Thickness of Impervious Face Membrane For Rockfill Dam

by

M.C. Goel*

M.M. Singhal**

Introduction

ROCKFILL dams had their origin in the gold mines regions of Seirra Nevada Mountains in California. In Eighteen fifty's, gold miners needed dams in inaccessible locations where earth was not available. Their development was logical because the rock was available in abundant and miners were well acquainted with the use of explosives. These circumstances resulted into the construction of first rockfill dam, English dam 24 m high in the year 1856. Later rockfill dams with a face membrane of timber or concrete developed. In comparison with the history of other types of dams, the history of rockfill dams with impervious face membrane is relatively short. During last three decades, development of rockfill dam with upstream face membrane has proceeded exceptionally rapidly.

Rockfill dam with impervious face membrane has three main components viz. (*i*) impervious face membrane whose fundamental function is to prevent passing of water, (*ii*) rubble cushion or selected placed rock which is provided in between the main rockfill of the dam proper and the face membrane, and (*iii*) rockfill.

Impervious Face Membrane

Impervious face membrane is the most delicate part of this type of dam. Its main function is to act as barrier in between reservoir and downstream side of dam. This membrane can be of any material like cement, asphalt, steel, wood or plastic. The selection of the type of impervious face membrane is dependent on many factors viz. (*i*) height of dam, (*ii*) availability of material, (*iii*) adaptability to foundation treatment, (*iv*) economic limitations on imported materials, (*v*) extent of wave protection required, (*vi*) scheme of reservoir operation, (*vii*) climatic conditions, (*viii*) hydrological factor (necessity to use the upstream portion of main dam as Coffer dam for diversion) and (*ix*) construction method employed.

Rockfill dams with upstream face membrane can be classified according to the material used in membrane viz.

(*i*) Rockfill dam with impervious face membrane of cement

---

*Reader, W.R.D.T.C., Roorkee University, Roorkee.

**Assist. Engineer, Tehri Design Circle, Roorkee.

This paper was received in March, 1979 and is open for discussion till the end of June, 1980.

(*ii*) Rockfill dam with impervious face membranes of asphalt

(*iii*) Rockfill dam with impervious face membrane of steel, wood or plastic.

Impervious Facing of Cement Concrete

Merits

(*i*) The upstream slope is steeper. Thus less amount of concrete and less volume of embankment material are required.

(*ii*) *The dam crest is the top of coping wall and is of non-erodible* material, thus splash is harmless.

Demerits

(*i*) The concrete face membrane is more rigid than of asphalt and steel, thus there are chances of crack development due to movement and settlement of embankment.

(*ii*) Dams with cement concrete face membrane involve more construction time and cost, as compared to those with asphalt facing, because construction of cushion is costly and time consuming.

(*iii*) Additional cost is involved in providing the slots for beams to support the joints of cement concrete face membrane.

Membrane Design—Thickness and Reinforcement

There is no theoretical procedure sufficiently tested by practice which would permit design of the thickness of reinforced concrete membrane. Wilkins, et al (1973) suggest the following general criteria governing design thickness.

(*i*) The moment resistance is not relevant in determining the membrane thickness, because membrane is uniformly supported against normal water load.

(*ii*) Strain in the slab is independent of its thickness, because slab is constrained to follow the rockfill strain in the plane of face, by the development of shear force between the underside of slab and rockfill.

As may be seen from Table 1, the membrane thickness as provided in various dams varies from 15 cm to 110 cm except in the case of guniting where it varies from 6 cm to 12.5 cm. In case of prestressed concrete membrane installed at Nechranice Dam (Czechoslovakia), the thickness is 8 cm i.e. 0.2 per cent of the height of the dam.

Efforts have been made to study the trend for providing the thinkness of cement concrete membrane for the dams of different heights. The maximum thickness provided at a particular dam with respect to its height has been plotted in Fig. 1. The plot indicates that a definite trend for the thickness adopted with respect to height of dam exists in relation to the year of construction. It is clear from the plot that dams constructed before 1970 have thicker face membrane, whereas dams constructed in seventies have thinner section. It is also noticeable that tendency to adopt

