Analysis of post-construction deformation characteristics of concrete faced rockfill dams

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SYNOPSIS : To get the possible for management and maintenance, it was analyzed the deformation characteristics, such as crest of embankment and concrete face slab, and leakage of concrete faced rockfill dams (CFRD). There are trends that embankment deformation depends on intact strength used rockfills rather than dam height, deformation normal to concrete face slab during the first reservoir filling is occurred more than 80% of the total deformation in general, and the magnitude and trend of concrete face slab deformation is similar to post-construction crest settlement. The results showed that the range of post-construction crest settlement suggested by Sherard and Cooke (1987), and Clements (1984) had a good agreement in the cases using rockfill with very high intact strength, but it had a trend which underestimated crest settlement in the cases using rockfill with medium to high intact strength. The maximum leakage rate in general was observed during the first reservoir filling and long-term leakage rate was rapidly increased when the dam height exceeds approximately 120m.

Key words: CFRD, Concrete faced slab, Rockfill, Crest settlement, Leakage.

1. Introduction

A rockfill dam rendered watertight by concrete slabs on the upstream slope surface is called a Concrete Faced Rockfill Dam (CFRD). For brevity because its terminology is long, "CFRD" is generally used to denote the concrete faced rockfill dam. Fig. 1 shows the cross section of a typical CFRD (Cooke and Sherard, 1987). As shown in Fig. 1, there are three main CFRD zones: the concrete face slab (Zone 1) which is impervious, Zone 2 for the filter or transition zone directly under the concrete slab, and the main rockfill (Zone 3). Compacted impervious soil (Zone 1) is necessary for defense which means to seal cracks or joint openings. The areas closer to the downstream than the upstream on each layer contain smaller average sized rock and more quarry fines rockfill. The maximum rock sizes at Zone 3C and Zone 2 are approximately lower than 1,500 ㎜ and 75–150 ㎜ respectively. Sherard and Cooke (1987) reported that CFRD has advantages over an earth core rockfill dam (ECRD) such as cost-effectiveness and great suitability at many sites as with the following reasons: ① the total cost of the earth core and filters in the ECRD will almost always be greater than the cost of the concrete face in the CFRD, and the cost of the CFRD foundation treatment is generally cheaper than the ECRD because the treated rock surface area in the CFRD is smaller; ② the CFRD allows to be constructed on various parts of the rockfill embankment simultaneously, and is affected less in rainy weather than ECRD because there is no earth core in the CFRD body.

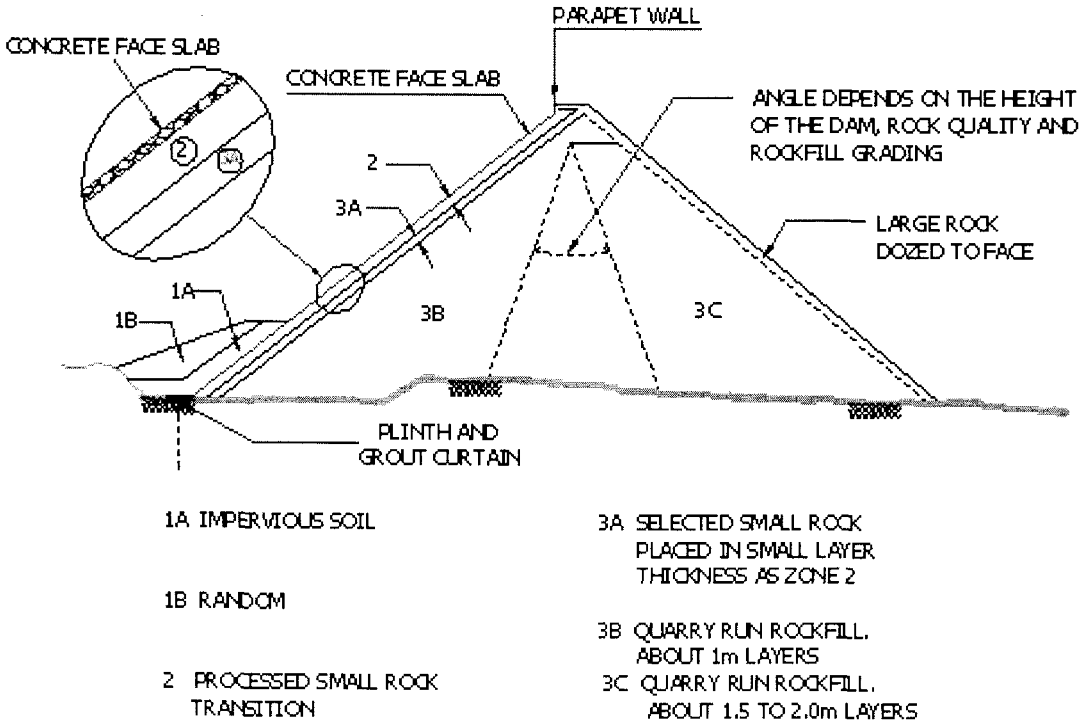


Fig. 1. Zone designations for CFRD of sound rockfill (Cooke and Sherard, 1987)

Due to advantages of the CFRD, including the use of local materials, cost-effectiveness, extensive adaptability, simple construction, and a short construction period, the CFRD is one of the most popular types of dams worldwide during recent decades (Xing, et al., 2006; Uddin and Gazetas, 1995; Khalid, et al., 1990; Sherard and Cooke, 1987). In Korea, 17 CFRDs have been and are being constructed since the first 45m high CFRD was constructed in Dongbok, Gwangju in 1985. Among them, 10 CFRDs have been constructed in the beginning of 2000, and 3 CFRDs are going to be constructed within 2010 (Park, et al., 2005). This means that most dams in Korea have been designed and constructed with the CFRD since the middle of 1990. The design and construction/performance of the CFRD is largely empirical and is based on past experience rather than theory. However, the most research related to the CFRD has a trend which limits the deformation behavior of CFRD during under construction and on first reservoir filling because of the short history of the CFRD in Korea (Yun, et al., 2006; Park, et al., 2005; Park et al., 2005; Park, et al., 2005, 2004; Kim, et al., 2004; Lee, etal., 2003). There are a few studies that used case data from many CFRD to analyze post-construction crest settlement and long-term leakage which generally can be used indexes for the maintenance and performance management of dams (Bang, et al., 2006; Hunter, 2003; Sherard and Cooke, 1987). Under these backgrounds, to know the general post-construction deformation characteristics of the CFRD, and to use the results as possible indexes for the maintenance and management of the CFRD, it was analyzed crest settlement, deformation normal to the face slab, the strain in the face slab, and the leakage on first filling and during long-term post-construction on the 27 CFRD.

