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THE INFLUENCE OF SLOPE UPON THE DISCHARGE CAPACITY OF ROOF DRAINAGE CHANNELS

By K. G. MARTIN and R. I. TILLEY

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DIVISION OF BUILDING RESEARCH
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Summary: The flow profiles of water in two rectangular and one vee channel have been determined for various channel slopes and flow loads, the water being applied from each side of the channel at various constant rates along the length of the channel. Results have been considered in terms of influence of channel slope upon maximum depth and a slope factor or increase of relative discharge capacity due to slope has been developed. The application of the findings to the design of long-length trough roofing and vee-valley gutters for a conventionally roofed dwelling at various Australian localities has been discussed.

I. INTRODUCTION

Following the issue of a report on sizes for roof gutters and downpipes for Australian localities (Martin 1965) many requests have been received for information on the influence of slope upon discharge capacity of roof drainage channels. Two cases that are of particular interest are valley gutters at intersections of sloping roofs of dwellings, and low-sloped roofs of continuous metal troughs where the shallow troughs, as well as providing most of the covering, may also be considered as internal drainage channels. Considerable savings may arise in both these cases if the enhanced discharge capacity of the channel due to slope can be taken into account at the design stage. While both cases may be designed in accordance with the formula of the Building Research Station (1963), this formula does not include a slope factor. The authority has considered only small slopes and regards the increased flow capacity due to increased slopes to be a safeguard against overflow. However, when the design is based upon maximum intensity rainfall for each locality, and includes a risk factor which is based upon the frequency of maximum intensity rainfall, it is considered that such safeguards are not necessary. This method of design is not used by the Building Research Station but has been adopted in the guide for Australian localities (Martin 1965) since the necessary rainfall data have been presented by the Institution of Engineers, Australia (1958). When using the guide any additional discharge capacity due to slope of the drainage channel may therefore be utilized in design.

II. THEORETICAL

The drainage of both the valley gutter and the continuous trough roofing complies with the case of gradually varied flow in open channels with approximately uniform inflow from both sides throughout the channel length. Under these conditions (Ven Te Chow 1959) appreciable energy loss occurs due to turbulent mixing of inflow water with that flowing in the channel, and uncertainties of considerable magnitude are thus introduced into any calculations. The case has been studied by Camp (1939) who developed a theoretical equation giving the water depth profile for rectangular channels of constant width.

The general equation is:

$$\left(\frac{1}{H_o^3}\right) d^3 + \left(\frac{fQ^2x}{12gb^2\bar{R}\bar{d}H_o^3} - \frac{2Sx\bar{d}}{H_o^3} - \frac{1}{H_o}\right) d + \frac{2Q^2}{gb^2H_o^3} = 0 \quad \ldots \ldots (1)$$

where H_o = depth in ft of water at the closed end of the channel
d = depth in ft at some distance x ft along the channel
f = Weisbach-Darcy friction factor
Q = discharge at x in cu. ft/sec
g = acceleration due to gravity = 32.2 ft/sec^2
b = channel width in ft

$\bar{R}$ = the average hydraulic radius in ft throughout the distance x = $\bar{d}/(b+2\bar{d})$

$\bar{d}$ = the average depth in ft throughout the distance x

S = the sine of the angle of slope

If we consider that d = H_o, substituting in (1) we obtain:

$$1 + \frac{fQ^2x}{12gb^2\bar{R}\bar{d}H_o^{\,2}} - \frac{2Sx\bar{d}}{H_o^{\,2}} - 1 + \frac{2Q^2}{gb^2H_o^{\,3}} = 0 \quad \ldots\ldots\ldots\ldots\ldots (2)$$

i.e.

$$Q^2\left(\frac{fx}{12gb^2\bar{R}\bar{d}H_o^{\,2}} + \frac{2}{gb^2H_o^{\,2}}\right) = \frac{2x\bar{d}}{H_o^{\,3}}\ S \quad \ldots\ldots\ldots\ldots\ldots (3)$$

Equation (3) indicates that the square of the discharge capacity is proportional to the sine of the angle of slope of the channel and offers promise of considerable advantage by taking slope into account when designing roof-drainage channels.

III. EXPERIMENTAL

Camp verified his equation for slopes up to 1 in 200, much lower than the slopes of present interest. An empirical investigation of the influence of much higher slopes has therefore been made using the structure shown in Figure 1.

Channels 12 ft long were supported at slopes from horizontal to $16\frac{1}{2}^{\circ}$, with total flow loads from 11 to 64 gal/min provided by adjustable cocks 1 ft apart down each side of the channel. After fixing the slope and adjusting and measuring the flow rate at each cock the depth of water in the channel was measured at 1-ft intervals to give the water profile in the channel for the particular flow load. Rectangular channels 12 in. and 6 in. wide were used to simulate the case of continuous trough roofing, and a vee-valley gutter of similar profile to that commonly used on dwellings was also used.

