Post-Construction Deformation of Rockfill Dams

By Ronald P. Clements[1]

Abstract: A study of the post-construction crest settlements and deflections of 68 rockfill dams has been made in order to assess the usefulness and accuracy of the prediction of such deformations using empirical equations. Graphs of deformation per unit height against time are plotted for membrane-faced (dumped and compacted rockfill), sloping, and central core dams. Comparisons of predicted and observed movements show that use of empirical equations can lead to large errors. An alternative approach is proposed, using only the deformation curves of existing dams with similar characteristics to the dam under consideration. Details are given in tabular form for each of the dams in the survey, as an aid to this approach.

Introduction

Rockfill dams continue to deform long after their construction has been completed. These movements are indicative of the structure's ability to perform its task. Initially large or unexpected movements may be the only indication of problems within a dam. If, however, the post-construction movements can be predicted, then a comparison of these values with those observed can alert the engineer to potential problems. Post-construction movements are also important at the design stage when the amount of camber required must be decided.

In this paper the findings of a survey of the observed movements of 68 dams are presented, in order to provide a method of predicting post-construction movements for membrane-faced, sloping, and central core rockfill dams. The survey concentrates on crest settlements and deflections because the majority of the reported information refers to these. Crest movements can be easily measured and facilities to record these may be the only instrumentation provided. The construction method, loading during the post-construction period, and the nature of the fill and foundation materials were noted for each dam where reported. Prediction methods based on similar information are discussed with reference to their usefulness and accuracy. Due to discrepancies between the conclusions of these methods and between predicted and observed movements, an alternative approach is proposed.

Survey of Observed Movements

Dams were classified according to their design cross-section, viz., central core, sloping core, and membrane-faced, with a distinction being made between membrane-faced dams constructed using compacted and dumped rockfill. This differentiation was necessary due to the wide range

[1]Grad. Civ. Engr., Scott Wilson Kirkpatrick & Partners, Basingstoke, England.

Note.—Discussion open until December 1, 1984. To extend the closing date one month, a written request must be filed with the ASCE Manager of Technical and Professional Publications. The manuscript for this paper was submitted for review and possible publication on September 9, 1983. This paper is part of the *Journal of Geotechnical Engineering,* Vol. 110, No. 7, July, 1984. ©ASCE, ISSN 0733-9410/84/0007-0821/$01.00. Paper No. 18988.

J. Geotech. Engrg., 1984, 110(7): 821-840

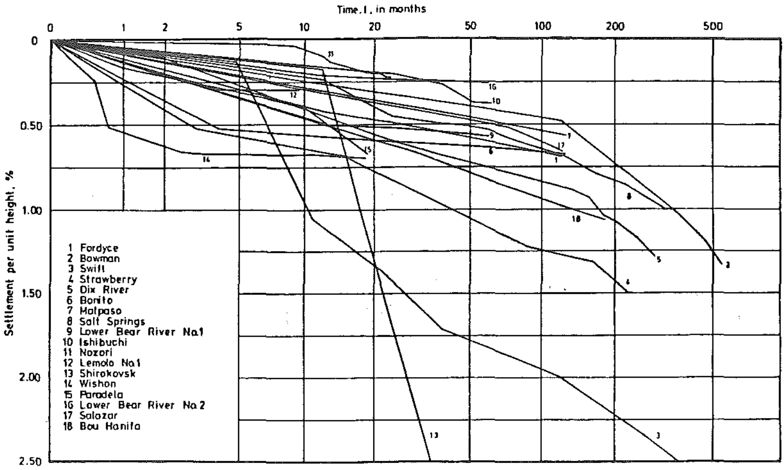

FIG. 1.—Crest Settlements of Membrane-Faced (Dumped Rockfill) Dams

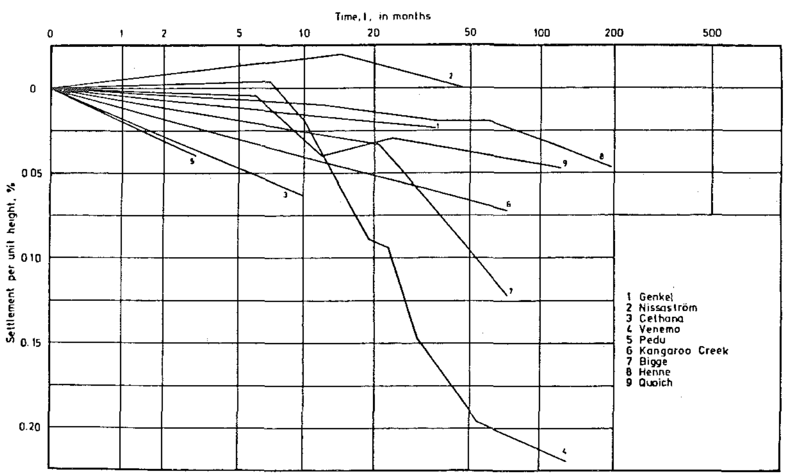

FIG. 2.—Crest Settlements of Membrane-Faced (Compacted Rockfill) Dams

of movements observed for membrane-faced dams.

Figs. 1–7 show the settlements and deflections per unit height plotted against log (time) for the dams in each cross-section category. A time scale of log $\{t + 1\}$ (t in months) has been used to give a full picture of the movements. The zero time point has been taken to be the time at which the initial measurements were made, i.e., when the datum point for readings after construction was established.