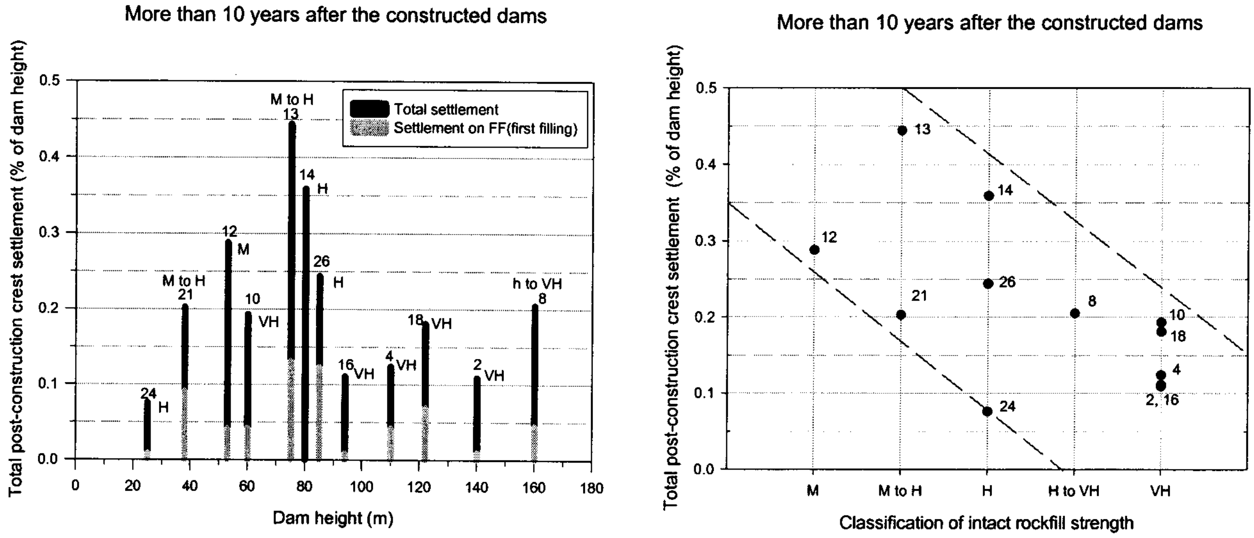


Fig. 2.1 Post-construction crest settlements on first filling and after 10 years

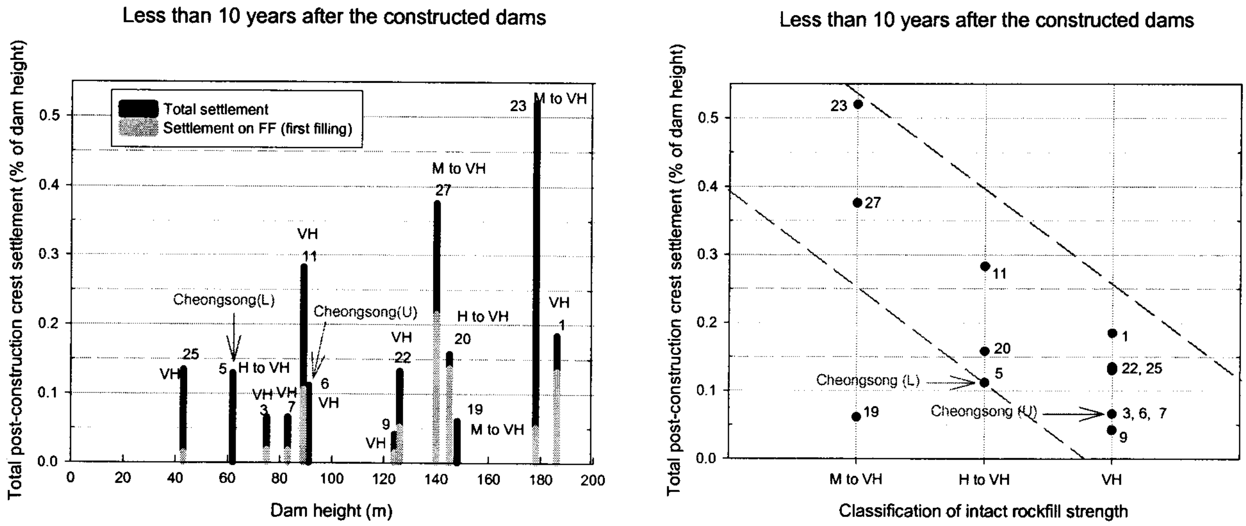


Fig. 2.2 Post-construction crest settlements less than 10 years after the constructed dams

2. Post-construction deformation behavior of the CFRD

2.1 Post-construction crest settlement

Table 1 is the data on the CFRDs. These data was taken from Hunter(2003), Cooke and Sherard(1985), and Won(2006). Table 1 shows respectively the basic information, post-construction crest settlement, deformation normal to the face slab, and leakage of 27 CFRDs. The period of measurement shown in Table 1 may be a little different with deformation of embankment and leakage.