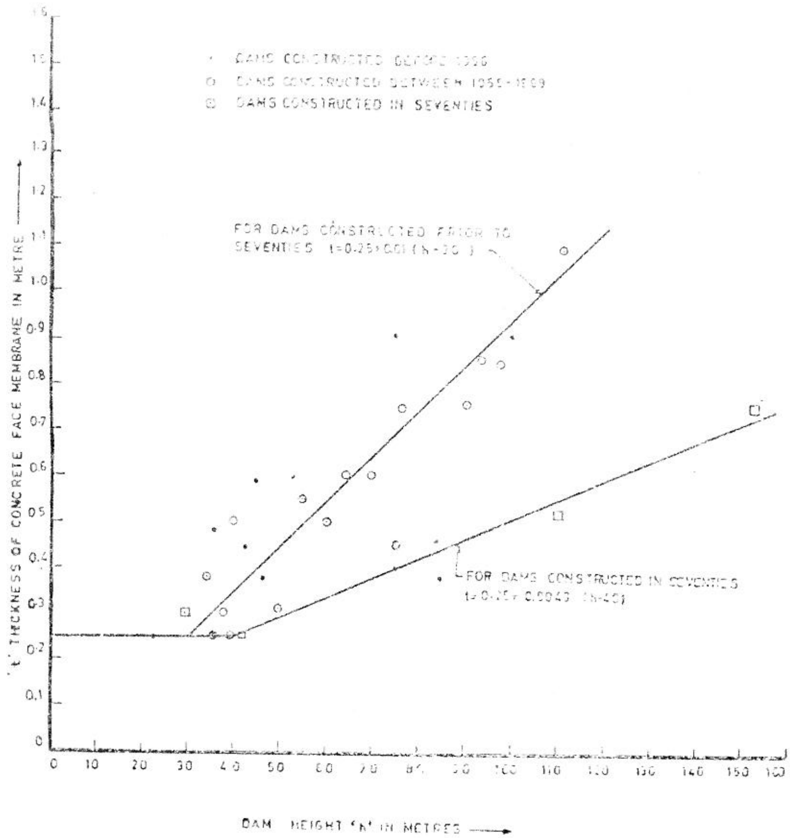


FIGURE 1 Relationship between height of dam and cement concrete face membrane thickness

thinner section started even in mid sixties as is evident from cabin Creek Dam (U.S.A.) 75 metre high, Mackey Dam (U.S.A.) 50 metre high, Piedras Dam (Spain) 40 metre high and Wilmot Dam (Australia) 36 metre high constructed in year 1966, 1967, 1967 and 1968 respectively. Points for three dams constructed earlier viz. San Gabrial Dam (U.S.A.) 85 metre high, Dix river Dam (U.S.A.) 84 metre high and Cogoti (Chile) 75 metre high also lie near 2nd line.

It may be seen that the points for dams constructed before seventies cluster nearer to one line where as the points for dam constructed in seventies lie nearer to another line.

(*iii*) The thickness of membrane should be able to provide water tightness.

(*iv*) Membrane thickness should be such that it is durable in long term.

In the design of the face membrane, precedent plays an important part, and the design aspect can best be reviewed by examples of dam already constructed. Consequently a study of 46 dams constructed all over the

TABLE 1

Rockfill Dams With Cement Concrete Face Membrane

S. No.	Name of Dam and country	Year of completion	Height in m.	Maximum Membrane thickness as percentage of height	Details of impervious face membrane
1	2	3	4	5	6
1.	Anchicaya (America)	Under construction	152	0.49	Membrane thickness varies from 75 cms. at bottom to 30 cms. at top.
2.	Bonita (USA)	1931	31	0.97	Membrane thickness varies from 30 cm at bottom to 20 cm at top
3.	Bourumba (Australia)	1964	44		Vertical joints at 9.14 m, horizontal joints at 9.14 m
4.	Bucks-Creek (USA)	1928	39	0.77	(*i*) Membrane thickness varies from 22.5 cm to 30 cm. (*ii*) No joints (*iii*) Continuous reinforcement 0.55 per cent in vertical and 0.7 per cent in horizontal direction.
5.	Cabin Creek (U.S.A.)	1966	75	0.60	(*i*) Slab thickness varies from 45 cm at bottom to 30 cm at top (*ii*) Vertical joints at 15 m spacing (*iii*) Horizontal joints at 24 m (slope distance)
6.	Canes (France)	1966	40	1.25	Thickness of membrane varies from 50 cm at bottom to 40 cm at top.
7.	Cethana (Australia)	1971	110	0.47	(*i*) Thickness of membrane varies from 52 cm at bottom to 30 cm at top (*ii*) Vertical joints at 12.2 m spacing (*iii*) Horizontal joints near abutment only (*iv*) Reinforcement 0.5 percent

8.	Cogoti (Chile)	1939	75	0.53	Membrane thickness varies from 40 cm at bottom to 20 cm at top
9.	Corella (Australia)	1957	23	0.44	Membrane thickness varies from 10 cm at bottom to 7.5 cm at top of cement and sand (1:3) gunite applied by gun over reinforcing mesh.
10.	Court Right (USA)	1959	97	0.88	(*i*) R.C.C. membrane thickness varies from 85 cm at bottom to 30 cm at top (*ii*) Vertical joints 2.54 cm—5.08 cm wide at 18 metre spacing (*iii*) Horizontal joints 1.9 cm wide at 16 m spacing
11.	Des Fades (France)	1966	70	0.86	(*i*) Membrane thickness varies from 60 cm at bottom to 35 cm at top (*ii*) Vertical joints at 13.7 m spacing (*iii*) Horizontal joints—9 Nos.
12.	Dix River (USA)	1925	84	0.55	(*i*) Membrane thickness varies from 46 cm at bottom to 20 cm at top (*ii*) Upto 50 metre height, 7.5 cm thick timber facing was left in place out side conc. facing (*iii*) Vertical joints at 14.6 m spacing (*iv*) Horizontal joints at 21.6 m (along slope) (*v*) Reinforcement 0.5 per cent in each direction.
13.	Fordyce (USA)	1927	43	1.05	Membrane thickness varies from 45 cm at bottom to 30 cm at top
14.	Huinco (S. America)	1970	30	1.00	(i) Reinforced concrete facing 30 cm thick (*ii*) Vertical joints at 10 m spacing (*iii*) No horizontal joints (*iv*) Reinforcement 0.5 per cent of cross-section in one layer at centre of slab
15.	Ishibuchi (Japan)	1953	53	1.13	(*i*) Membrane thickness varies from 60 cm at bottom to 40 cm at top (*ii*) Vertical änd Horizontal joints at 10 m spacing (*iii*) Reinforcement 0.5 per cent of slab section
16.	Kangaroo-Creek (Australia)	1969	64	0.94	(i) Membrane thickness varies from 60 cm at bottom to 30 cm at top (*ii*) Vertical joints at 12.2 m spacing (*iii*) No horizontal joint (*iv*) Reinforcement 0.55 percent (*v*) Cement used at the rate 328 Kg/m^3 of conc.
17.	Karaoun (Lebanon)	1966	60	0.83	Membrane thickness varies from 50 cm at bottom to 30 cm at top