Figs. 8 and 9 show the envelopes of the curves plotted in Figs. 1–4 and 5–6, respectively. An envelope of the deflections of central core dams has not been drawn, since the movements can take place in either the upstream or downstream direction, or both [note curves for Gepatsch

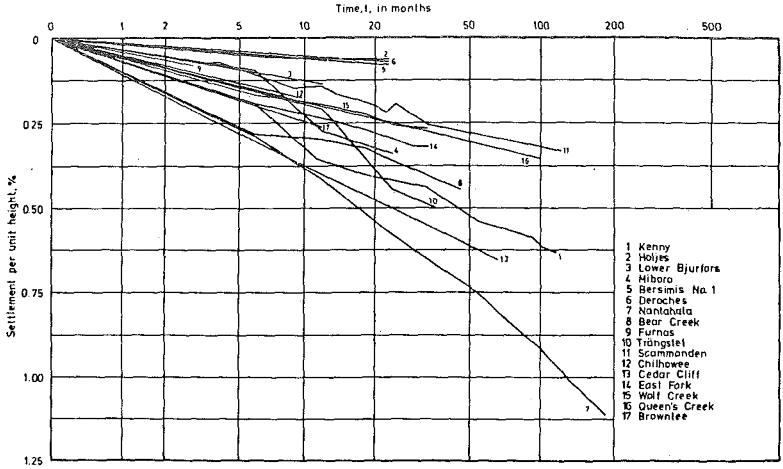

FIG. 3.—Crest Settlements of Sloping Core Dams

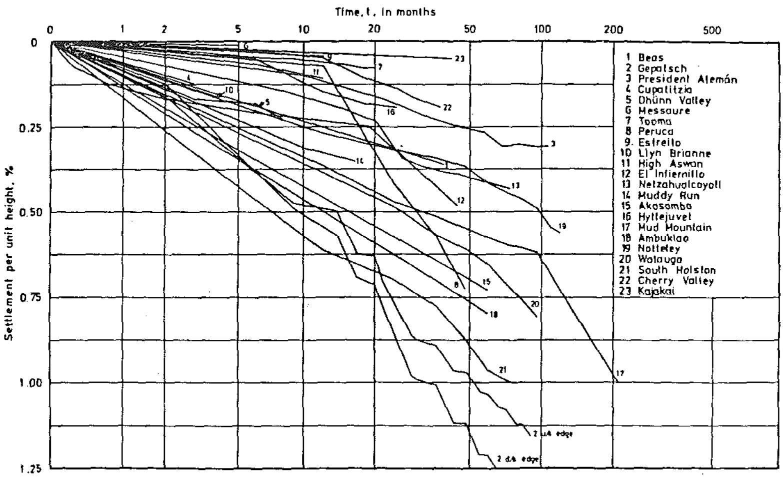

FIG. 4.—Crest Settlements of Central Core Dams

Dam (Fig. 7)]. The envelopes indicate that the greatest settlements and deflections may be anticipated in dumped rockfill membrane-faced dams. Sloping and central core dams would also be expected to settle and deflect more than compacted rockfill membrane-faced dams. Deflections are usually less than the settlements, although the opposite behavior has been observed, e.g., Malpaso Dam.

From these observed movements, it is possible to investigate the prediction of the movements of other dams. Empirical equations, proposed by other researchers from data such as that shown in Figs. 1–7, are considered below. An alternative approach is given.

J. Geotech. Engrg., 1984, 110(7): 821-840

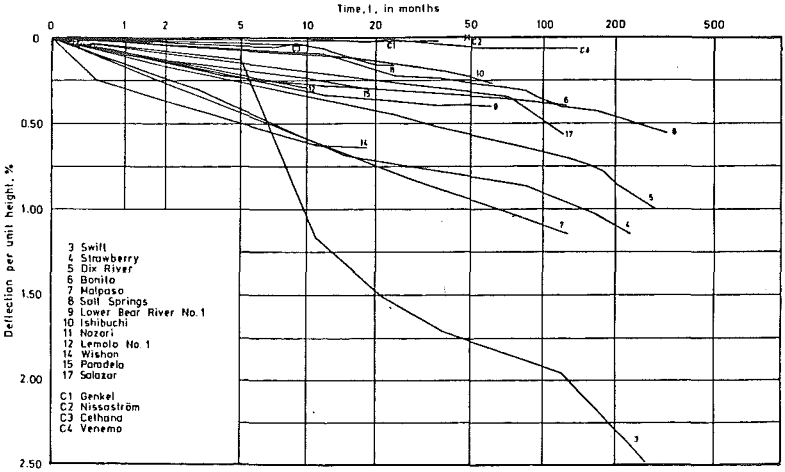

FIG. 5.—Crest Deflections of Membrane-Faced Dams

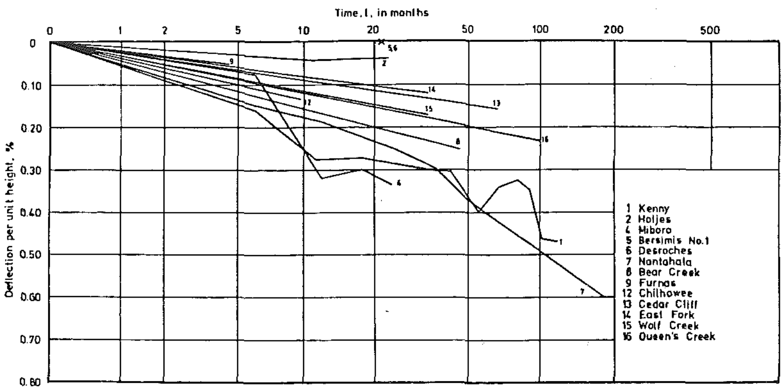

FIG. 6.—Crest Deflections of Sloping Core Dams

Prediction of Crest Settlements and Deflections

Existing methods of prediction based on observed movements express the crest movements in terms of the height of fill, the post-construction period, or both, since these are readily available parameters. Such approaches produce a single displacement for a given height and time, irrespective of the many other factors (location, construction method, fill material, etc.) which influence the behavior. Unfortunately, the error involved in this assumption is not always reported when establishing the displacement relationship.