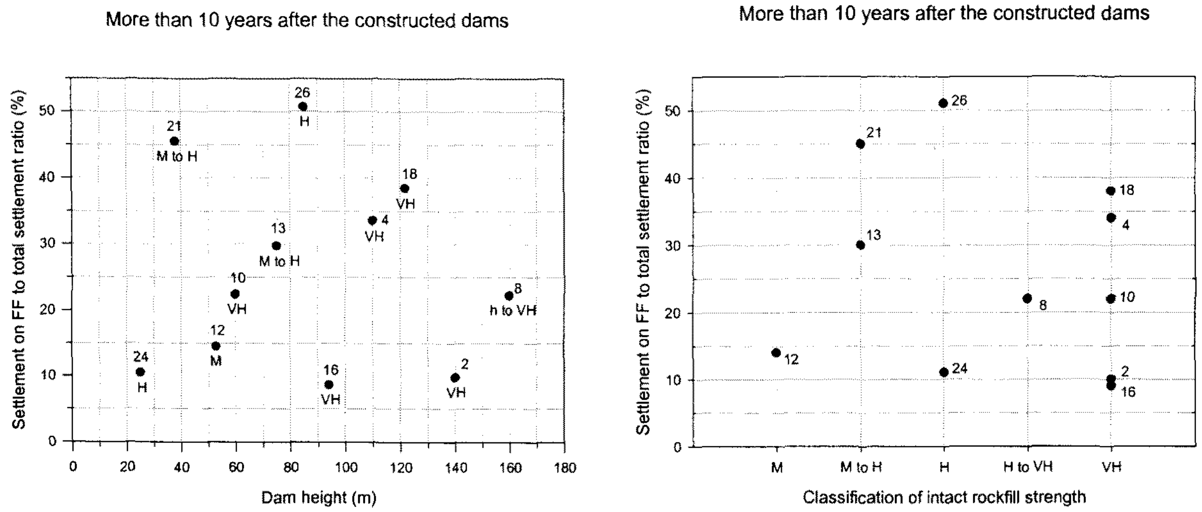


Fig. 3.1 Crest settlement on first filling to total crest settlement ratio after 10 years

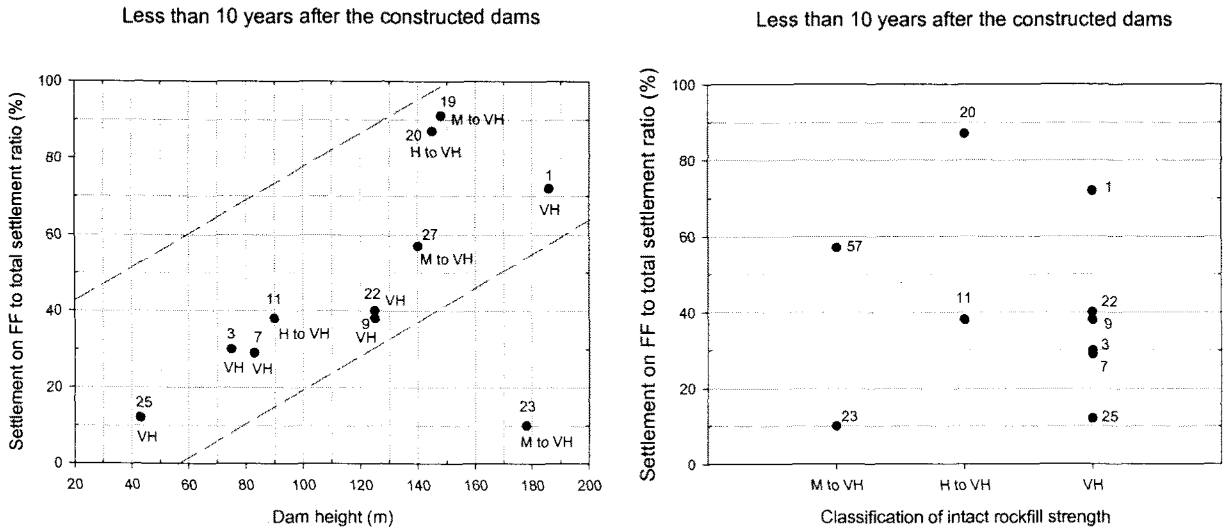


Fig. 3.2 Crest settlement on first filling to total crest settlement ratio less than 10 years after the constructed dams

Figs. 2 and 3 respectively show the total post-construction crest settlement after at least 10 years and on first filling, and the ratio of the crest settlement on first filling to the long-term settlement. The serial numbers in Figs. 2 and 3 indicate the number of the dam shown in Table 1. M, H, and VH indicate the intact rock strength used in the rockfill zone. The ranges of the strength and definition of M, H, and VH are given at the lower part of Table 1.