TABLE 1 (*Contd.*)

S. No.	Name of Dam and country	Year of completion	Height in m.	Maximum Membrane thickness as percentage of height	Details of impervious face membrane
1	2	3	4	5	6
18.	Leichhardt (Australia)	1957	26	0.48	Membrane thickness varies from 12.5 cm at bottom to 7.5 cm at top of cement and sand gunite (1:3) applied by gun over reinforcing mesh.
19.	Lemolo (USA)	1954	36	1.33	(*i*) Membrane thickness varies from 48 cm at bottom 30 cm at top (*ii*) Vertical joints at 18 m spacing (*iii*) Horizontal joints at 12-15 metre spacing (*iv*) Reinforcement 0.5 per cent in both direction
20.	Lower Bear-I (USA)	1952	75	1.2	(*i*) Membrane thickness varies from 91 cm at bottom to 30 cm at top (*ii*) Reinforcement 0.5 per cent each way
21.	Lower Bear-II (USA)	1952	45	1.30	Membrane thickness varies from 59 cm at bottom to 30 cm at top
22.	Mackey (USA)	1967	50	0.62	Membrane thickness 31 cms.
23.	Madeco (Mexico)	1933	47	0.90	Membrane thickness varies from 42 cm at bottom to 20 cm at top
24.	Meadow-Lake (USA)	1930	22	0.45	(*i*) Membrane thickness varies from 10 cm at bottom to 5 cm at top of gunite (*ii*) No joints *Note*: Dam was built in the year 1903 with timber facing, In 1930, timber facing was destroyed by forest fire, then cement conc. facing was installed.
25.	Nechranice (Czechoslavakia)	1966	40	0.20	(*i*) Prestressed concrete slab 8 cm thick (*ii*) Vertical joint at 8 m spacing (*iii*) Bottom layer of porous concrete 20 cm thick

26.	New-Exchequer (America)	1966	152 (uses 56 metre of existing gravity dam)	0.57	(*i*) Concrete face slab thickness varies from 86 cm at bottom to 46 cm at top (*ii*) Vertical joints at 18 m spacing (*iii*) Horizontal joints at 6.4 m at bottom and 15.25 m at top
27.	Nissastrom (Sweden)	1950	15	—	(*i*) Double reinforced concrete slab with vertical expansion joints and horizontal construction joints. (*ii*) In addition, wooden lining and bituminous sheeting
28.	Nozori (Japan)	1956	44	1.50	(*i*) Membrane thickness varies from 66 cm at bottom to 30 cm at top (*ii*) Vertical and horizontal joints at 12 m spacing i.e. slabs of 12 m square. (*iii*) Reinforcement 0.5 per cent of slab section
29.	Paloona (Australia)	1970	42	0.60	(*i*) Thickness of concrete face slab = 25.4 cm (*ii*) Vertical joints at 12.2 m spacing
30.	Parade la (Portugal)	1958	110	1.00	(*i*) Thickness of membrane varies from 110 cm at bottom to 30 cm at top (*ii*) Vertical joints at 15 m spacing, joints sealed by copper water stops. (*iii*) Horizontal joints at 10-15 m spacing (*iv*) Reinforcement 0.5 per cent both ways
31.	Piedras (Spain)	1967	40	0.62	(*i*) Membrane thickness 25 cms. (*ii*) Vertical joints at 15 m spacing, asphalt painted rubber water stops. Joint filler not used. (*iii*) No horizontal joints (*iv*) Reinforcement 0.5 per cent each way
32.	Pindari-Creek (Australia)	1969	76 m (46 metre in first stage)	0.99	(*i*) Membrane thickness varies from 75 cm at bottom to 48 cm at top (*ii*) Vertical joints at 18.3 m spacing, asphalt painted (*iii*) No horizontal joints
33.	Pinzanes (N. America)	1956	55	1.00	(*i*) Membrane thickness varies from 55 cm at bottom to 30 cm at top (*ii*) Vertical joints at 12 m spacing (*iii*) Reinforcement 0.5 per cent (double mesh of 25 mm round bars at the rate 35 cm c/c in lower part of dam and in single layer near top of dam).