The Bureau of Reclamation, USA (13) recommends a camber of 1% of the height plus the anticipated foundation settlement for the design of small dams (i.e., less than 15 m high). Sowers, et al. (58) collected data from 14 dams, noting the heights, design cross-section, fill type, and

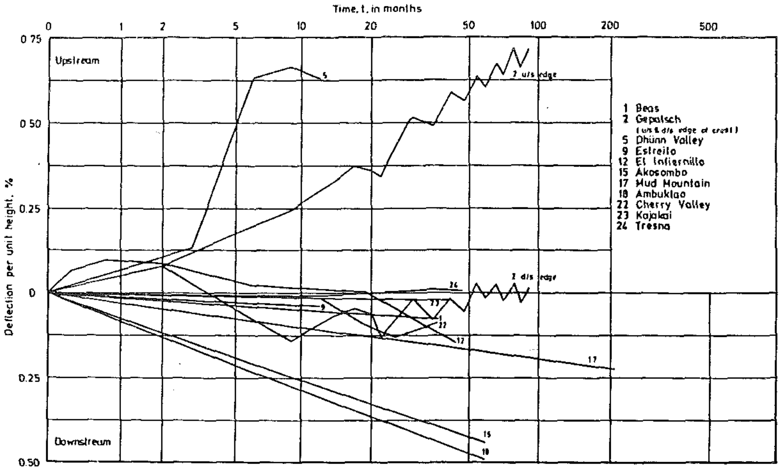

FIG. 7.—Crest Deflections of Central Core Dams

construction method. They plotted crest settlement per unit height against log (time), using the mid-point of the construction period as zero time. While noting that better construction techniques (viz., better compaction and sluicing) decreased settlement, they concluded that the settlement per unit height was independent of the dam height, design cross-section and the fill material. This was expressed in the following equation:

$$s = \frac{\alpha H}{100} (\log t_2 - \log t_1) \qquad (1)$$

in which s = settlement, in meters; H = height, in meters; and t = time, in months. The coefficient, α, was found to have values between 0.2 and 1.05 but no guidelines are given to determine appropriate values for other dams. Penman (47) has observed that α may increase with time and this is born out by the survey reported here.

Parkin (44,45) reviewed Sowers, et al.'s work and used a creep rate analysis to reproduce the equation determined by them for one of the dams. He argues that analysis based on total settlements is subject to uncertainty and alternative interpretation, whereas a rate analysis eliminates time-independent factors and amplifies imperfections in the data. The usefulness of a rate analysis has been found to be limited however, since "events" occurring during the post-construction period make it difficult to distinguish the basic creep pattern from the irregularities.

Lawton and Lester (31) took data from 11 dams which were settling at less than 0.02% of their heights per year. The time required for each dam to reach this state was not taken into account, although they suggest that 8–10 yr service should be sufficient. The following relationship was obtained using a best fit analysis:

$$s = 0.001 H^{3/2} \qquad (2)$$

in which s = the total settlement; and H = the height in meters. This

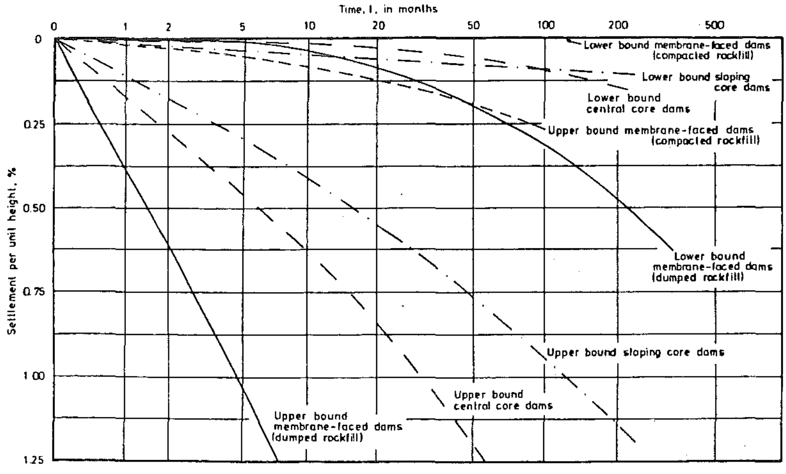

FIG. 8.—Envelopes of Settlement Curves

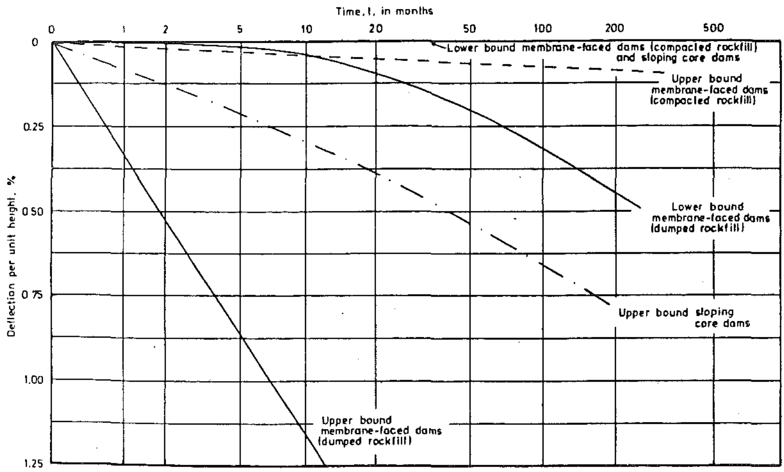

FIG. 9.—Envelopes of Deflection Curves

assumes the settlements to be correct and has a correlation coefficient of 0.976 (1.0 representing complete agreement). Lawton and Lester themselves show that the error in using this equation is up to ±30% of the settlement predicted. This can represent a significant amount for a large dam (e.g., ±1.5 m for 300 m of fill). Use of a rate less than 0.02%/yr, as the point at which total settlement has occurred, may also be more appropriate for large dams. For example, 60 mm/yr for a 300 m high dam may be an unacceptable proportion of the freeboard.