Table 1. Case studies of CFRDs

No.	Dam Name	Location	Year Completed	Height, H(m)	Length, L(m)	Foundation (Soil/Rock)	IRSC	Post Construction Crest Settlement						Post Construction Deformation Normal to Face Slab			Leakage (ℓ/sec)	
								Period Surveyed (year)	TS (mm)	TS (%)	SFF (mm)	SFF (%)	SFF/TS (%)	TD (mm)	DFF (mm)	DFF/TD (%)	Max. Rate	Long-term
1	Aguamilpa	Mexico	1993	186	475	Rock-gravels in part of river section	VH	0.4–5.7	307	0.185	222	0.133	72	320	-	-	FF 200	160
2	Alto Anchicaya	Columbia	1974	140	260	Gravels in river section	VH	0.11–10.3	153	0.109	15	0.011	10	160	130	81	FF 1,800	-
3	Bastyan	Australia	1983	75	430	Rock	VH	0.2–7.5	50	0.066	15	0.02	30	68	-	-	FF 10	5
4	Cethana	Australia	1971	110	213	Rock	VH	0–28.6	137	0.124	46	0.043	34	170	-	-	70	7.5
5	Cheongsong(Lower)	Korea	2007	62	300	Rock	H to VH	0-3.2	67	0.112	-	-	-	-	-	-	FF 43.0	1.5
6	Cheongsong(Upper)	Korea	2007	90	400	Rock	VH	0-3.3	117	0.130	-	-	-	-	-	-	FF 43.0	10
7	Crtotty	Australia	1991	83	240	Rock	VH	0-8.5	55	0.066	16	0.019	29	46	-	-	45	33
8	Foz Do Areia	Brazil	1979	160	828	Rock	H to VH	0–11	328	0.205	73	0.046	22	780	620	79	FF 240	70
9	Golillas	Columbia	1978	125	108	Rock	VH	0.46–6.4	52	0.042	20	0.016	38	160	-	-	FF 1,080	385
10	Kangaroo Creek	Australia	1969	60	178	Rock, some gravels	VH	0–26	116	0.193	26	0.043	22	-	-	-	FF 11	2.5
11	Kotmale	Sri Lanka	1984	90	560	Rock	H to VH	0–2.46	255	0.283	96	0.107	38	98	-	-	FF <10	-
12	Little Para	Australia	1977	53	225	Rock	M	0–22.6	152	0.288	22	0.042	14	-	-	-	19.2	-
13	Mackintosh	Australia	1981	75	465	Rock	M to H	0–20.6	333	0.444	99	0.132	30	228	173	76	FF 21	10
14	Mangrove Creek	Australia	1981	80	380	Weathered Rock	H	0.67–15	287	0.359	<287	<0.359	-	-	-	-	FF 5.6	2.5
15	Miryang	Korea	2001	89	535	Rock	-	0(?)-3	-	-	-	-	-	-	-	-	77	9
16	Murchison	Australia	1982	94	200	Rock	VH	0.08–17.6	104	0.111	9	0.01	9	77	28	36	FF 3.5	2
17	Namgang	Korea	1999	34	1,126	Rock, some gravels		5	-	-	-	-	-	-	-	-	51	4
18	Reece	Australia	1986	122	374	Gravels in river section	VH	0.12–15	221	0.181	85	0.07	38	264	215	81	12	1.5
19	Salvajina	Columbia	1984	148	362	Rock and soil, gravels in river section	M(?) to VH	0.33–0.75	90	0.061	<90	<0.061	91	55	-	-	74	-
20	Segredo	Brazil	1972	145	720	Rock	H to VH	?-0.4(?)	229	0.158	200	0.138	87	340	-	-	FF 390	45
21	Serpentine	Australia	1971	38	134	Rock, gravels in river section	M to H	0.24-25.5	77	0.203	35	0.092	45	-	-	-	-	-
22	Shiroro	Nigeria	1983	125	560	Rock	VH	0–1.8	166	0.133	<66	<0.053	40	90	-	-	FF 1800	100
23	Tianshengqiao-1	China	1999	178	1,168	Rock	M to VH	0.05-0.8	926	0.52	<926	<0.052	-	-	-	-	FF 53	-
24	Tullabardine	Australia	1979	25	214	Rock	H	0.2-12.8	19	0.076	2	0.01	11	-	-	-	2	0.8
25	White Spur	Australia	1989	43	146	Rock	VH	0.04–5.9	58	0.135	7	0.016	12	38	15	39	FF 7	2
26	Winneke	Australia	1978	85	1,050	Rock	H	0.17–16.2	270	0.244	105	0.124	51	160	145	91	FF 58	13
27	Xingo	Brazil	1993	140	850	Rock, gravels in lower river bed	M to VH(?)	1.0–6.2	526	0.376	302	0.216	57	510	290	57	200	140

• IRSC : Classification of unconfined compressive strength of intact rock used in rockfills (Australian Standard AS 1726-1993) ; -. VH(Very high) : 70-240MPa, -. H(High) : 20-70MPa, -. M(Medium) : 6-20MPa.

• TS : Total Settlement, • SFF : Settlement on First Filling, • TD : Total deformation, • DFF : Deformation on first filling, • FF : First filling

Figs. 2 and 3 show that crest settlement is largely affected by the intact rock strength rockfill more than the height of dams. That is, as shown in Table 1 and Fig. 2, the total magnitude of settlement for embankments constructed of medium to high intact strength rockfill after 10 years is, on average, approximately twice that of very high strength rockfills. The magnitude of long-term post-crest settlement for embankments constructed of very high strength rockfill in Fig. 2 appeared 0.1~0.2% of dam height, and embankments constructed of medium to high intact rockfill was 0.2~0.45% of dam height. According to Clements (1984) and Sherard and Cooke (1987), the range of post-construction crest settlement of compacted CFRDs is 0~0.25% of dam height. So, the range of post-construction crest settlement suggested by Sherard and Cooke (1987), and Clements (1984) shows a good agreement in the case analyses using rockfill with very high intact strength, but it has a trend which underestimated crest settlement in the cases using rockfill with medium to high intact strength. Fig. 3 shows that approximately 10–50% of the total long-term crest settlement occurred during the first filling. Therefore post-construction crest settlement seems to have been significantly affected by the intact rockfill strength and water load during the first reservoir filling. However, in fig. 3.2, FF ratio shows a proportional relation to dam height on the dam cases less than 10 years after completion.

2.2 Deformation of concrete face slab

Figs. 4 and 5 respectively show the dam face strain contours at the end of construction and the changes due to the first reservoir filling, at 148m high Salvajina Dam (Hacelas et al., 1987).

Table 2. Maximum face strains

Dam Name	Hight(m)	Yaer completed	Period Surveyed (years)	Maximum Strains ($\times 10^{-6}$)		Remark
Cheongsong Lower	62	2007	First filling	Compression	96	
				Tension	135	
Cheongsong Upper	90	2007	First filling	Compression	385	
				Tension	121	
Cethana	110	1971	10	Compression	665	Fitzpatrick et al. (1986)
				Tension	-	
Winneke	85	1978	5	Compression	500	Casinader and Watt (1985)
				Tension	200	
Shiroro	125	1983	First filling	Compression	500	Bodtman and Wyatt (1985)
				Tension	200	
Salvajina	148	1984	First filling	Compression	400	Hacelas et al. (1987)
				Tension	90	

The strain in the face slab is significantly affected by the water load, and tension zones caused by the water load are developed near the toe, the crest, and near the abutments. Table 2 shows the measured maximum slab strains. The strains appeared in Table 2 show that the maximum compressive and tensile strains are respectively 665×10^{-6} and 200×10^{-6}. According to Fitzpatrick (1986), the failure range for concrete is between 1000×10^{-6} for rapid loading and 3000×10^{-6} for gradual loading.