TABLE 1 (*Contd.*)

S. No.	Name of Dam and country	Year of completion	Height in m.	Maximum Membrane thickness as percentage of height	Details of impervious face membrane
1	2	3	4	5	6
34.	Portillon (France)	1950	23	0.26	(*i*) Reinforced gunite coating 6 cm thick (*ii*) Flat reinforcement 260×6 mm in expansion joints
35.	Quoich (G. Britain)	1956	34	1.12	(*i*) Membrane thickness 38 cm at bottom and 30 cm at top (placed by vacuum conc. process) (*ii*) Vertical and horizonlal joints at 6 m spacing
36.	Rama (Yogoslavia)	1969	100	—	(*i*) Reinforced concrete membrane (*ii*) Vertical joints at 13 m spacing (*iii*) Horizontol joints at 12 m spacing
37.	Salt Spring (USA)	1931	100	0.91	(*i*) Membrane thickness varies from 91 cm at bottom to 30 cm at top (*ii*) Vertical joints at 18 m spacing (sealed by copper water stops) (*iii*) Horizontal joints at 12 m-23 m spacing (along slope) (*iv*) Reinforcement 0.5 per cent each way (2.5 cm square bars)
38.	Sassiere (France)	1959	38	0.79	(*i*) Membrane thickness 30 cms (*ii*) Joints sealed by rubber water stops
39.	San Gabriel-2 (USA)	1935	85	0.45	(*i*) Membrane thickness of permanent cement concrete = 38 cms. (*ii*) Vertical and horizontal joints at 9.15 m spacing (*iii*) Temporary facing of timber in lower half face 5 cm×25 cm×3 m.
40.	Strawberry (USA)	1916	46	0.84	Membrane thickness varies from 38 cm at bottom to 22 cm at top

41.	Taum-Sauk (N. America)	1963	36	0.71	(*i*) Membrane of sprayed concrete 25 cm thick (*ii*) Vertical joints at 18 m spacing (*iii*) No horizontal joints
42.	Uortotokoisky (USSR)	—	59	0.25	(*i*) Reinforced concrete facing of thickness 15 cm (*ii*) Vertical and horizontal join at 7.5 m spacing
43.	Upper Bear (USA)	1953	24	0.52	(*i*) Membrane thickness varies from 12.5 cms. at bottom to 7.5 cm at top. (*ii*) Reinforcement 4×4 and 6×6 mesh *Note:* Dam was completed in year 1900 with wood facing and cement facing was done in 1953.
44.	Wilmot (Australia)	1968	36	0.70	(*i*) Membrane thickness 25.4 cms. (*ii*) Vertical joints, at 12.2 m spacing
45.	Wishon (USA)	1958	90	0.85	(*i*) Membrane thickness varies from 76 cm at bottom to 30 cm at top. (*ii*) Vertical joints 2.54 cm-5.08 cm wide at 18 m spacing (*iii*) Horizontal joints 1.9 cm wide at 16 m. spacing (*iv*) Reinforcement 0.5 per cent both ways.
46.	Zigoneni (Romania)	1950	23	1.09	(*i*) 25 cm thick reinforced concrete membrane (*ii*) Vertical joints at 4 m spacing (*iii*) Horizontal joints at 3 m spacing.

world in last fifty years has been made and the salient features such as concrete membrane thickness, joint details, provision of reinforcement etc. have been summarised in Table 1.

Usually the concrete face membrane thickness is not uniform. It varies with the height of the dam having minimum thickness at top and maximum at bottom. The criteria adopted for some of the important dams is shown in Table 2.

TABLE 2

Criteria for membrane thickness

Sl. No.	Name of Dam	Criteria adopted for fixing the Membrane Thickness
1.	Cethana (Wilkins et. al, 1973)	$t = 0.3 + 0.002 \times h$
2.	Kangaroo-Creek (Good-1976)	$t = \frac{h \times 0.305}{60.96} + 0.305$
3.	Lemolo-1 (Boyle & Barrow, 1960)	$t = 0.3 + 0.005 \times h$
4.	Nozori (Steele & Cooke, 1960)	Thickness at bottom equal to 1.5 per cent of water head
5.	Paradela (Fernandes et. al, 1960)	$t = 0.3 + 0.00735 \times h$
6.	Pindari-Creek (Steele & Cooke, 1969)	$t = 0.3048 + 0.0067 \times h$

Where t = thickness normal to the face of the dam in metres
h = depth with relation to crest of dam in metres

These two lines giving the following two relationship between the membrane thickness and dam height indicate that the thickness provided before seventies was conservative one, as compared to the recently built dams.

(*a*) Relationship for dams constructed prior to seventies

$$t = 0.25 + 0.01\ (h\text{-}30)$$

where t = thickness of cement concrete face membrane, normal to the face of dam in metre

h = height of the dam in metres.

(*b*) Relationship for dams constructed recently

$$t = 0.25 + 0.0043\ (h\text{-}40)$$

where t = thickness of cement concrete face membrane, normal to the face of dam in metres.

h = height of the dam in metres.

Steele and Cooke (1969) have also mentioned that due to recent design trends, there have been substantial improvements in all features of concrete face rockfill dams and thus thinner face membrane is provided.