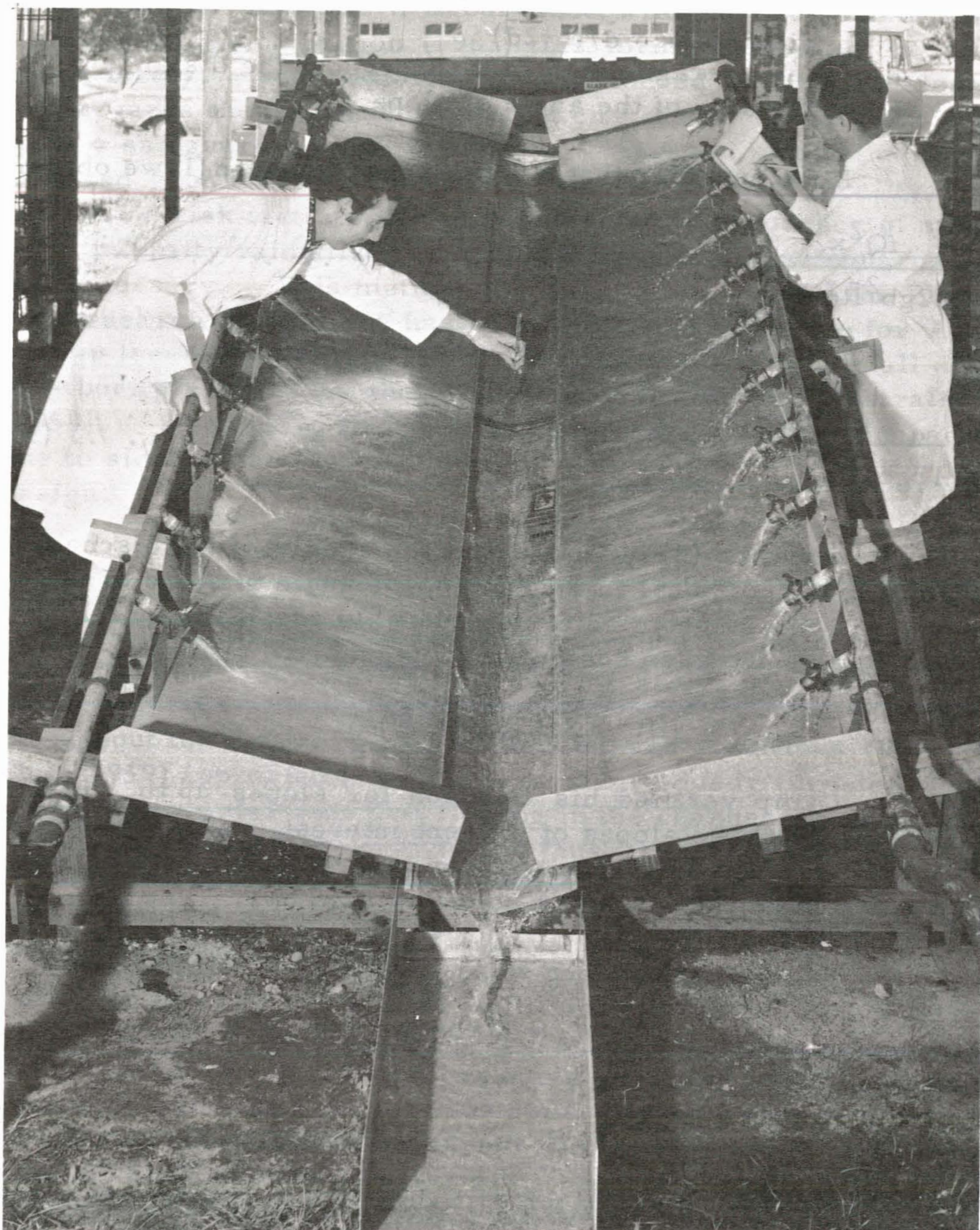

Fig. 1 - Drainage structure used in experiments

IV. RESULTS AND DISCUSSION

A typical set of flow profiles is shown in Figure 2, and Table 1 shows the maximum depth of water that was measured in each channel for a given slope and flow load.

Using experimentally determined values of H_o and $\bar{d}$, the Camp formula (equation (1)) was solved numerically to give predicted values of d at various points along the channel for slopes of 0^o, $1/3^o$, 1^o and 2^o. Table 2 compares the predicted and the observed results and indicates excellent agreement at horizontal and $1/3^o$ slope. At 1^o slope the results show only approximate agreement, but at the 2^o slope they deviate markedly. Thus, the Camp formula is applicable only for slopes less than 1^o.

At higher slopes an approximately linear relationship exists between the reciprocal of the maximum depth and the square root of the sine of the slope for a particular channel and flow load. This is illustrated in Figure 3. The general equation which describes the family of lines shown in Figure 3 can be written as follows:

$$S^{0.5} = \frac{K}{d_M} + C \quad \ldots \qquad (4)$$

where d_M = the maximum depth in in., and K and C are constants.

In the case of the 12-in. rectangular channel M has the values 0.38, 0.22, 0.15 and 0.08 corresponding to flow loads (Q) of 64, 33, 24 and 11 gal/min respectively. If each value of K is divided by the corresponding flow load a fairly constant term averaging 0.0066 is obtained. When the values of C are divided by the corresponding values of $Q^{0.5}$ a constant term, averaging -0.02, is again obtained. If these two terms are incorporated in equation (4) it becomes:

$$S^{0.5} = \frac{0.0066Q}{d_M} - 0.020Q^{0.5} \quad \ldots \qquad (5)$$

Rearranging;