Soydemir and Kjaernsli (59,60) have attempted to combine displacement-time and displacement-height equations by producing displace-

TABLE 1.—Settlement-Height Relationship $s = \beta H^{\delta}$ after Soydemir and Kjaernsli (60)

Equation data (1)	Membrane-Faced (Dumped Rockfill) and Sloping Core Dams		Membrane-Faced (Compacted Rockfill) Dams	
	Initial impounding (2)	10 years service (3)	Initial impounding (4)	10 years service (5)
β	5.0×10^{-4}	1.0×10^{-3}	1.0×10^{-4}	3.0×10^{-4}
δ	1.5	1.5	1.5	1.5

ment-height equations for different time periods. They have considered the crest movements of 48 dams. Table 1 gives their results for the index and coefficient values of an equation of the form

$$s = \beta H^{\delta} \quad (3)$$

where s = settlement, in meters; and H = height, in meters for two time periods. Curves for periods up to 30 yr and for central core dams are presented in their 1975 report. Table 2 shows a simple comparison of

TABLE 2.—Comparison of Observed Settlements, (S_{OBS}), with Values Predicted by Equation (3), (S_{CALC})

Dam type (1)	RATIO S_{CALC}/S_{OBS}					
	Initial Impounding			10 Years Service		
	Mean value (2)	Maximum value (3)	Minimum value (4)	Mean value (5)	Maximum value (6)	Minimum value (7)
Membrane-faced (dumped rockfill)	1.22	3.32	0.29	0.96	1.47	0.31
Membrane-faced (compacted rockfill)	3.21	7.50	1.56	3.79	6.47	0.99
Sloping core	2.68	7.59	0.89	1.71	2.52	0.90

TABLE 3.—Settlement-Height Relationship $s = \beta' H^{\delta'}$ Using Best-Fit Analysis

Equation data (1)	Membrane-Faced (Dumped Rockfill) Dams		Membrane-Faced (Compacted Rockfill Dams)		Sloping[a] Core Dams	Central[a] Core Dams
	Initial impounding (2)	10 years service (3)	Initial impounding (4)	10 years service (5)	Initial impounding (6)	Initial impounding (7)
β'	1.8×10^{-3}	9×10^{-3}	2×10^{-4}	1.4×10^{-6}	7×10^{-4}	2×10^{-4}
δ'	1.2	0.9	1.1	2.6	1.3	2.0
Correlation coefficient	0.633	0.683	0.274	0.437	0.897	0.550

[a]Insufficient data for reasonable assessment of 10 yr service.

J. Geotech. Engrg., 1984, 110(7): 821-840

TABLE 4.—Details of Membrane-Faced

Name (1)	Country (2)	Year (3)	Height, in meters (4)	Main rock type (5)	Foundation (6)
Bonito	USA	1932	28.0	—	—
Bou Hanifa	Algeria	1938	53.0	Hard sandstone and conglomerate	—
Bowman	USA	1876	29.3	—	—
Dix River	USA	1925	84.2	Dense, finely crystalline, light grey limestone	Limestones and shales
Fordyce	USA	1926	42.7	—	—
Ishibuchi	Japan	1953	53.0	Dacite	Decomposed and jointed liparite
Lemolo No. 1	USA	1954	36.6	Basalt	Dense basalt, tuff, basalt agglomerate layers
Lower Bear River No. 1	USA	1952	74.7	Grey, fine-grained grano-diorite	Granite
Lower Bear River No. 2	USA	1952	45.7	Grey, fine-grained grano-diorite	Granite
Malpaso	Peru	1936	67.4	—	Boulders, gravels, sand and clay
Nozori	Japan	1956	44.0	Andesites and propylites	—
Paradela	Portugal	1957–1958	110.0	—	Granite—weathering variable
Salazar	Portugal	1949	62.8	Prophry	Silicious and argillaceous shales; intensely fractured and folded
Salt Springs	USA	1931	100.0	Sound granite	Granite; compacted gravel and boulders under d/s section
Shirokovsk	USSR	1947	40.0	—	Argillite and sandstone, alluvial deposits in riverbed
Strawberry	USA	1916	42.7	—	Gravels in riverbed
Swift	USA	1914	47.9	—	Gravels in riverbed
Wishon	USA	1958	90.2	—	Exposed glaciated granite

Note: 1.00 ft = 12.0 in. = 305 mm; 1.00 psi = 6.9 kPa.

(Dumped Rockfill) Dams

Construction method (7)	Sluicing water/rock volume ratio (8)	Reservoir filling (9)	Remarks (10)	References (11)
—	—	—	Reinforced concrete membrane	12
4.5 m lifts—placed by derricks; interstices filled by hand with small stones	—	—	Reinforced concrete membrane	42,63
Moderate to high lifts	None	—	Timber deck, dismantled in 1926	12
Dumping heights up to 35 m	Poor to moderate	—	Reinforced concrete membrane. Flood during construction	12,21,53
—	—	—	Reinforced concrete membrane	12
u/s dumped first from 29 m and 53 m levels	2:1 (100 psi)	Filled Dec. 1953–April 1954 Drained Oct. 1954 Refilled Dec. 1954	Concrete membrane	23
3 lifts	3:1	Partially filled and drained 1954; Filled May 1955	Concrete membrane Fault at site	4
2 lifts at 37 m and 44 m. 1 lift used at one section of dam	3:1 (9 psi)	Seasonal variation	Concrete membrane	61
1 lift	?	Filled 1953 seasonal variation	Similar design to Lower Bear River No. 1	61
—	Some	—	Concrete membrane	12
3 lifts of 17 m, 15 m and 12 m	4:1 (170 psi)	—	Concrete membrane	38
3 lifts at levels 68 m, 98 m and 108 m	4:1	First filling Oct. 1957–July 1958. Emptied July 1958 (seasonal variation)	Reinforced concrete slabs placed during construction	14
—	—	Filled 1949–50	Steel membrane	6,7,39
Lifts of 20–56 m	Nominal for bottom half, substantial for top half	Filled 1932 (seasonal variation)	Concrete membrane	61
—	—	—	Timber membrane	41
Lifts 10 m	None	—	Concrete membrane	12
Moderate to high lifts	—	—	Concrete membrane	12
—	3:1 (100 psi)	Filled May 1958 in 13 days (seasonal variation)	Concrete membrane placed during construction	11

settlements predicted by Soydemir and Kjaernsli's equations and observed movements. The mean values show an overestimation of the settlements in all but one case. For some dams there are large errors in the predicted settlements.

