. At the initial stage of a dam construction, the maximum internal settlement appears at the mid-lower portion of the dam.

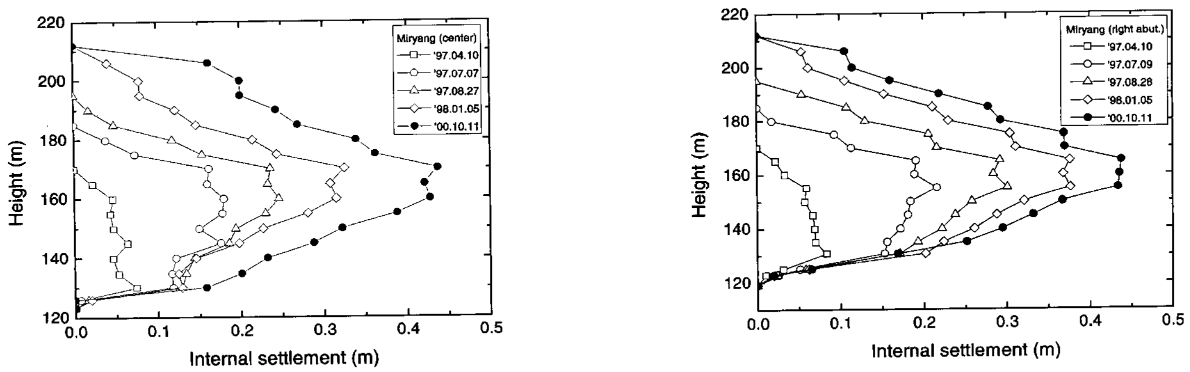
However, at the end of the construction, the maximum internal settlement has moved to the middle of the dam. In case of Daegok dam, the maximum internal settlement was found at the mid-upper portion of the dam. And, its amount of settlement was lower than that of other CFRD. It showed behaviors that are somewhat significant than others.

Fig. 17 represents a generalized relationship between the dam height and its internal settlement that is measured from Foz do Areia (Brazil), Miryang (Korea), Tamjin (Korea), and Daegok (Korea), and its plotting via parabola model. It is seen that the internal settlement has a maximum measurement at the middle of the dam height. A numerical formula of a generalized relationship between dam height and internal settlement data from 4 CFRD (7 points) is shown in equation (8) (see Fig. 17).

$$y = -4.18\,x + 4.375\,x^2, \quad R^2 = 0.96 \qquad (8)$$

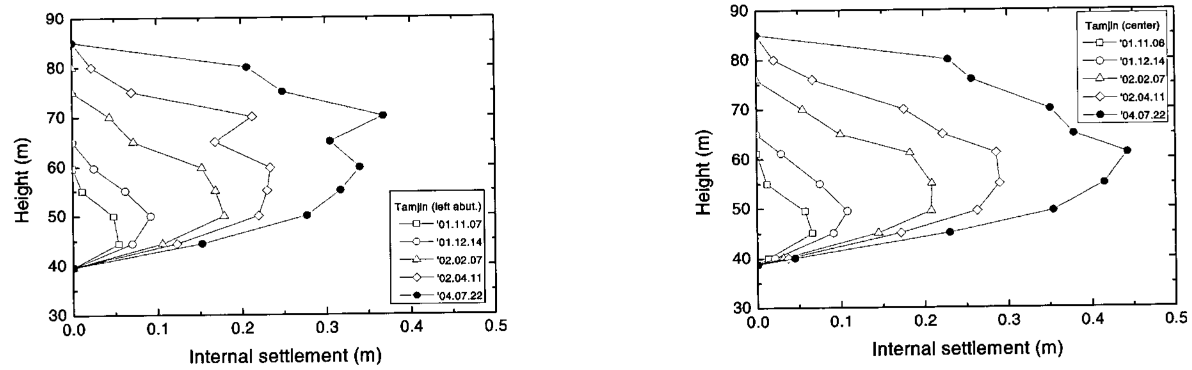
where, y is generlaized maximum internal settlement (δ/δ_{max}), x is generalized height (h/H) and R^2 is coefficient of multiple correction.