$$d_M = \frac{0.0066Q}{S^{0.5} + 0.020Q^{0.5}} \quad \ldots \qquad (6)$$

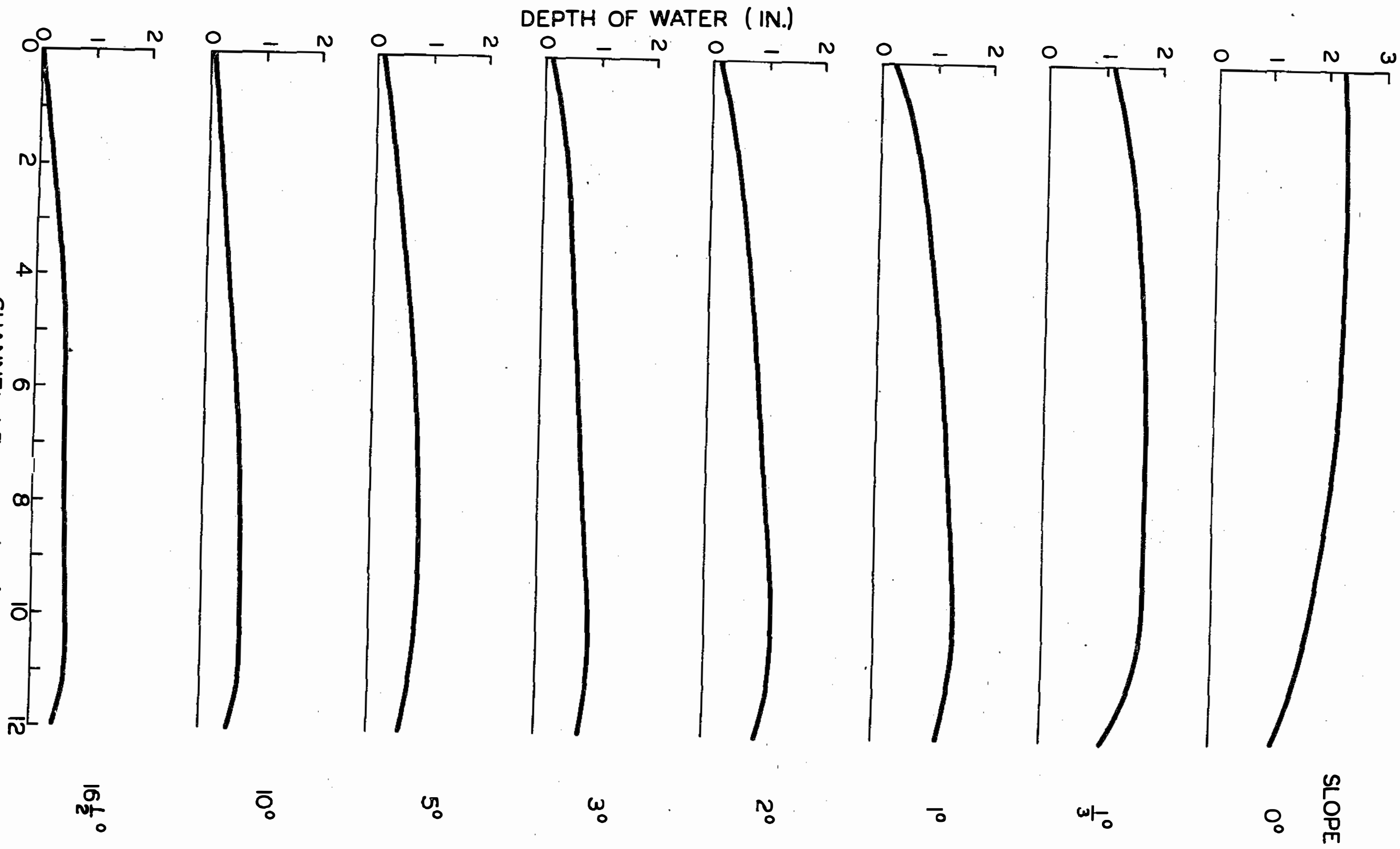

Fig. 2 - Flow profiles for flow load 33 gal/min in 6-in. rectangular channel

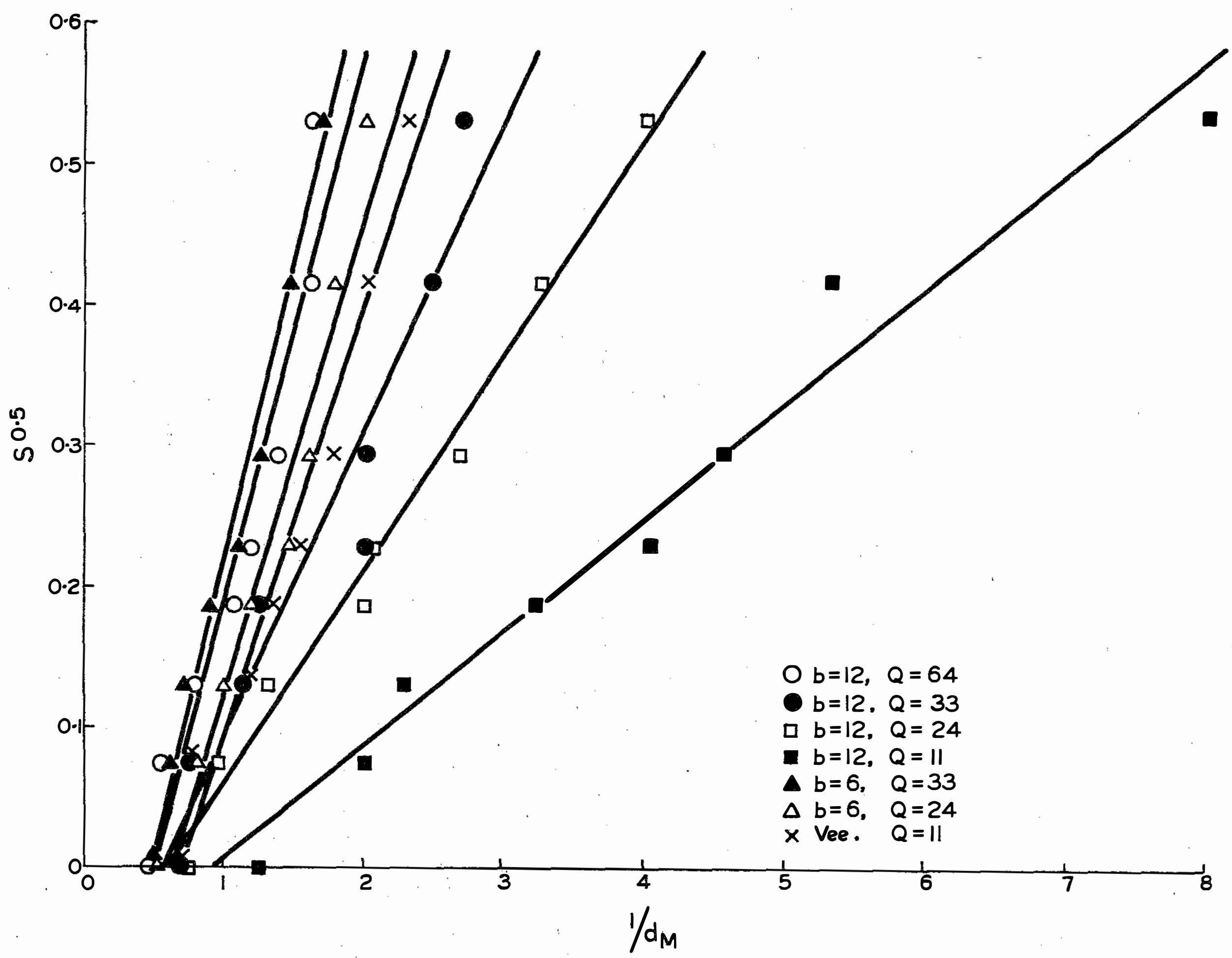

Fig. 3 - Relationship between reciprocal of maximum depth and square root of sine of angle of slope