In order to study further the possibility of using empirical equations to predict post-construction crest movements, a best fit analysis of the data shown in Figs. 1–7 was carried out for 1 and 10 yr periods, assuming the heights to be correct. The indices and coefficients calculated are shown in Table 3. The results indicate that an index nearer 1.0 would be reasonable and there is little correlation of the coefficient values with those given by Soydemir and Kjaernsli. This may be due to the method of curve fitting used. More significantly, the correlation coefficients range from 0.274–0.897, which suggests that the errors are too large to make

TABLE 5.—Details of Membrane-Faced

Name (1)	Country (2)	Year (3)	Height, in meters (4)	Main rock type (5)	Foundation (6)
Bigge	Germany	1964	52.0	Shale and shaley greywacke	—
Cethana	Tasmania	1971	110.0	Clean quartzite	Hard, bedded quartzite and quartzite conglomerate
Genkel	Germany	1952	43.0	—	—
Henne	Germany	1955	52.0	Crystalline limestone and sound graywacke	Volcanic ash and keratophyre tuff
Kangaroo Creek	Australia	1969	59.4	Zn 1: quartz gneiss Zn 2: schist gneiss Zn 3: weak schist	Left bank: sericite schist Right bank: gneiss
Nissastrom	Sweden	1950	15.0	—	—
Pedu	Malaya	1969	63.0	Mudstones and quartzites	Conglomerates, quartzites and mudstone strata
Quoich	UK	1954	38.0	—	Moine schists
Venemo	Norway	1963	51.0	—	Granitic gneiss and zones of mica amphibolite

reasonable predictions from simple relationships with height or time. Other factors must be considered in the prediction calculations. The discrepancies between the conclusions of the approaches discussed above also suggest that such analyses are inconsistent with the data.

An alternative to simple empirical relationships with discrete solutions is the use of a comparative prediction approach. This recognizes the large number of factors influencing dam behavior and takes into account the scatter of the data. However, it does rely on the experience and good judgment of the design engineer.

Comparative Prediction Approach

The envelopes of crest settlement and deflection shown in Figs. 8–9

(Compacted Rockfill) Dams

Construction method (7)	Sluicing water/rock volume ratio (8)	Reservoir filling (9)	Remarks (10)	References (11)
Initial 0.8 m layers 3 ton tamper. Later 1.2 m layers 5 ton vibrating roller	—	Filled 1965	Asphaltic concrete deck	28,29,60
Layers 0.45 m, 0.9 m, 1.85 m; 4 passes 10 ton vibrating roller	>0.15	Filled February to April 1971	Face rolled 10 ton vibrating roller. Reinforced concrete deck	15,65
2.5 ton vibrating roller and smooth steel roller	—	—	Asphaltic concrete deck	57,60
Layers 0.8 m; 3 ton tamper	—	—	Asphaltic concrete deck	1,28,29, 30,60
Sluiced prior to compaction; 4 passes 10 ton roller	1.1	—	Reinforced concrete deck	16
0.45 m–0.6 m layers, sluiced; 10 ton roller and then 1.6 ton vibrating roller	Some	—	Timber deck	20
1.8 m layers; 8 passes 10.5 ton vibrating roller	—	—	Asphaltic concrete deck	10
10 ton roller and then 3.5 ton vibrating roller	Some	—	Concrete slab deck	47,52
Initial dumped 15–20 m. Later 8 ton vibrating roller	Some (not winter)	Filled June–October 1964 (seasonal variation)	Asphaltic concrete deck. Roller: 1.5 m layers 10 passes (*S*) 1 m layers 15 passes (*W*)	27,60

TABLE 6.—Details of

Name (1)	Country (2)	Year (3)	Height, in meters (4)	Main rock type (5)	Foundation (6)
Bear Creek	USA	1953	65.5	Good quality schist	Massive schist
Bersimis No. 1	Canada	1955	61.0	Sound granite gneiss	Gneiss; North abutment thick layers of till and silt
Brownlee	USA	1958	122.4	—	Basalts with tuff interlayers; riverbed alluvials
Cedar Cliff	USA	1952	50.3	Good quality schist	—
Chilhowee	USA	1957	27.7	—	—
Desroches	Canada	1955	68.6	Sound granitic gneiss	Gneiss
East Fork	USA	1955	41.2	Good quality schist	—
Furnas	Brazil	1962	125.0	Hard, fine-grained quartzites	Quartzites with thin mica-schist interlayers
Holjes	Sweden	1961	81.0	—	—
Kenny	Canada	1952	100.0	Massive basalt	Basalt
Lower Bjorfors	Sweden	?	30.0	—	—
Miboro	Japan	1960	131.0	Granite	Quartz porphyry with granite porphyry intrusions
Nantahala	USA	1942	77.7	Hard massive arkose	Arkose
Queen's Creek	USA	1948	23.8	Arkose	Alluvium material in riverbed
Scammonden	UK	1969	70.0	Sandstone	Layers of sandstone and shale
Trangslet	Sweden	1960	125.0	Porphry	Syenite and porphry
Wolf Creek	USA	1955	50.3	Good quality schist	—

[a]PC = Private Communication (Data used with permission of Yorkshire Water Authority, UK).

can provide a quick estimate of the expected range of movements for a certain design cross-section. Due to the wide range of values, specific displacements cannot be calculated and therefore any results taken from these curves must be considered a first approximation. Better predictions can be obtained using the curves in Figs. 1–7. These show the movements of a large number of dams, some of which will have similar

J. Geotech. Engrg., 1984, 110(7): 821-840

Sloping Core Dams

Construction method (7)	Sluicing water/rock volume ratio (8)	Reservoir filling (9)	Remarks (10)	References (11)
Lift 52.5 m; Top 12 m constructed separately	Some	Filled 1953	In narrow gorge; Core wet of opt.	17,19
High lifts dumping from south abutment	4:1	Started 1955 during construction. Max 1957, drawdown 1958	—	46
Coarse rock dumped. Fine rock 45 cm layers—3 passes 50 ton roller	4:1	—	Loam Core. Flooding during construction	1,31
—	—	—	—	17,19
—	—	—	—	19
Dumping in high lifts 42 m from north bank	4:1	Same as Bersimis No. 1	Sited next to Bersimis No. 1—similar design	46
—	—	Filled 1955	—	17,19
Compacted in 30–70 cm layers	None	Filled shortly after construction	Decomposed schist and quartzite core	34,37,50
2–10 m lifts; Sluicing in summer, not winter	2:1	Filled 1961–62 (seasonal variation)	Moraine material core	51
12 m lifts from left abutment	2:1	Filled 3 years after construction	Boulder clay core	31
2 m lifts	Some	Filled during 6 months after construction	—	51
<4 m lifts u/s (no sluicing) <8 m lifts d/s	3:1	—	Fault zone on right abutment. Earthquake in 1961	2
Lifts 15–40 m	4:1	Filled February–July 1942 (seasonal variation)	Core—2% dry of opt.	17,18,19
—	—	Filled 1948, emptied rapidly on several occasions	Core of poor material	17,19
1 m layers; 5 passes 11.5 ton vibrating roller or 6 passes of two 5 ton rollers	Some	—	Zoned clay core	9, PC[a]
2–3 m layers u/s, sluicing and compaction with tractors; 20 m layers d/s, no sluicing	4:1	—	Core of moraine material	48
—	—	Filled shortly after construction	—	17,19