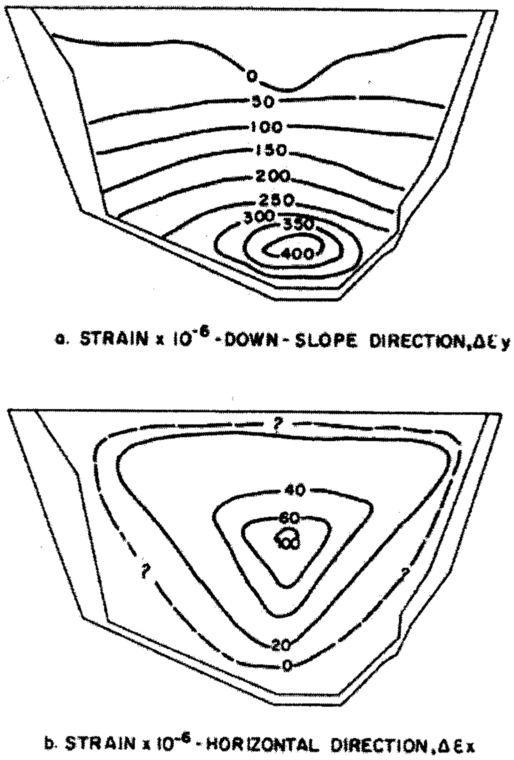


Fig. 4. Salvajina Dam: concrete face strains at the end of construction (Hacelas et al., 1987)

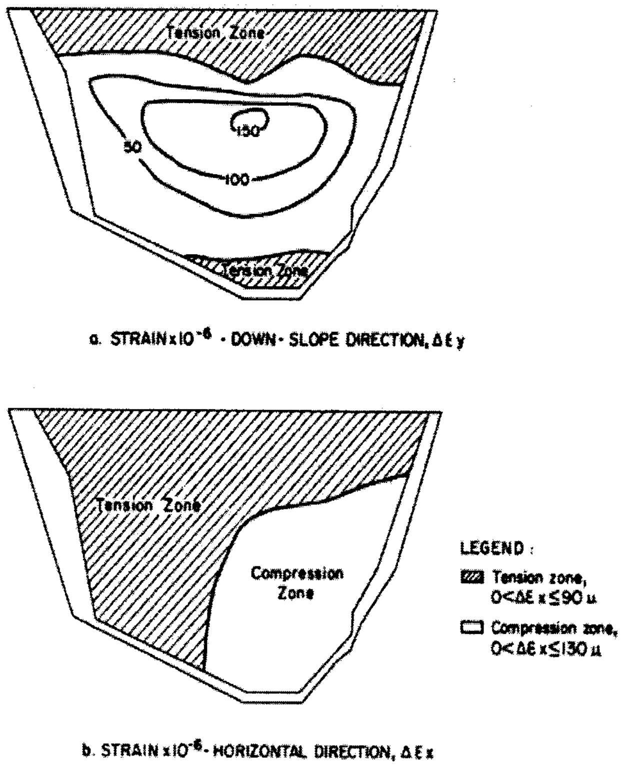


Fig. 5. Salvajina Dam: concrete face strains due to water load (Hacelas et al., 1987)

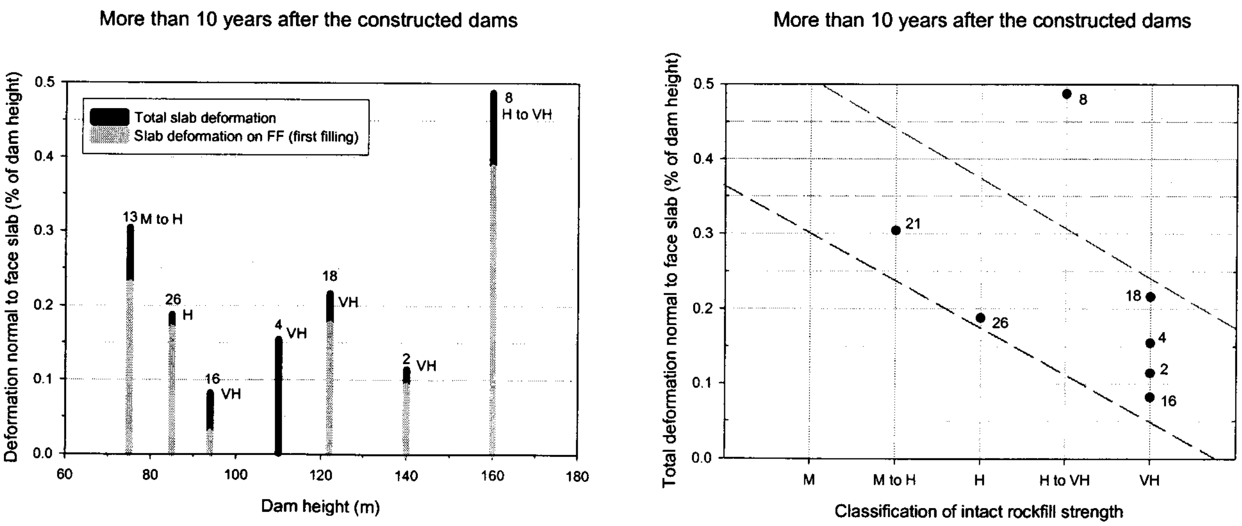


Fig. 6.1 Deformations normal to face slab on first filling and after at least 10 years

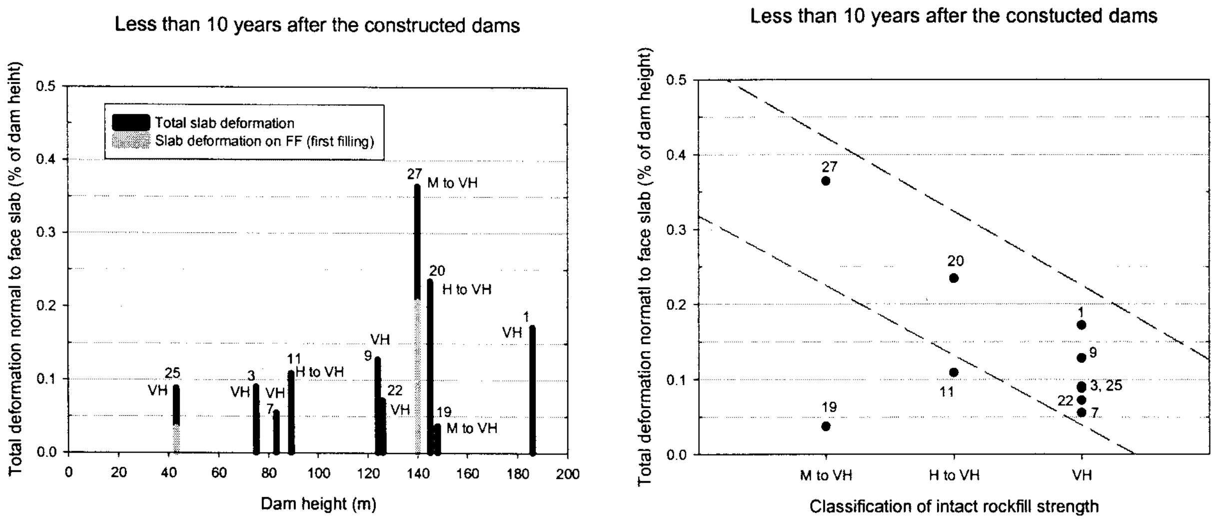


Fig. 6.2 Deformations normal to face slab on first filling and less than 10 years after the constructed dams