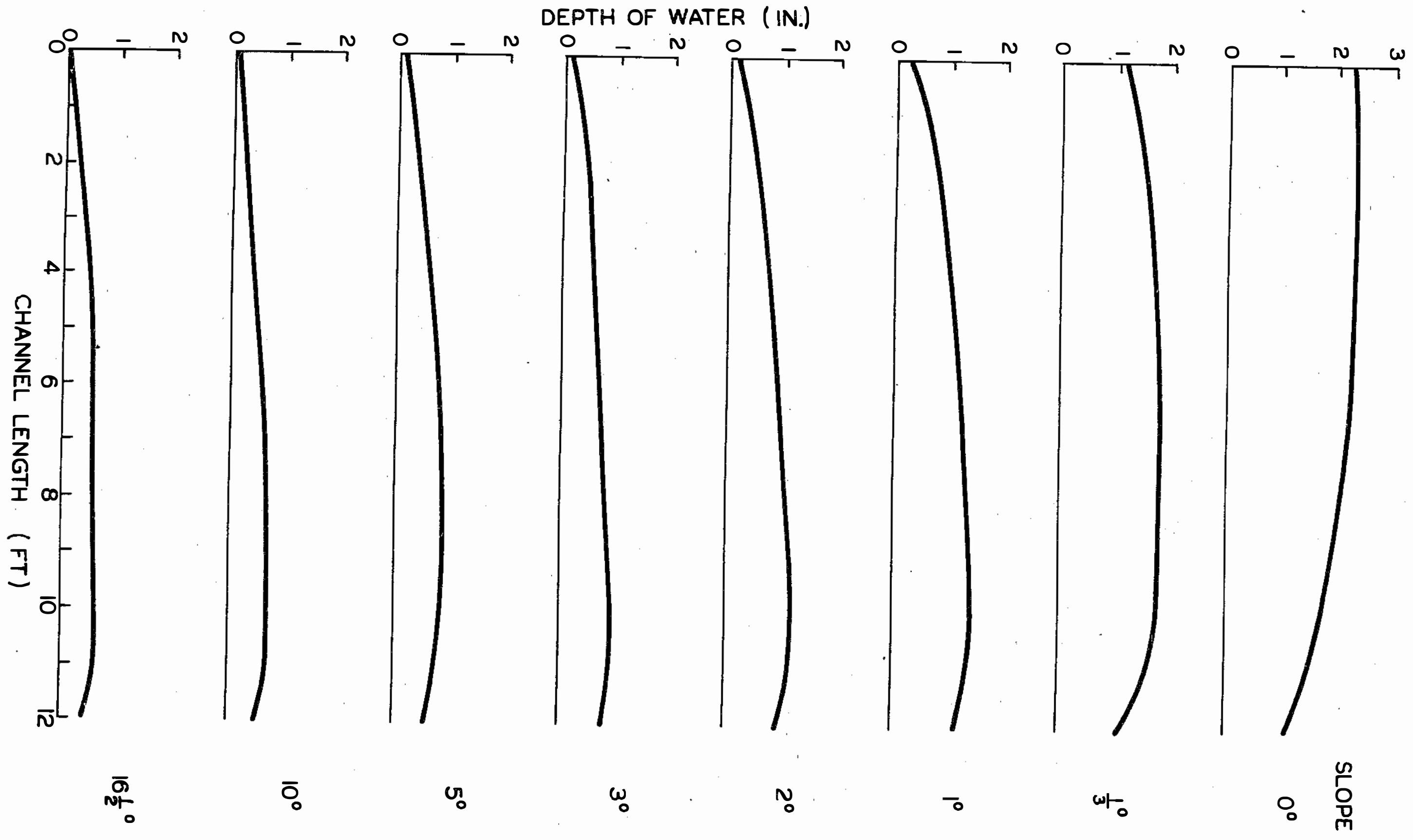

Fig. 2 - Flow profiles for flow load 33 gal/min in 6-in. rectangular channel

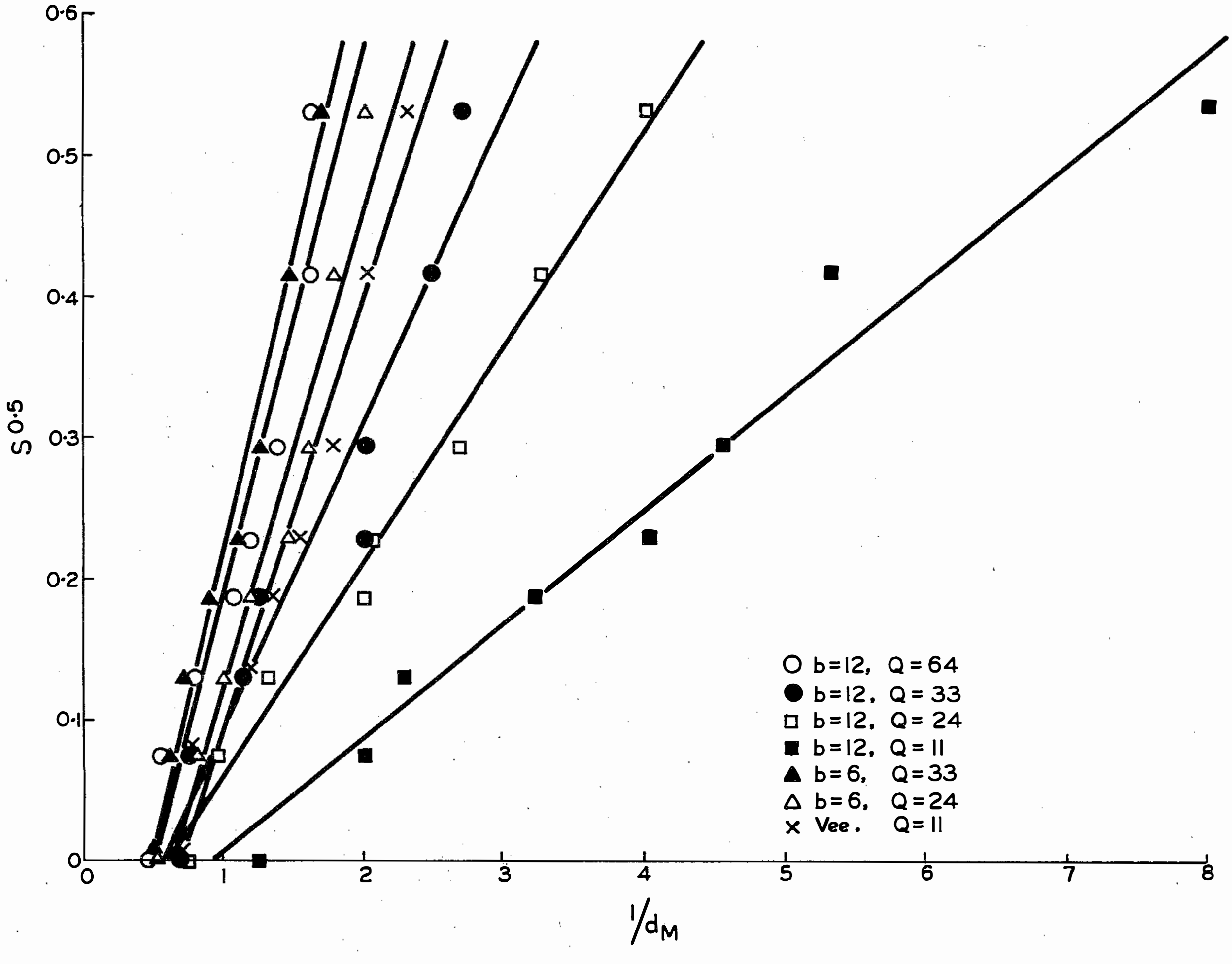

Fig. 3 - Relationship between reciprocal of maximum depth and square root of sine of angle of slope

By a similar procedure to that described above empirical equations for a 6-in. rectangular channel and a vee-valley channel may also be obtained. For a 6-in. rectangular channel the equation is:

$$d_M = \frac{0.013Q}{S^{0.5} + 0.038Q^{0.5}} \quad \ldots \ldots \quad (7)$$

and for a vee-valley gutter;

$$d_M = \frac{0.029Q}{S^{0.5} + 0.071Q^{0.5}} \quad \ldots \ldots \quad (8)$$

Equations (6), (7) and (8) are of the general form;

$$d_M = \frac{\alpha Q}{S^{0.5} + \beta Q^{0.5}} \quad \ldots \ldots \quad (9)$$

where α and β are constants.

If the values of α are multiplied by the corresponding widths, b, of the rectangular channels (in inches), a constant value of 0.08 is obtained. In the case of the vee-valley gutter there is no fixed width, however the multiplier $1/\tan\theta$, where θ is the angle of slope of the sides of the gutter, may be used. Considering the particular channel used in the investigations, for which $\theta = 20^o$, $1/\tan\theta$ is 2.75 and when this is multiplied by α (for vee gutters $\alpha = 0.029$) the product agrees very closely with that found for the two rectangular channels, viz. 0.08. Thus for the rectangular channels $\alpha = \frac{0.08}{b}$, and for the vee-valley gutter $\alpha = 0.08 \tan\theta$.