characteristics to the dam under consideration. The designer must decide how appropriate these characteristics are and then calculate displacement values using only the curves of those dams he has selected. Of most value are the observed results from similar dams close to the proposed site. For example, Bersimis No. 1 and Desroches Dams, Figs. 3 and 6, were built next to each other using similar materials and meth-

TABLE 7.—Details of

Name (1)	Country (2)	Year (3)	Height, in meters (4)	Main rock type (5)	Foundation (6)
Akosombo	Ghana	1965	112.8	Clean, strong quartzite	Riverbed sand deposits up to 38 m deep
Ambuklao	Philippines	1955	128.5	Diorite	Weathered andesite, tuff and lava. Riverbed deposits
Beas	India	1974	132.5	—	Layers of sandstone and clay shales (well consolidated)
Cherry Valley	USA	1955	100.6	Grano-diorite	Granite
Cupatitzio	Mexico	1961	72.4	Sound diorite	Right bank—diorite Left bank—conglomerate
Dhunn Valley	Germany	1962	35.0	Slate	Sandstone and slate, gravel in valley bed
El Infiernillo	Mexico	1963	148.0	Sound diorite and silicified conglomerate	Conglomerates, alluvial deposits in riverbed
Estreito	Brazil	1968	97.0	Quart-schist sound quartzite	Sound quartzite
Gepatsch	Austria	1964	153.0	Gneiss	Gneiss, overlain by alluvial material, talus, boulder clay
High Aswan	Egypt	1968	111.0	Granite, migmatites	Alluvial deposits up to 255 m deep
Hyttejuvet	Norway	1965	93.0	—	—
Kajakai	Afghanistan	1952	100.0	Sound limestone	Massive dolomite limestone
Llyn Brianne	UK	1971	91.0	Slatey mudstone	Slatey, argillaceous rocks. Fault in left abutment
Messaure	Sweden	1962	101.0	Granite	Hard, sound granite with zones of faulted, crushed rock
Muddy Run	USA	1966	76.2	Weathered, laminated, micaceous schist	—
Mud Mountain	USA	1941	122.0	—	Tuff, andesite, quartzite. Alluvial deposits in riverbed

Central Core Dams

Construction method (7)	Sluicing water/rock volume ratio (8)	Reservoir filling (9)	Remarks (10)	References (11)
1.8 m layers: 4 passes of 4 ton vibrating roller or 3 m layers: 4 passes of 8 ton vibrating roller	Some	Filled 1969	Core 0–2% wet of opt.	67
d/s dumped in 9–27 m layers. *u/s* compacted in 60 cm layers with 50 ton roller	Some	—	Loam core	1,31
—	—	—	Clay and sand core (?)	64
Dumped in 4.5–9 m lifts	Some	Filled to 2/3 cap May 1956; drawndown and filled July 1957 (seasonal variation)	Sandy silt core	1,33
2 m layers	None (good rainfall)	Filled quickly 1961	Silt core—7.7% wet opt.	36,37
0.6 m layers: 7 ton sliding vibrator	—	—	Vertical bituminous concrete core	5
<1 m layers: 4 passes of D-8 tractor	None	Filled June–September 1964	Thin core; 2–6% wet of opt.	1,67
0.5–0.6 m layer with 2 passes of D-8 tractor	—	Filled in 10 days November 1968	Thin clayey sand core	35
2 m layers; 4 passes of 8.5 ton vibrating roller	Rainfall	Filled to 2/3 cap during construction (seasonal variation)	Talus and moraine material core	54,55,56,40
Dumping: sluiced with sand	Some	—	Zoned dam; clay core	24,25
3–5 m lifts	Some	Filled May–October 1966. Drawndown February 1967. Filled 1967	Moraine material core—narrow at top of dam	26
Dumped in 10 m lifts	2:1	Filled 1952	Core-mixture of sand, silt and clay: 2–4% dry of opt.	62
1 m layers; 4 passes of 8.6 ton roller or 13.5 ton vibrating roller	Some	Filling started 2 months after completion	Moraine till core	8
1.5 m layers with sluicing in summer 2 m layers, no sluicing in winter	Some	—	Moraine material core	3
0.3–1 m layers with vibrating roller	—	—	Clayey silt core	67
—	—	—	Sandy gravel and clay	1,31

J. Geotech. Engrg., 1984, 110(7): 821-840

TABLE 7.—

(1)	(2)	(3)	(4)	(5)	(6)
Netzhualcoyotl	Mexico	1964	137.5	Conglomerate	Conglomerate
Notteley	USA	1942	56.1	Quartzite (20% mica schist)	—
Peruca	Yugoslavia (?)	1959	60.0	Limestone	'Firm rock'
Presidente Aleman	Mexico	1953	75.0	Limestone	Limestone
South Holston	USA	1950	86.9	Sandstone, some shale	Sandstone
Tooma	Australia	1961	68.0	*u/s* dense fine-grained quartzite *d/s* weathered granite	Biotite granite and granitic gneiss—generally weathered
Tresna	Poland	1964	38.0	—	'High modulus of compressibility'
Watauga	USA	1948	96.8	Quartzite	Quartzite

ods of construction and have exhibited very similar behavior.

In addition to the curves, Tables 4–7 give information obtained in the survey for each dam. These provide a quick means of determining which dams have similar characteristics to the one being considered. Appendix I gives the references used for each dam. These often discuss problems encountered during and after construction which may have affected the post-construction behavior, as well as giving more details of the dam characteristics.