There exists no procedure for defining the quantity of reinforcement other than empirical rules based on experience. Actually calculations must be based on computation of relative settlements which can not be predicted with accuracy. Thus it is based on experience. Fernandes, et al (1960) have cited that experience at various dams has shown that a reinforcement mesh of density corresponding to a section of 0.5 per cent of the concrete section in both directions (horizontal and in direction of slope) is sufficient, and should be increased to 0.6 per cent in the area surrounding contact with abutment.

The steel provided in the face membrane should fulfill the following criteria :

(*i*) Over most of its extent, the face membrane is in compression. In this area the reinforcement should be capable of controlling cracking due to thermal and drying shrinkage prior to filling of the reservoir.

(*ii*) In tension zone horizontal steel should be increased to control tension cracking of concrete.

(*iii*) Tension steel should be sufficient to take the full water load transmitted to the steel by friction on the underside of the membrane.

(*iv*) Additional light reinforcement should be placed around perimetric joints, vertical and horizontal contraction joints to prevent spalling of membrane corners.

Asphaltic Concrete Membrane

Merits

The asphaltic face membrane has following merits as compared to other types of membrane.

(*i*) Preparation of suitable stone base surface on upstream slope is simple and less costly as compared to that of cement concrete face membrane.

(*ii*) At ordinary temperature, asphaltic concrete membrane is more flexible than portland cement concrete membrane.

(*iii*) Asphaltic concrete membrane is self adjusting to the settlement normally to be expected in a reasonably well constructed rockfill dam.

(*iv*) If some crack occurs, this type of membrane is some what self healing.

(*v*) Asphaltic concrete membrane is believed to be more easily repairable than cement concrete face membrane.

(*vi*) Construction of asphaltic concrete membrane is quick, because one layer can be placed over the previous layer with only a few hours lapse of time.

In Montgomery Dam it was estimated that for covering the given area of deck surfaces less time was required with asphaltic concrete membrane than with cement concrete face membrane (Scheittenhelm 1960).

(*vii*) Unlike cement concrete face membrane, this type do not require formed joints which are costly and time consuming.

(*viii*) Asphaltic concrete membrane is less likely to crack than cement concrete membrane.

(*ix*) Overall construction cost is less with asphaltic membrane, than with cement concrete membrane. At Montgomery dam site, estimated saving in cost as compared to cement concrete membrane was 50 per cent.

Demerits

(*i*) The upstream slope of the dam with asphaltic concrete is much gentler than that of cement concrete. Hence considerable increase in total volume of dam.

(*ii*) Plasticity and flexibility of asphaltic concrete membrane decreases with fluctuation in reservoir level and exposure to atmosphere.

(*iii*) Asphaltic membrane is less flexible than upstream face membrane of steel. According to Sherard, (1960), "flexibility greater than that of asphaltic concrete facing with reasonably good construction of underlying rockfill, is probably not required."

(*iv*) This type of membrane has smaller strength and is more liable to war damage.

Membrane Design

This type of face membrane consists of single or more layer of asphaltic concrete laid and compacted whilst still not over a layer of well graded gravel or over a cushion of stone. It is also possible to place the binder direct on the gravel layer. In most cases a single course of asphalt layer has been placed over the binder course. But in some cases the asphaltic concrete has been placed in two layers with a drainage layer in between. A sealing on the surface is applied to protect the asphaltic concrete against atmosphere influence. In design of the membrane thickness, the following factor should be considered :

(*i*) Impermeability

(*ii*) Wave pressure and water pressure

(*iii*) Durability

(*iv*) Hydro-static Uplift

(*v*) Water drainage

(*vi*) Base conditions

(*vii*) Unequal settlement at cutoff

The calculation for the thickness of asphalt membrane for impermeability by the following formula has been suggested by Sawada, et al (1973).

$$T_n = K_1 H_n h_2 \operatorname{Cosec} a/q$$

for different symbols refer Figure 2.

From the test results carried on model on impact pressure of waves, the another formula given below gives thickness calculation (considering pressure of waves)

$$T_h = 60 \sqrt{\frac{P}{b} F_s}$$

Where

T_h = thickness required in centimetres

P = Impact pressure of waves in kg/cm²

b = Allowable bending strength

F_s = Factor of safety 1.0 to 1.5

The greater of the above two values calculated should be adopted.

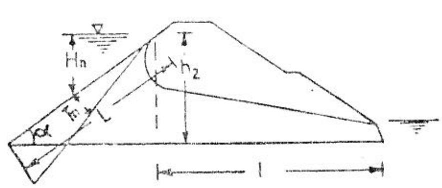
According to Lohr and Feiner (1970) the thickness should not be less than the following values

(*i*) 6 cm asphaltic concrete for low dams

(*ii*) 6-12 cms asphaltic concrete for dams of medium height

(*iii*) 12-18 cms asphaltic concrete for high dams.

In the design of the asphaltic face membrane, precedent plays an important role, and the design aspect can best be reviewed by the examples of dams already constructed. Therefore 60 dams already constructed with asphaltic face membrane, were studied. The salient features of dam along with membrane details have been summarised in Table 3.