If the values of β are multiplied by $b^{0.8}$, or by $1/(\tan\theta)^{0.8}$ in the case of the vee channel, a constant value of 0.16 is obtained. Hence for the rectangular channel $\beta = \frac{0.16}{b^{0.8}}$ and for the vee channel $\beta = 0.16(\tan\theta)^{0.8}$.

If these values of α and β are substituted in equation (9) two general formulae covering all the cases investigated can be stated, viz.

$$d_M = \frac{0.08(Q/b)}{S^{0.5} + 0.16(Q^{0.5}/b^{0.8})} \quad .. \; .. \; .. \; .. \; .. \; (10)$$

and for vee channels whose sides have an angle of slope of θ °

$$d_M = \frac{0.08Q \tan \theta}{S^{0.5} + 0.16Q^{0.5}(\tan \theta)^{0.8}} \quad .. \; .. \; .. \; .. \; (11)$$

Figure 4 shows the influence of slope upon the discharge capacity of a drainage channel according to numerical solutions of equation (10). It can be seen that the discharge capacity is doubled as the slope increases from 0 to 1.75°, trebled at a slope of 7.5° and quadrupled at 19° slope.

V. APPLICATION TO SHALLOW GUTTERS

In the previous treatment of shallow gutters (Martin 1965) the general formula given by the Building Research Station (1963) for calculating flow capacity was simplified by assuming that the depth of water at the outlet of the gutter (D) was half the maximum depth of water in the gutter (d_M). The present observations involving the determination of 56 profiles, some of which are shown in Figure 2, now indicate that this assumption applies only to the case of horizontal channels. At slopes of 1° and higher it is found that the ratio of D/d_M is approximately 0.8 in all cases. Thus the simplified formula, given previously for 12 in. wide, shallow gutters (Martin 1965) as

$$a = (0.127\,Ap)^{0.66} \quad .. \; .. \; .. \; .. \; .. \; (12)$$

where a, = the required cross-sectional area of the gutter (sq. in.)
A, = the catchment area (sq. ft), and
p, = the rainfall intensity (in. /h)

applies only to the case of the horizontal rectangular gutter commonly used as a box gutter. Where slopes of 1° and higher are involved equation (12) should be modified by taking the ratio D/d_M as 0.8 and by considering any width of water surface (w in.) at depth d_M. This yields the following equation:

$$a = (2w)^{0.33}\,(0.0130Ap)^{0.66} \quad .. \; .. \; .. \; .. \; .. \; (13)$$

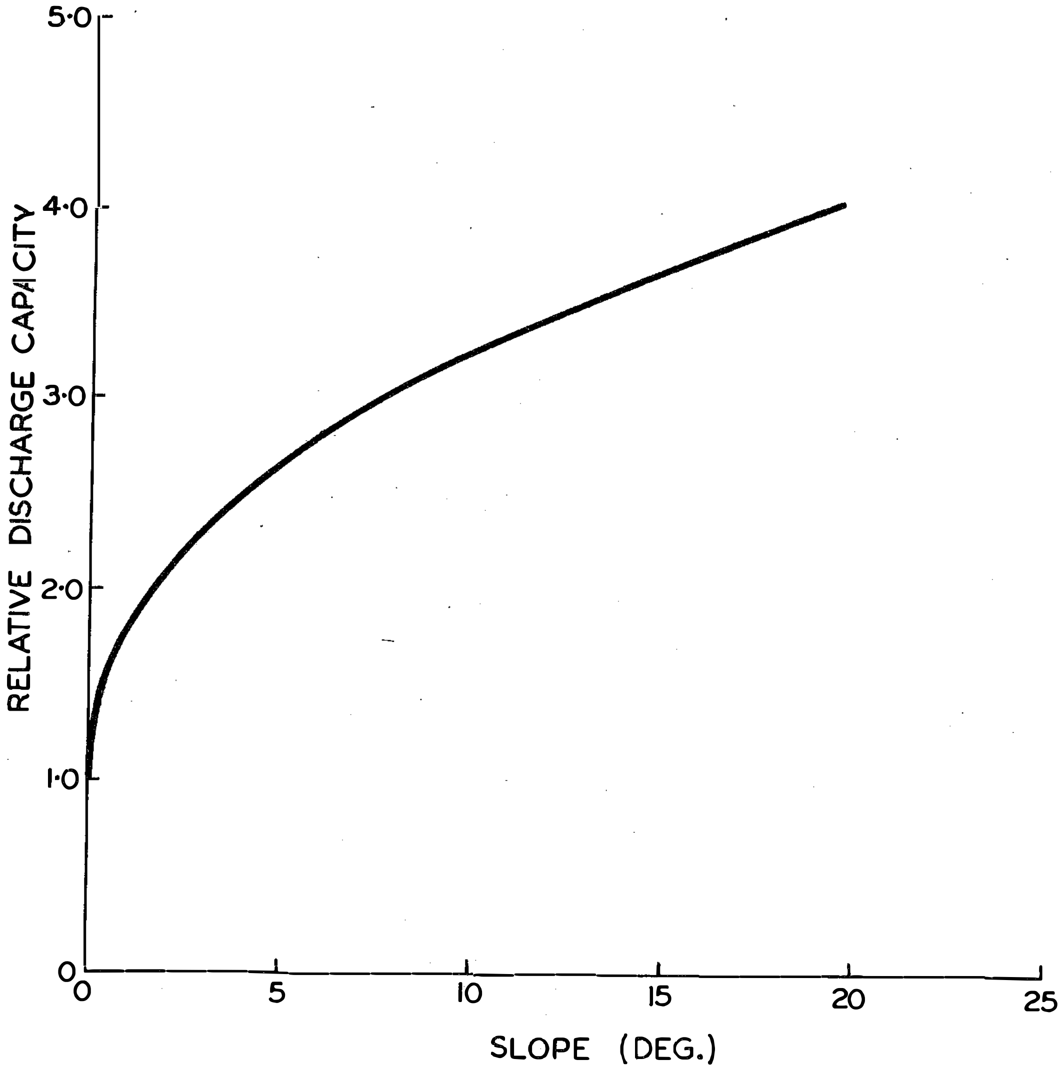

Fig. 4 - Influence of slope on discharge capacity of a drainage channel

The equation requires further modification to take into account the increase, due to slope, of the relative discharge capacity of the gutter. This increase means that the cross-sectional area of the gutter may be reduced. A slope factor "n", indicated in Figure 4, may be introduced such that

$$a = na' = (2w)^{0.33} (0.0130\ Ap)^{0.66} \quad \ldots \quad \ldots \quad \ldots \quad \ldots (14)$$

where a' is the actual cross-sectional area of the gutter.

When equations (14) and (10) are compared by substitution of common numerical values it is found that equation (10) gives smaller requirements. Since equation (14) gives the more conservative design it is recommended that its use be retained and that the empirical observations made in this study be utilized only for the evaluation of the slope factor.

VI. APPLICATION TO TROUGH ROOFING

The observations on rectangular channels and the resultant Figure 4 and equation (14) are directly applicable to trough roofing, although two minor points need to be considered. Firstly, a smooth channel was used in the experiments whereas slightly rougher, and in the case of several materials, embossed sheets, are used to fabricate actual roofing. Two of the commercially-embossed aluminium roofings were compared with smooth channel roofing by determining flow profiles at a flow load of 33 gal/min for the horizontal channel. The average increased depth over the complete length of channel was 8 per cent for the roughest channel and the maximum depth increased by this amount also. Secondly, only one length of channel (12 ft) was examined whereas 50-ft lengths of roofing are often installed and up to 100-ft lengths have been employed in two pieces with an overlapping junction. Such increases of length increase the relative drainage capacity of low sloping channels and the Building Research Station (1961) has given an estimate of the magnitude of the effect. It states that a 50-ft gutter at a slope of 1 in 300 has 8 per cent greater capacity than a 20-ft gutter at the same slope. Thus the effects of both surface roughness and channel length are small, and since they work in opposite directions they may be neglected.

Design considerations to prevent overflow of trough roofing may therefore be made in accordance with equation (14). The area of catchment is the length of roofing multiplied by the width module of the particular profile, and since the channels are within the building perimeter the rainfall intensity should be taken at the risk level of once in 100 yr for the locality involved. It may be noted that some of the roofing profiles available in Australia are more efficient as drainage channels than others simply because they have a higher ratio of width available for drainage to width available for catchment. This ratio may be termed the width draining efficiency and is found to vary from 0.93 to 0.5. It is important to note that while channels that approximate to the corrugated form have a width drainage efficiency of 0.5 they also have a width to depth ratio near 2:1, and so are classified as normal gutters rather than as shallow ones. When the slope factor is incorporated the required cross-sectional area of channel for the normal case is obtained from Martin (1965) as;