Summary and Conclusions

A survey of the crest settlements and deflections of 68 rockfill dams has been carried out. This has been used to investigate the reliability of existing methods of prediction of crest movement. These predicted values can be used in determining the requisite camber and provide an "early warning system" of problems within the dam. Existing methods are based on simple empirical relationships of displacement with height or time. The errors involved, however, are considered to be too significant to allow reasonable predictions to be made. An alternative approach has been proposed, based on the comparison with dams having similar characteristics. Information has been presented which will aid this comparison and which can easily be added to as further information is published.

Acknowledgments

The writer is grateful to J. W. Dougill, Prof. of Concrete Structures

Continued

(7)	(8)	(9)	(10)	(11)
500–100 cm layers compacted by tractor	High rainfall	Filled May–September 1966	Red laterite core, 7% wet of opt.	67
Dumped in one stage	Some	Filled 8–9 months after completion (seasonal variation)	Wide sandy clay core	32
Dumped in 6 m lifts	4:1	Filled 1960 (seasonal variation)	Clay core at opt.	43
2 m layers with no sluicing	High rainfall	Seasonal filling to 2/3 cap 1954–56. Full 1957 and kept full	Lateritic clay core; 4% wet of opt.	36,37
Dumped in 3 stages	Some	Filled 8–9 months after construction (seasonal variation)	Medium clay core	1,32
3 m layers	1.5:1	Filled 1961. Sudden drawdown 1962	Weathered biotite granite core	49
—	—	—	Silty loam core; wet of opt. Culvert under dam	22,66
Dumped in 2 stages	Some	Filled 8–9 months after construction (seasonal variation)	Clayey sand and clay	1,32

and Technology, Imperial College, London; and P. A. Green of Scott, Wilson, Kirkpatrick, & Partners for reviewing this paper. This research was carried out with the financial assistance of the Science and Engineering Research Council, United Kingdom.

Appendix.—References

1. Airapetyan, R. A., "Modern Rockfill Dams," Israel Program of Scientific Translations, Jerusalem, Israel, 1973.
2. Asao, I., "The Miboro Dam," Vol. III, 8th ICOLD, 1964.
3. Bernell, L., "Measurements in the Messaure Dam, a Rockfill Structure with Wet-Compacted Moraine Core," Vol. II, 8th ICOLD, 1964.
4. Boyle, J. C., and Barrows, W. R., "Rockfill Dams: Lemolo No. 1 Dam," SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
5. Breth, H., "Measurements on a Rockfill Dam with a Bituminous Concrete Diaphragm," Vol. III, 8th ICOLD, 1964.
6. Carlos, A. Palma, Discussion Paper 3076, SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
7. Carlos, A. Palma, "Valeurs Prevues et Valeurs Observees pour les Tassements des Enrochments du Barrage Salazar, Pendant et Apres sa Construction," Vol. III, 5th ICOLD, 1955.
8. Carlyle, W. J., "The Design and Performance of the Core of Brianne Dam," Vol. III, 11th ICOLD, 1973.
9. Charles, J. A., "Correlation between Laboratory Behaviour of Rockfill and Field Performance with Particular Reference to Scammonden Dam," PhD thesis, University of London, 1973.
10. Clarke, C. L., and Taylor, R. G., "Lessons Learned from Two Rockfill Dams in the Tropics," Vol. I, 10th ICOLD, 1970.
11. Cooke, J. B., "Rockfill Dams: Wishon and Cartwright Concrete Face Dams," SORD. Transactions, ASCE, Vol. 125, Part II, 1960.

12. Davis, C. V., "Handbook of Applied Hydraulics," 2nd ed., McGraw-Hill, 1952.
13. *Design of Small Dams*, 2nd ed., Bureau of Reclamation, United States Department of the Interior, Washington, D.C., 1977, p. 311.
14. Fernandes, L. H. G., Oliveira, E., and Vasconcelos Porto, N., "Rockfill Dams: Paradela Concrete Face Dam," SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
15. Fitzpatrick, M. D., et al., "Instrumentation and Performance of Cethana Dam," Vol. III, 11th ICOLD, 1973.
16. Good, R. J., "Kangaroo Creek Dam, Use of a Weak Schist as Rockfill for a Concrete Faced Rockfill Dam," Vol. I, 12th ICOLD, 1976.
17. Growden, J. P., "Rockfill Dams: Dams with Sloping Earth Cores," SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
18. Growden, J. P., "Rockfill Dams: Nantahala Sloping Core Dam," SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
19. Growden, J. P., "Rockfill Dams: Performance of Sloping Core Dams," SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
20. Hellstrom, B., "Compaction of a Rockfill Dam," Vol. III, 5th ICOLD, 1955.
21. Howson, G. W., "Design of Rockfill Dams," Transactions, ASCE, Vol. 104, 1939.
22. Karminski, R., et al., "Distribution of Stresses in Earth Dams Estimated by Means of Small Computer ODRA 1204-D," Criteria & Assumptions for Numerical Analysis of Dams Conference, University of Swansea, U.K., 1975.
23. Kawase, M., Discussion Paper 3065, SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
24. Kinawy, I. Z., and Shenovda, W. K., "Observations on Performance Settlement and Movement Measurements of High Aswan Dam," Vol. III, 11th ICOLD, 1973.
25. Kinawy, I. Z., Shenovda, K., and Sheta, M., "Selection of Construction Materials and Methods of their Placement in the High Aswan Dam," Vol. III, 11th ICOLD, 1973.
26. Kjaernsli, B., and Torblaa, I., "Leakage Through Horizontal Cracks in the Core of Hyttejuvet Dam," NGI Publication No. 80, 1968.
27. Kjaernsli, B., and Torblaa, I., "The Venemo Asphalt Faced Rockfill Dam," NGI Publication No. 69, 1969.
28. Koenig, H. W., and Idel, K. H., "Deformation and Loading of a Rockfill Dam with Bituminous Surface Membrane," Vol. III, 9th ICOLD, 1967.
29. Koenig, H. W., and Idel, K. H., "Report on the Behaviour of Impervious Surface of Asphalt," Vol. III, 11th ICOLD, 1973.
30. Koenig, H. W., and Idel, K. H., "Settlement Measurements on a 52 m High Rockfill Dam with Bituminous Surface Membrane," Vol. III, 8th ICOLD, 1964.
31. Lawton, F. L., and Lester, M. D., "Settlement of Rockfill Dams," presented at the May 1964 Eighth International Congress on Large Dams, held at Edinburgh, Scotland, Vol. III, pp. 599–613.
32. Leonard, G. K., and Raine, O. H., "Rockfill Dams: TVA Central Core Dams," SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
33. Lloyd, H. E., Moore, O. L., and Getts, W. F., "Rockfill Dams: Cherry Valley Central Core Dam," SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
34. Lyra, E. H., and Queiroz, L., "The Furnas Rockfill Dam," Vol. III, 8th ICOLD, 1964.
35. Lyra, F. H., and Fernandes, F., "Estreito Rockfill Dam," Vol. I, 10th ICOLD, 1970.
36. Marsal, R. J., and Ramirez de Arellano, L., "Field Measurements in Rockfill Dams," 2nd Pan-American Conference SM and FE, Vol. II, 1963.
37. Marsal, R. J., General Report, 2nd Pan-American Conference SM & FE, Vol. II, 1963.
38. Mitukoshi, T., Discussion Paper 3065, SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
39. Morais, A. T., and Carlos, A. Palma, "Design & Construction of Earthfill