T_n = THICKNESS OF IMPERMEABLE LAYER FOR ANY WATER HEAD 'Hn' IN METRES

H_n = WATER HEAD AT ANY POINT ON SLOPE IN METRES.

h_2 = HIGH WATER LEVEL IN METRES

α = SLOPE IN DEGREES

q = ALLOWABLE SEEPAGE FOR ONE METRE BANK LENGTH Cum/min

FIGURE 2 Calculation of membrane thickness for impermeability

TABLE 3

Rockfill Dams with Impervious Face of Asphalt

Sl. No.	Name of Dam	Country	Year of completion	Height in metres	Upstream slope	Details of impervious face membrane
1	2	3	4	5	6	7
1.	Abono	Spain	1969	17	2.35 : 1	4 cm ES, 3 cm BC, 6 cm AC, 10 cm BD, 2×5 cm AC, SC
2.	Alesani	France	1969	65	1.7 : 1	10 cm BC, 2×6 cm AC, SC
3.	Bigge	W. Germany	1964	55	1.75 : 1	ES, 4 cm BC, 6 cm AC, 11 cm BD, ES, 12 cm AC, SC
4.	Bostal-Speree	W. Germany	1973	23	2 : 1	6 cm BC, 6 cm AC, SC
5.	Bou-Hanifia	Algeria	1938	55	0.8 : 1 to 1 : 1	PC, 12.5 cm AC, with reinforced concrete protection
6.	Coo-Trois. Ponts	Belgium	1969	25	1.2 : 1	1.5 cm BC, 6 cm BD, 6 cm AC, SC
7.	Diessbach	Austria	1964	36	1.7 : 1	ES, 6 cm BC, 8 cm AC, SC
8.	Diga-DI-Codelago	Italy	1893	20	—	5 cm AC covered by stone blocks in cement mortar
9.	Dungonnell	N. Ireland	1969	17	1.7 : 1	ES, 8 cm AC, 13 cm BD, 2×5 cm AC, SC
10.	Fedaia	Italy	1954	16	—	PC, 10 cm AC, with reinforced concrete protection
11.	Freilingen	W. Germany	1974	20	1.9 : 1	8 cm BC, 8.5 to 10.5 cm AC, SC
12.	Genkel	W. Germany	1952	43	2.25 : 1	CS, 6 cm BC, 6 cm AC, 12 cm BD, 6 cm BC, 9 cm AC, SC
13.	Ghrib	Algeria	1937	72	1 : 1	PC, 2×6 cm AC, PC (Reinforcement of steel grating used)

14.	Gijon	Spain	1969	15	2.35 : 1	BC, 6 cm AC, 12 cm BD, 12 cm AC, SC
15.	Grane	W. Germany	1969	67	1.75 : 1	8 cm BC, 2×6 cm AC, SC
16.	Hardap	S.W. Africa	1961	36	1.7 : 1	CS, BC, 2×5 cm AC, SC
17.	Henne	W. Germany	1955	61	2.15 : 1	6 cm BC, 3+3.5 cm AC, 10 cm BD, ES, 3+3+3.5 cm. AC, SC
18.	Home stake	U.S.A.	1967	80	1.6 : 1	BC, 35-17.5 cm AC in layers of 9 cm
19.	Innerste	W. Germany	1966	35	1.75 : 1	ES, 8 cm BC, 5 cm AC, 10 cm BC, 2×4 cm AC, SC
20.	Iril-Emda	Algeria	1954	75	—	PC, 12 cm AC, with reinforced concrete protection
21.	Kessenhamm	W. Germany	1964	18	1.2 : 1	3 cm ES, 3 cm BC, 2×4 cm AC, SC
22.	Kindaruma	Kenya	1967	28	1.7 : 1	ES, 6 cm BC, 4 cm AC, 8 cm BD, 2×5 cm AC, SC
23.	Kronenberg	W. Germany	1975	20	1.65 : 1	3 cm BC, 6 cm AC, SC
24.	Lega-dadi	Ethiopia	1969	21	1.55 : 1	5 cm ES, 3 cm BC, 2×6 cm AC, SC
25.	Man-Zanaresel-Real	Spain	1969	40	1.75 : 1	ES, 3 cm BC, 5 cm AC, 8 cm BD, 5+6 cm AC, SC
26.	Miyama	Japan	1971	67	1.85 : 1	ES, 15 cm AC, 20 cm BD, 2×6 cm AC, SC
27.	Montgomary	U.S.A.	1957	35	1.7 : 1	3.7 cm BC, 10+9+7.5 cm AC
28.	Moravka	Czechoslovakia	1966	38	1.75 : 1	6.7 cm BC, 5+2×4 cm AC, 4+4 cm AC, SC
29.	Nægold	W. Germany	1967	31	1.2 : 1	ES, 6 cm BC, 4 cm AC, 7 cm BD, 2×4 cm AC, SC
30.	Nida	W. Germany	1970	33	1.6 : 1	4 cm ES, 3.5 cm BC, 2×4.5 cm AC, SC
31.	Ninokura	Japan	1969	37	1.2 : 1	4 cm AC, 5 cm AC, 10 cm BD, 2×4 cm AC, SC
32.	Obenau	W. Germany	1971	60	1.95 : 1	ES, 6 cm BC, 4 cm AC, 8 cm BD, ES, 2×4.5 cm AC, SC
33.	Obernaud	W. Germany	1971	60	1.93 : 1	6 cm BC, 4 cm AC, 10 cm BD, ES, 2×4 cm AC, SC
34.	Ohra	E. Germany	1966	59	1.2 : 1	5 cm BC, 4 cm AC, 10 cm BC, 2×4 cm AC, SC
35.	Otsumata	Japan	1968	52	1.8 : 1	3 cm BC, 4 cm AC, 13 cm BD, 2×5 cm AC, SC