$$a = na' = (0.00757\ Ap)^{0.8} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (15)$$

As a design example consider a 100 ft long roofing trough system with 1.75 in. rib height, 6 in. profile module and 0.93 width draining efficiency used as a low slope roof in Darwin. The once in 100 yr rainfall intensity is 20 in./h (according to Table 1, Martin (1965) and the solution of equation (14) gives a required value of na' of 12.3 sq. in. Assuming a freeboard of 0.5 in. to allow for any wave action the effective flow area of the channel available for drainage is 7.0 sq. in. (6 x 0.93 x 1.25). This means that a slope factor "n" of at least 1.75 is required, and reference to Figure 4 indicates that this would be given by a channel slope of 1°.

An alternative roofing of square-corrugated profile having a width-profile module of 4 in., a width efficiency of 0.5 and a height of 1.25 in., would be classified as an ordinary gutter rather than as a shallow one. In this case equation (15) may be used, giving a value of na' of 3.65 sq. in. Since the effective cross-sectional area of the drainage channel after allowing for 0.5-in. freeboard is only 1.5 sq. in. (4 x 0.5 x 0.75 in.) a slope factor of 2.5 is required, which means a roof slope of 4°.

VI. APPLICATION TO VEE-VALLEY GUTTERS

The empirical results on the vee-valley gutters may be directly applied to the design of these gutters on dwellings. Calculations may be based upon equation (14) utilizing Figure 4 to give the value of the slope factor "n".

As an example consider straight vee-valley gutters on hip and gable roofs of dwellings of about 12 squares in Melbourne. A common case concerns 200 sq. ft of roof sloping at 23^{o} which is drained by a vee gutter having a slope of 17^{o} and sides sloping at $16\frac{1}{2}^{o}$. Traditional practice is to use an overall gutter width of 18 in. which with two ½-in. folds at the edges gives 8½-in. sides to the vee and a maximum depth of 2.4 in. Allowing ½-in. freeboard (which also allows the roofing to overlap the gutter by 2 in.) this gives by simple trigonometry a cross-sectional area of flow of 12.3 sq. in. With the slope factor of 3.8 from Figure 4 this provides a value of na' of 46.8 sq. in. The requirement given by equation (14) with values of w, A and p of 12.9 in., 200 sq. ft and 6.8 in./h respectively is only 20 sq. in., which indicates that such gutters are over-designed. Further similar calculations show that vee gutters made from 14 in. wide strips would be suitable for Melbourne with a considerable margin of safety. Table 3 gives the results of calculations on the same roof design but situated at various localities in Australia. It should be noted that these results are based upon a rainfall intensity likely to occur once in 100 yr, and that the conventional 18 in. gutter is required only at localities with a high rainfall intensity, such as Cairns and Darwin. Obviously roofing must not be allowed to obstruct the flow in these vee-valley gutters and in order to comply with the design the roofing should not overlap the gutter by more than 2 in. If a greater overlap is used the available cross-sectional area of flow given by the gutter must be reduced accordingly.