and Rockfill Dams and Their Waterproofing Blankets. Salazar & Vale Do Gaio Dams, Vale Do Sadd Irrigation Scheme of the Junta Autonoma Das Obras De Hidraulica Agricola," Vol. IV, 4th ICOLD, 1951.
40. Neuhauser, E., and Wessiak, "Placing the Shell Zones of the Gepatsch Rockfill Dam in Winter," Vol. IV, 9th ICOLD, 1967.
41. Nitchiporovitch, A. A., "Deformations and Stability of Rockfill Dams," Vol. III, 8th ICOLD, 1964.
42. Nonveiller, E. E., General Report-G Qu 22, Vol. III, 6th ICOLD, 1958.
43. Nonveiller, E., "Post Construction Deformation of Rockfill Dam Peruca," Vol. II, 8th ICOLD, 1964.
44. Parkin, A. K., "Application of Rate Analysis to Settlement Problems Involving Creep," presented at the 1971 First Australia-New Zealand Conference on Geomechanics, held at Melbourne, Australia, Vol. I, pp. 138–143.
45. Parkin, A. K., "The Compression of Rockfill," *Australian Geomechanics Journal*, Australia, G7, 1977, pp. 33–39.
46. Patterson, F. W., and MacDonald, B. H., "Rockfill Dams: Bersimis Sloping Core Dams," SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
47. Penman, A. D. M., "Rockfill," *CP 15/71*, Building Research Establishment, Garston, Watford, England, Apr., 1971, pp. 6–8.
48. Persson, T., "The Trangslet Dam. Results and Interpretation of Measurements Made on the Dam," Vol. II, 8th ICOLD, 1964.
49. Pinkerton, I. L., and McConnell, A. D., "Behaviour of Tooma Dam," Vol. II, 8th ICOLD, 1964.
50. Queiroz, L., "Geotechnical Properties of Weathered Rock and Behaviour of Furnas Rockfill Dam," Vol. I, 8th ICOLD, 1964.
51. Reinus, E., "Design and Construction of Holjes Dam," Vol. III, 8th ICOLD, 1964.
52. Roberts, C. M., "The Quoich Rockfill Dam," Vol. III, 6th ICOLD, 1958.
53. Schmidt, L. A., "Rockfill Dams: Dix River Dam," SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
54. Schober, W., "Behaviour of the Gepatsch Rockfill Dam," Vol. III, 9th ICOLD, 1967.
55. Schober, W., "Considerations and Investigations for the Design of a Rockfill Dam with a 92 m High Bituminous Mix Core," Vol. III, 11th ICOLD, 1973.
56. Schober, W., Technical Session Qu 34, Vol. VI, 9th ICOLD, 1967.
57. Sherard, J. L., et al., "Earth and Earth-Rock Dams," J. Wiley and Sons, New York, N.Y., 1963.
58. Sowers, G. F., Williams, R. C., and Wallace, T. S., "Compressibility of Broken Rock and the Settlement of Rockfills," presented at the September 1965 Sixth International Conference on Soil Mechanics and Foundation Engineering held at Toronto, Canada, Vol. 2, pp. 561–565.
59. Soydemir, C., and Kjaernsli, B., "Deformation of Membrane-faced Rockfill Dams," presented at the September 1979 Seventh European Conference on Soil Mechanics and Foundation Engineering, held at Brighton, England, Vol. 3, pp. 281–284.
60. Soydemir, C., and Kjaernsli, B., "A Treatise on the Performance of Rockfill Dams with Unyielding Foundations in Relation to the Design of Storvass Dam," *Report 53203*, Norwegian Geotechnical Institute, Oslo, Norway, Nov., 1975.
61. Steele, I. C., and Cooke, J. B., "Rockfill Dams: Salt Springs and Lower Bear River Concrete Face Dams," SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
62. Sudman, G. F., "Rockfill Dams: Kajakai Central Core Dam, Afghanistan," SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
63. Terzaghi, K., Discussion Paper No. 3065, SORD. Transactions, ASCE, Vol. 125, Part II, 1960.
64. Varma, R. K., and Raj, B. B., "Performance Analysis of Embankment—Case Studies," Geocon Proceedings, Conference on Geotechnical Engineering, India, 1978.

65. Wilkins, J. K., et al., "The Design of Cethana Concrete Face Rockfill Dam," Vol. III, 11th ICOLD, 1973.
66. Wolski, W., and Furstenburg, A., "Comparison of Deformation of the Tresna Dam, Observed and Computed by means of the FEM," 9th International Conference SM and FE, Vol. II, 1977.
67. Wilson, S. D., "Deformation of Earth and Rockfill Dams," Embankment-Dam Engineering Casagrande Vol., J. Wiley and Sons, 1973.