TABLE 3—(*Continued*)

Sl. No.	Name of Dam	Country	Year of completion	Height in metres	Upstream slope	Details of impervious face membrane
1	2	3	4	5	6	7
36.	Pedu	Malaysia	1969	60	1.7 : 1	ES, 5 cm BC, 2×5 cm AC, SC
37.	Perlenbach	W. Germany	1954	18	1.75 : 1	2.5 cm BC, 6 cm AC, SC
38.	Ponte-Liscione	Italy	1970	60	1.2 : 1	6 cm BC, 6 cm AC, 10 cm BD, 2×6 cm AC, SC
39.	Poza Honda	S. America	1970	40	2.5 : 1	5 cm ES, 5 cm AC, 8 cm BD, 2×5 cm AC, SC
40.	Prem-Power	Germany	1971	18	1.75 : 1	BC, 12 cm AC, SC
41.	Radoina	Yugoslavia	1960	42	0.8 : 1	15 cm PC, 9 cm AC, facing protected by 12 cm thick R.C.C. have 10 cm dia. bar net in both direction
42.	Riveris	W. Germany	1956	45	1.2 : 1	CS, 6 cm BC, 4 cm AC, 15 cm BD, 8 cm AC, SC
43.	Ronkhausen	W. Germany	1967	27	1.8 : 1	ES, 4 cm BC, 7 cm AC, SC
44.	Ry-Derone	Belgium	1970	22	1.85 : 1	5 cm BC, 6 cm AC, 8 cm BD, 2×6 cm AC, SC
45.	Salagou	France	1969	60	1.5 : 1	10 cm BC, 2×6 cm AC, 10 cm AC
46.	Schevelinger	Germany	1940	15	1.75 : 1	8 cm ND, 3 cm BC, 6 cm AC, SC
47.	Schombach	E. Germany	1971	14	2.5 : 1	8 cm BC, 4 cm AC, 8 cm BD, 2×4 cm AC, SC
48.	Silbergrund	E. Germany	1964	12	1.7 : 1	5 cm BC, 2×3 cm AC, 10 cm BD, 5 cm AC, SC
49.	Ste-Cecile-Dandorge	France	1966	45	1.7 : 1	10 cm BC, 2×6 cm AC, SC
50.	Steinbach	W. Germany	1964	35	1.75 : 1	ES, 5 cm BC, 4 cm AC, 7 cm BD, 8 cm AC, SC
51.	Trapan	France	1967	24	2.5 : 1	8 cm BC, 10 cm BD, 2×5 cm AC, SC

52.	Ulmbach	W. Germany	1965	20	1.8 : 1	7 cm BC, 2×4 cm AC, SC
53.	Upper Blue River	U.S.A.	1966	22	1.7 : 1	25 cm AC, (in three layers)
54.	Vallond'ol	France	1971	45	1.2 : 1	10 cm BC, 2×6 cm AC, SC
55.	Venemo	Norway	1963	64	1.7 : 1	BC, 15 cm AC (in three layers), SC
56.	Villarino	Spain	1968	23	1.75 : 1	ES, 4 cm AC, 6 cm BD, 7 cm AC, SC
57.	Vrla-II	Yugoslavia	1955	25	—	Two layers AC, with wire reinforcement in between, facing protected by layer of R.C.C.
58.	Wahnbach	W. Germany	1956	48	1.6 : 1	CS, 6 cm BC, 4 cm AC, 11 cm BD, 9 cm AC, SC
59.	Wehrasperre	W. Germany	1974	40	1.75 : 1	6 cm BC, 8 cm AC, SC
60.	Zoccolo	Italy	1964	66	2.5 : 1	7 cm BC, 5+4+4 cm AC, SC

AC = Dense asphaltic concrete, BC = Binder and/or levelling course, BD = Bituminous drainage layer, CS = Cement stabilisation ES = Blinded with coated chippings, ND = Non-bituminous, drainage layer, PC = Porous cement concrete, R.C.C. = Reinforced cement concrete, SC = Bituminous seal coat, 2×6 cm = Two layers of six centimetre

As may be seen from the Table, the thickness of the asphaltic membrane as provided in various dams, varies from 6 cm to 27 cms. Efforts have been made to study the criteria of providing the membrane thickness for dams of various heights. The membrane thickness provided at a particular dam with respect to its height have been plotted in Figure 3. From this plot, no definite relationship could be established, however broadly speaking, the following is quite clear—

(*i*) For dams above 65 metre height, sufficient data is not available to arrive at some conclusion and hence level of confidence is only upto this height.

(*ii*) About 70 per cent dams of height upto 30 metre have been constructed having asphaltic membrane thickness as 6 cm-12 cm.