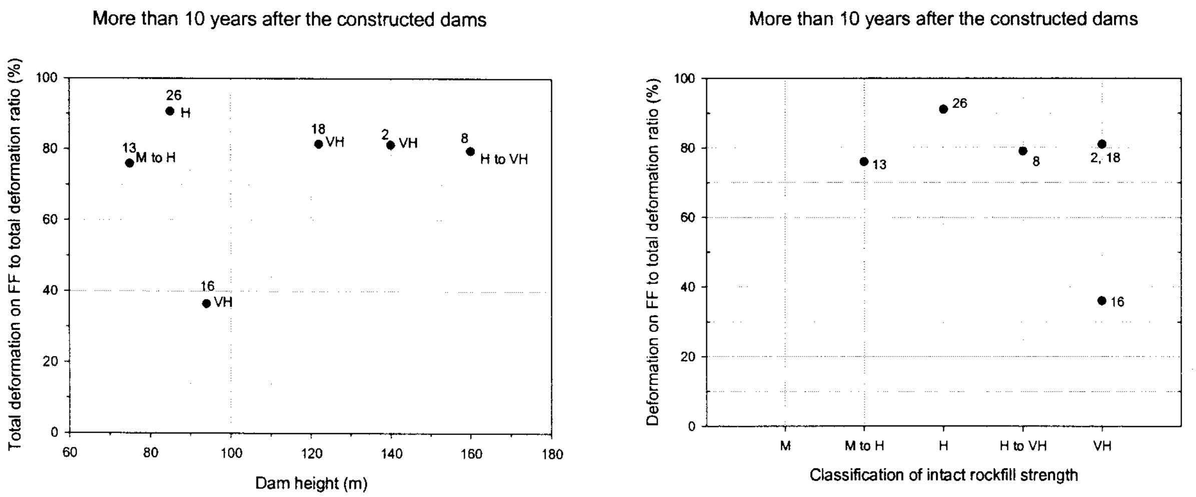


Fig. 7.1 Ratio of deformation normal to face slab on first filling to long-term deformation

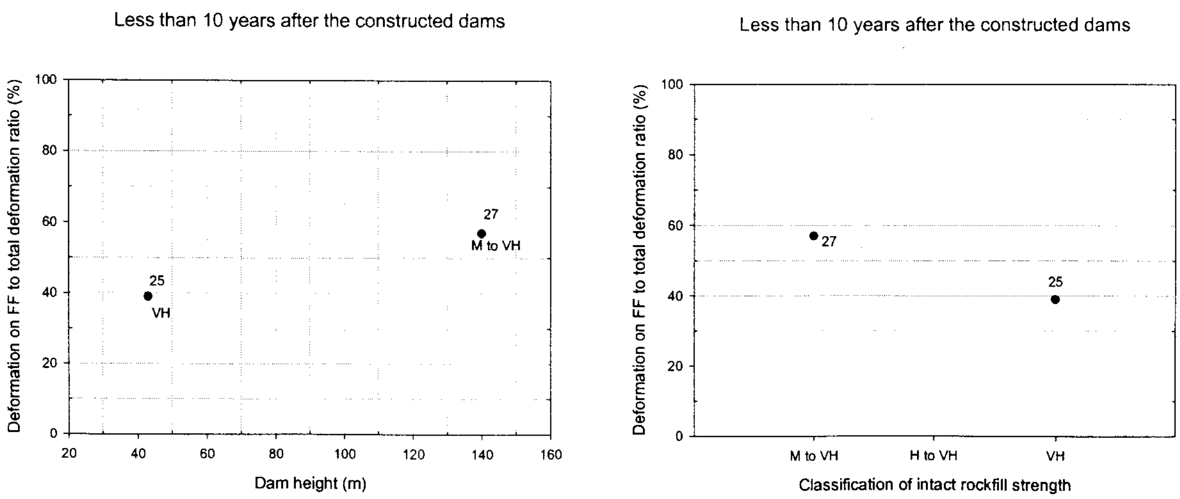
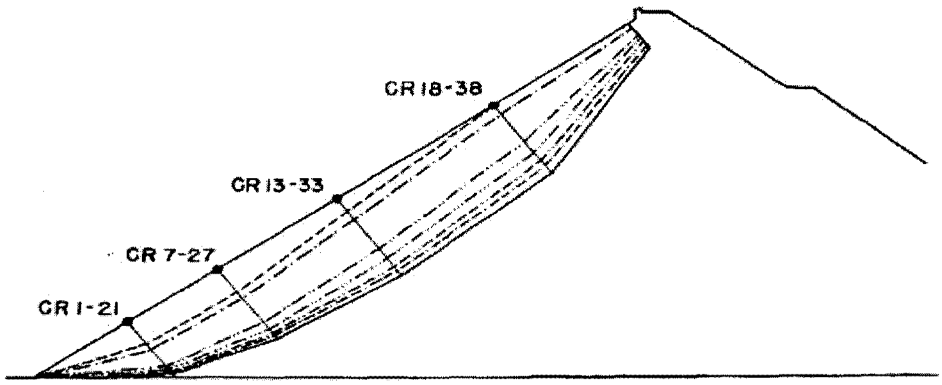


Fig. 7.2 Ratio of deformation normal to face slab on first filling to short-term deformation

Figs. 6 and 7 show the deformation normal to the face slab on CFRDs after construction and on first filling which are appeared in Table 1. The magnitude of the deformation normal to the face slab on CFRDs appear 0.1~0.5% of dam height which are similar to the post-construction crest settlement, and less than 0.25% of dam height in most cases. Approximately 80% of the total long-term deformation normal to the face slab occurred during the first filling as shown in Fig. 7. This means that most deformation occurs during the first filling, and is significantly affected by the water load rather than the crest settlement. It may cause cracks in the concrete face slab as most deformation normal to the face slab occurs during the first filling. Fig. 6 also showed the face slab deformation is trend to proportional to the rockfill strength rather than dam height.