VII. CONCLUSIONS

1. The slope has a considerable influence upon the discharge capacity of roof drainage channels.

2. The equation developed by Camp (1939), which indicates that

the square of the discharge capacity is proportional to the sine of the slope of the channel, holds for roof channels up to 1^{o} slope but deviates at higher slopes.

3. At slopes between 1^{o} and 20^{o} the reciprocal of the maximum depth of flow in the channel is directly proportional to the square root of the sine of the channel slope.

4. A slope factor or increase of relative discharge capacity of drainage channels may be introduced. When this factor is used to modify the equation previously developed for shallow gutters (Martin 1965) conservative estimates of discharge capacity are obtained compared with the observed values for rectangular and vee channels.

5. Application of the findings to an available trough roofing system indicates that the roofing may be applied in Darwin at 1^{o} slope in 100-ft lengths with a risk of overflow occurring once in 100 yr.

6. Application of the findings to vee-valley gutters on a typical conventional roof to a dwelling erected in various localities in Australia provides a table of suitable gutter sizes for the different localities.

VIII. ACKNOWLEDGMENTS

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TABLE 1 - EXPERIMENTALLY DETERMINED MAXIMUM DEPTHS (d_M, in.)

Channel Type	Slope (deg)	Total Flow Load (gal/min)			
		11	24	33	64
Rectangular (12 in. wide)	0	0.81	1.38	1.50	2.19
	1/3	0.50	1.03	1.28	1.75
	1	0.44	0.75	0.88	1.25
	2	0.31	0.50	0.81	0.94
	3	0.25	0.50	0.50	0.84
	5	0.22	0.34	0.50	0.72
	10	0.19	0.31	0.41	0.63
	16½	0.13	0.25	0.38	0.63
Rectangular (6 in. wide)	0		1.88	2.19	
	1/3		1.31	1.72	
	1		1.00	1.39	
	2		0.75	1.13	
	3		0.69	0.91	
	5		0.63	0.81	
	10		0.56	0.69	
	16½		0.50	0.63	
Vee (Slope of side 20°)	0	1.38			
	1/3	1.13			
	1	0.88			
	2	0.75			
	3	0.66			
	5	0.56			
	10	0.50			
	16½	0.44			

TABLE 2 - COMPARISON OF OBSERVED DEPTHS AND DEPTHS CALCULATED USING CAMP'S FORMULA

Slope (degrees)	Rate (gal/min)	Distance Along Channel (ft) 3		6		9	
		Obs'd Depth (in.)	Calc'd Depth (in.)	Obs'd Depth (in.)	Calc'd Depth (in.)	Obs'd Depth (in.)	Calc'd Depth (in.)
0	11	0.7	0.7			0.7	0.7
	24	1.2	1.1			1.0	1.0
	33	1.4	1.4			1.3	1.1
	64	2.1	2.0			1.8	1.8
1/3	24	0.8	0.8	1.0	1.0	0.9	1.1
	33	1.0	1.0	1.3	1.1	1.2	1.3
	64	1.6	1.6	1.8	1.8	1.6	1.8
1	64	0.8	1.1	1.0	1.4	1.2	1.8
2	64	0.6	1.5	0.8	2.4	0.9	3.4

TABLE 3 - SIZES FOR VEE-VALLEY GUTTERS ON A TYPICAL DWELLING* FOR AUSTRALIAN LOCALITIES

Locality	Rainfall Intensity, p. (in./h)	Overall Strip Size for Gutters + (in.)	Cross-sectional Area of Flow (sq. in.)	
			Available	Required ‡
Mildura	4.7	10	2.04	3.06
		12	3.80	3.39
Broken Hill) Hobart) Port Augusta)	5.3	10	2.04	3.31
		12	3.80	3.67
Melbourne) Ballarat) Mt. Gambier)	6.8	12	3.80	4.34
		14	6.16	4.70
Alice Springs) Canberra)	7.3	12	3.80	4.55
		14	6.16	4.93
Adelaide) Bathurst) Geraldton) Perth)	7.6	12	3.80	4.67
		14	6.16	5.06
Sydney	9.4	12	3.80	5.38
		14	6.16	5.83
Cloncurry	9.8	12	3.80	5.53
		14	6.16	6.00
Brisbane	10.3	14	6.16	6.20
		16	8.97	6.60
Newcastle) Port Moresby)	11.0	14	6.16	6.48
		16	8.97	6.90
Rockhampton	14.2	14	6.16	7.68
		16	8.97	8.18
Cairns	19.4	16	8.97	10.1
		18	12.3	10.6
Darwin	20.7	16	8.97	10.5
		18	12.3	11.1

*Gutter sloping at 17° and draining 200 sq. ft of roof sloped at 23°.
+Sides slope 16½°.
‡Based on a rainfall intensity likely to occur once in 100 yr.