(*iii*) For almost all dams of height between 30 metre to 65 metre, the thickness adopted of asphaltic membrane is usnally 12-18 cms. The placement is usually in two layers with drainage layer in between.

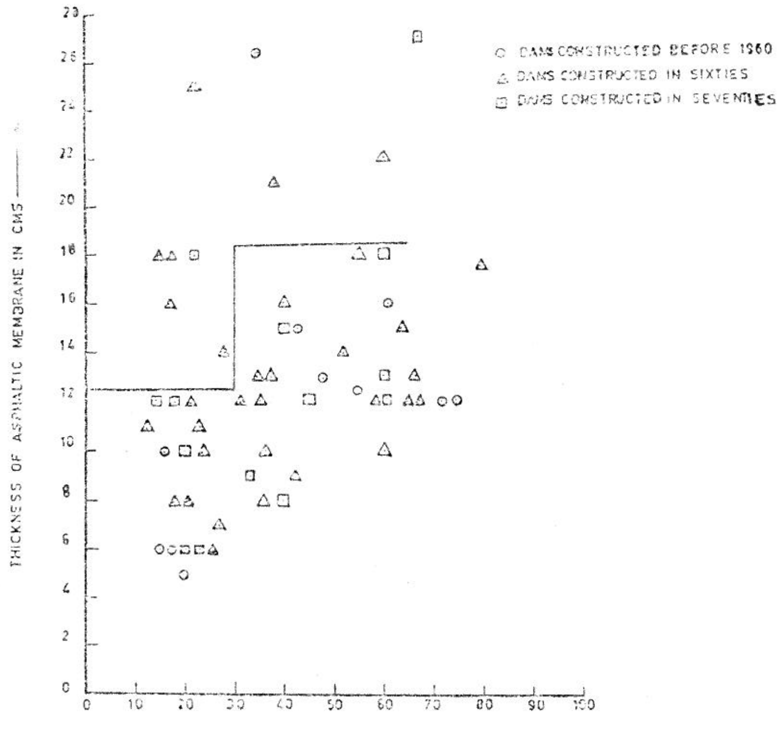


FIGURE 3 Plot between asphaltic face membrane thickness and dam height

Conclusion

Among the rockfill dams with impervious face membrane, the concrete face type is most commonly used. Examples of concrete face membrane dams upto 152 metre height exist in the world. Recent trend is to provide a thinner face membrane. The study has revealed that the concrete face membrane thickness for the dams of height and constructed in seventies, conform to the relationship

$$t = 0.25+0.0043\ (h\text{-}40)$$

The concrete face membrane thickness is not uniform throughout and instead it varies with the height of the dam, having maximum thickness at bottom and minimum at top. In general the relationship $t = 0.3 + K\,h$ exists with value of K ranging in between .002 to .00735.

In most of the dams upto 30 metre height, asphaltic concrete membrane of 6-12 cm thickness has proved sufficient. In dams of height between 30-65 metres, thick layer of asphaltic concrete (12-18 cm) has been used in two layers with drainage layer in between. Rockfill dams of height upto 80 m have been constructed with asphaltic face membrane, but level of confidence is upto 65 metres.

References

BOYLE, J.C. AND BARROWS, W.R. (1960) "Rockfill dams Lemolo No. 1 dam" *Transactions of American Society of Civil Engineers,* Vol. 125, Part II, pp 322-335.

FERNANDES, OLIVEIRA AND PORTO, (1960). "Rockfill dams; Paradela Concrete face dam" *Transaction of American Society of Civil Engineers,* Vol. 125, Part-II, pp 365-418.

GOOD, R.J., (1976). "Use of a weak schist as rockfill for a concrete face rockfill dam", *12th International Congress on large Dams,* Mexico, pp 645-676.

LOHR, A & FEINER, (1970). "Asphaltic Concrete Blanket for rockfill dam" *X Internatianal Congress on Large Dams,* Vol. I—Montreal-Canada, pp 661-667.

SAWADA, NAKZIMA & TANAKA, (1973). "Emperical Research & Practical design of rockfill dams with asphalt facing" *Transactions of 11th International Congress on Large Dams,* Madrid Spain, Vol. III pp 281-313.

SCHEIDENHELM, SNETHLAGE & VANDERLIK, (1960). "Montgomery Dam with asphaltic Concrete Deck", *Transaction af American Society of Civil Engineers,* Vol. 125, Part II, pp 431-464.

SHERARD JAMES L. (1960). "Steel faced Dam", *Transactions of American Society of Civil Engineers,* Vol. 125, Pt. II, pp 465-472.

STEELE, I.C. & COOKE, J.B., (1960), "Salt spring & lower Bear river Concrete face dams", *Transactions of American Society of Civil Engineers,* Vol. 125, Part 2, pp 74-149.

STEELE, I.C, & COOKE J.B., (1969). "Concrete face rockfill dams" *Hand Book of Applied Hydraulics by* Davis & Sorensen, 3rd Edition, pp 19-1.

WILKINS J.K., MITCHELL, W.R., FITZPATRICK, M.D., AND LIGGINS T. (1973). 'The Design of Cethana Concrete face rockfill dam", *11th International Coagress on Large Dams,* Madrid-Spain, Vol. III, pp 25-44.