CR	DEFLECTION (cm)						
	05/80	06/80	07/80	08/80	11/80	10/82	03/84-85
1-21	21.8	27.7	44.0	47.4	50.1	52.5	52.5
7-27	22.8	30.9	55.8	61.4	64.8	68.1	70.0
13-33	12.6	20.7	50.4	61.2	69.2	72.8	77.5
18-38	—	8.7	35.6	47.0	56.6	62.1	68.9
W.L.	702.50	714.00	735.80	739.50	739.00	742.00	743.60

Fig. 8. Slab deformation after reservoir filling (Pinto et al., 1985)

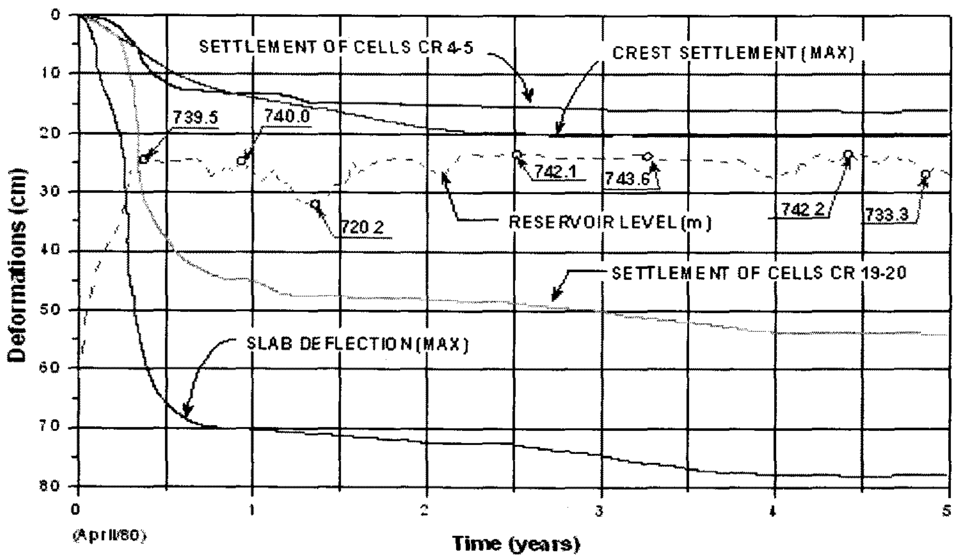


Fig. 9. Dam deformation after reservoir filling (Pinto et al., 1985)

Figs. 8 and 9 respectively show the embankment deformations and slab deformation after reservoir filling (Pinto et al., 1985). The first reservoir filling was started in April, 1980 and completed in October, 1980. The deformation mostly occurred during the first filling. The deformation normal to the face slab was the maximum near the center of the face in down slope direction, and was gradually decreased approaching to the toe. So, tensile crack and tensile stress might be developed near the toe due to uneven settlement.

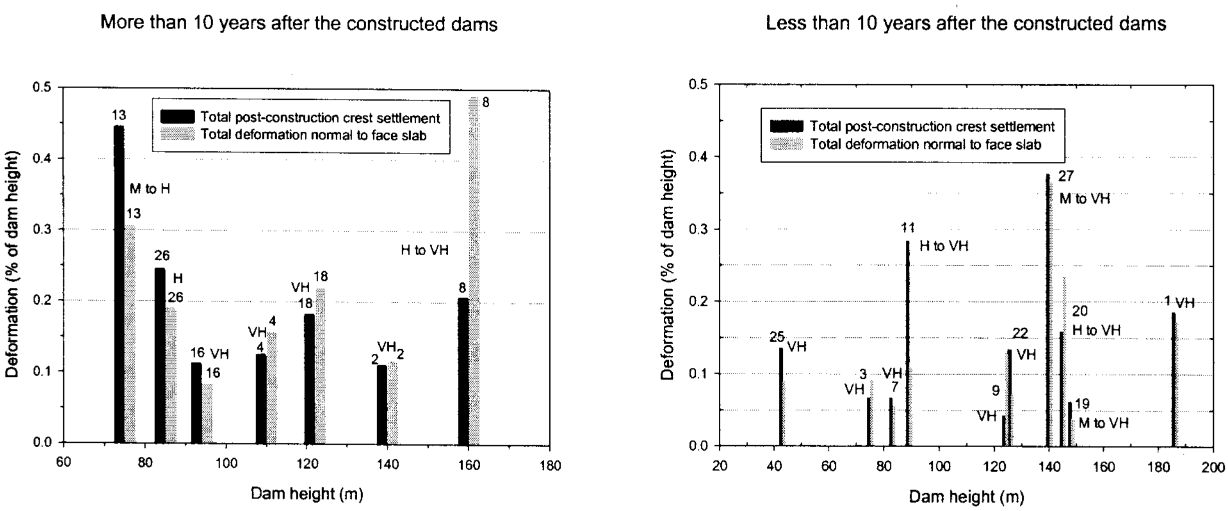


Fig. 10. Total post-construction crest settlement and total deformation normal to face slab

Fig. 10 shows the dam heights versus the total long-term post-construction crest settlements and the total long-term deformations normal to the face slab. The post-crest settlement and the deformation normal to the face slab are generally similar to each other, and they are smaller than 0.5% of the dam height. One of the interesting phenomena is that the crest settlement is larger than the deformation normal to the face slab when the dam height is less than 100m, and the deformation normal to the face slab is larger than the crest settlement when the dam height is greater than 100m. This phenomenon may easily cause the development of tensile crack near the toe, and increased movement displacement at the parametric joint if dam height is over 100m.