In Fig. 17, Miryang and Tamjin dam show a behavior that is similar to equation (8). Foz do Areia, and Daegok dam showed a small amount of settlement at 0.3~0.4H



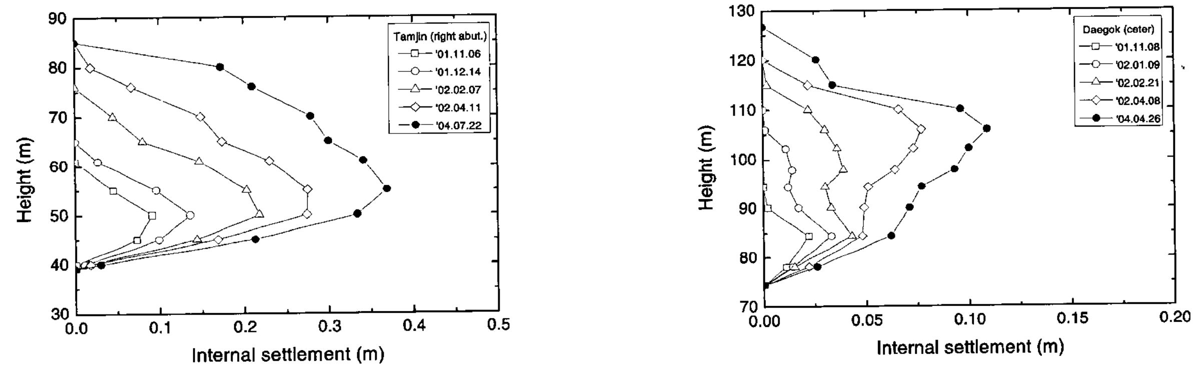
(a) Miryang (center)

(b) Miryang (right abut.)



(c) Tamjin (letf abut.)

(d) Tamjin (center)



(e) Tamjin (right abut.)

(d) Daegok (center)

Fig. 16 Maximum internal settlement of Miryang, Tamjin and Dagok dam

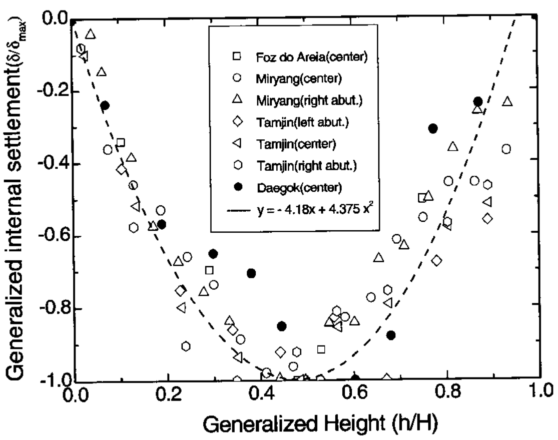


Fig. 17. Generalized height vs. generalized settlement

and 0.8H. In case of Daegok dam, the amount of settlement massively increased at 0.6H~0.7H.

4. Conclusions

In this study, the deformation behavior of Daegok dam during the construction was analyzed based on the measurement data and a comparative analysis with foreign CFRD measurements was performed. Followings are the main conclusions drawn from this study.

(1) The settlement data varying with the Daegok dam's depth indicated that current maximum settlement is 10.7 cm (0.21% of dam height) at EL. 106.0 m, which is located at about 6m above from the center of the dam (almost 0.6H from the bottom). The overall behavior is similar to general CFRD behaviors.

(2) According to the analysis of 38 CFRD measurements, the maximum internal settlement is proportional to the void ratio and shape factor.

(3) From the relationship between the maximum internal settlement and the height of a dam, 26 dams were assessed to have its relative modulus ranging between 0.001 and 0.01. In case of general CFRD, the relative modulus of maximum internal settlement to the height of a dam is estimated to be 0.005 (0.5% of dam height).

(4) In case of a low void ratio, the construction modulus was high and its shape factor was less than 4. On the contrary, in case of a high void ratio, the relative settlement was high and its shape factor was more than 4.

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