3. Leakage

FF denoted in front of maximum leakage rate in Table 1 means that maximum leakage occurred during first reservoir filling or just after the first highest water level. As shown in Table 1, the maximum leakage at a CFRD generally occurs during the first filling because of large deformation at the joints or cracks in the face slab due to the water load (Amaya and Marulanda, 1985; Arrau et al., 1985; Hunter, 2003; Leps et al., 1985; Millet et al., 1985). Sherard and Cooke (1987) showed that leakage emerging downstream of a CFRD has a basically different significance from leaks through dams with earth cores, because there is no possibility of earth core erosion and no potential threat to the dam safety. Not only Shrerard and Cooke (1987) but also many others (Amaya and Marulanda, 1985; Arrau et al., 1985; Hunter, 2003; Leps et al., 1985; Millet et al.,

1985) have reported that leakage in the CFRD has posed no threat to the safety and stability of the dam. However, a large leakage causes an economic loss of water resources, and may have an impact on the function of the reservoir or dam.

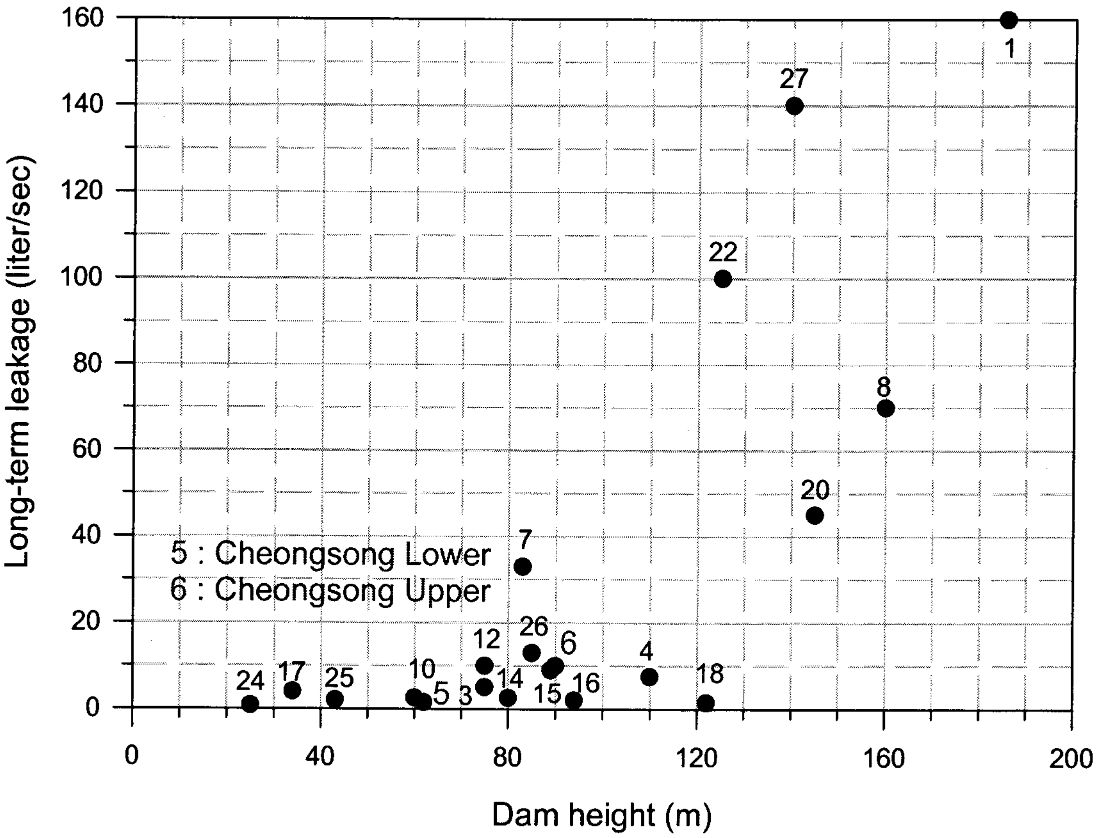


Fig. 11. Long-term leakage rate versus dam heights

Fig. 11 shows the relationship of long-term leakage rate versus dam heights. According to Sherard and Cooke (1987), for most reservoirs on rivers of any significant size, a leakage of a few tens of liters per second has negligible economic value. As shown in Fig. 11, the long-term leakage rate in cases of less than 120m dam height shows a acceptable value which is less than 10ℓ/sec, except for Crotty and Winneke Dams, but the cases of dams having more than 125m height rapidly increases between 45 and 160ℓ/sec. Typical CFRDs which are higher than 125m, such as Alto Anchicaya (Materon, 1985; 140m), Foz Do Areia (Pinto et al., 1985; 160m), Golillas (Amaya and Marulana, 1985; 125m), New Exchequer (Leps et al., 1985; 145m), and Shiroro (Bodtman and Wyatt, 1985; 125m), have experienced some leakage problems, and may have generally needed to repair face slab joints during the first filling. From these experiences, it can be concluded that CFRD's having more than 120m height may have some problem with leakage during, as well as after, the first filling. Perhaps, this phenomenon is caused by face slab deformations due to the water load, and the deformation normal to the face slab is larger than the crest settlement when the dam height is greater than 100m.

4. Conclusion

The characteristics of post-construction crest settlement, concrete face slab deformation, and leakage of CFRDs have been described, and have reached the following conclusions.

(1) The crest settlement and face slab deformation are proportional to the strength of rockfill rather than dam height.
(2) The range of post-construction crest settlement suggested by Sherard and Cooke (1987), and Clements (1984) had a good agreement in the cases using rockfill with very high intact strength, but it had a trend which underestimated crest settlement in the cases using rockfill with medium to high intact strength.
(3) The total magnitude of crest settlement for embankments constructed of medium to high intact strength rockfill is, on average, approximately twice that of very high strength rockfill.
(4) The post-construction crest settlement and the deformation normal to the face slab are generally similar to each other, and they are smaller than 0.5% of the dam height. However, there is a trend that the crest settlement is larger than the deformation normal to the face slab when the dam height is less than 100m, and the deformation normal to the face slab is larger than the crest settlement when the dam height is greater than 100m.
(5) The maximum leakage rate in general was observed during the first reservoir filling, and long-term leakage rate was a trend to rapidly increase when the dam height exceeds approximately 120m. Perhaps, this phenomenon is caused by large face slab deformations due to the water load.

The maintenance and management of the CFRD could be operated effectively using the trend of the concrete face slab deformation and crest settlement rather than other data.

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