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DRAINAGE OF LEVEL OR NEARLY LEVEL ROADS

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ABSTRACT

This report considers the drainage of surface water from roads of constant crossfall. Two systems are studied:–

1. a channel of constant depth along the lower edge with outlets at regular intervals and

2. a channel formed by a raised kerb again with outlets at regular intervals.

The results in the report are based mainly on theoretical considerations though these are co-ordinated with practical measurements. They apply mainly to level or nearly level roads and supplement the results given in an earlier report LR 277 "The hydraulic efficiency and spacing of road gulleys".

The theoretical equations are comparatively complex and not suitable for use in design offices and so the results have been analysed statistically to give a simpler formula. Tables are provided which give the solutions of this latter formula for a wide variety of conditions.

1. INTRODUCTION

The Laboratory Report LR 277[1] described measurements of the hydraulic efficiency of the various types of gulley grating commonly used in road surface water drainage systems. The report contained information for estimating the spacing of the gulleys along the kerbs of roads having crossfalls ranging from 1.6 to 6.6 per cent (ie. from 1/60 to 1/15) and longitudinal gradients ranging from 0.33 to 1.67 per cent (1/300 to 1/15), the object being to restrict the width of the water flowing along the edge of the road by the kerb to 0.5, 0.75 or 1.0 m. The present report deals with the drainage of flatter roads from zero longitudinal gradient up to the minimum studied in the earlier report.

Surface water is sometimes drained from longitudinally level or nearly level roads by varying the elevation of the left hand edge of the road to provide a fall to the outlet from both directions[1]. The resultant variations of the crossfall along the road provide a somewhat uncomfortable ride for vehicles travelling along the left hand lane and this is particularly unwelcome where the traffic flows at high speeds. This method is not considered in this report.

Water can otherwise be drained from level or nearly level roads either by:–

1. providing a longitudinal channel along the left hand edge of the carriageway or hard shoulder with outlets at intervals (see Fig. 1(a) for a possible cross-section of such a system).

or

2. using part of the hard shoulder itself as the drainage channel by permitting the water to flow along it against the face of the verge, kerb, or other boundary. Drainage outlets are provided at intervals (see Fig. 1(b) for a typical cross-section).

Both systems have to cope with rainstorms which have been in progress sufficiently long for the water reaching the outlets in unit time to be approximately equal to that falling on the road. Both systems are fed laterally with water at a uniform rate along the length of the road and the maximum depth of water in the channel or on the hard shoulder against the lower boundary occurs at a point between each pair of outlets.

In case (1), the design problem is to determine the dimensions of the channel and the spacing between the outlets so that the water just does not overflow from the channel under a storm of specified intensity. In case (2), the nearside boundary of the road is assumed to be sufficiently high to prevent overflow and the design problem is to determine the outlet spacing to restrict the width and depth of the water flowing along the left hand edge of the road to acceptable values.

The Laboratory began studying the drainage of longitudinally level or nearly level roads when the North Eastern Road Construction Unit (NERCU) asked for help in designing drains for a level section of new motorway. For constructional reasons, the NERCU indicated a preference for a longitudinal channel of constant depth below the level of the edge of the hard shoulder and having a trapezoidal cross-section with a horizontal flat bottom. It was specified that the side of the channel adjacent to the hard shoulder should be inclined at 30° to the horizontal and the other side should be at 45° (see Fig. 1(a)). The Laboratory estimated the channel dimensions and outlet spacings from data derived from experiments made by Beij of the American Bureau of Standards[2] and the Hydraulics Research Station (HRS) studied the problem theoretically at the request of the NERCU[3]. A computer program developed by the HRS was later modified by the Laboratory to suit an ICL.4/70 computer and used to obtain data for computing the outlet spacings for water flowing along the hard shoulder (case 2).

The main objective of the present report is to present design data and formulae for use by engineers. To help achieve the latter objective, a comparison is made between designs of trapezoidal channel based on Beij's experimental data with those derived from the theoretical study by HRS and a detailed analysis is made of the designs for the case (2) system provided by the HRS/TRRL computer programme.

2. THEORETICAL DESIGN OF TRAPEZOIDAL CHANNELS BY THE HYDRAULICS RESEARCH STATION

To make the present Report complete, the theoretical treatment of the problem is outlined in Appendix 1.

In the calculations made by the HRS, it was assumed that the carriageway was 11 m wide with a hard shoulder 3 m wide giving a drained area 14 m (46 ft) wide. The depth of the trapezoidal channel was assumed to be 76 mm (3 in), 114 mm (4.5 in) or 152 mm (6 in). The width of the flat bottom of the channel was assumed to lie between 102 mm (4 in) and 305 mm (12 in). The calculations were made for rainfall intensities between 38 mm (1.5 in) and 57 mm (2.25 in) per hour and for longitudinal gradients of zero, 1/2000 (0.05 per cent), 1/1000 (0.10 per cent) and 1/500 (0.20 per cent). In these calculations, the surface roughness ** was assumed to be 0.6 mm.

At zero longitudinal gradient, additional calculations were made for channel depths of 89 and 102 mm (3.5 and 4.0 in) because it was thought they lie in the region of greatest interest to highway engineers.

In this theoretical work, a successive approximation technique was found necessary and two programs were prepared in Algol for use on an ICL 1903 digital computer, one for a road of zero longitudinal gradient and the other for the range of slopes mentioned earlier.

The results of the calculations were given in graphical form relating the width of the channel bottom to the distance between the drainage outlets for each channel depth, rainfall intensity and longitudinal gradient. The Table 1 of the present report gives values of outlet spacing read off these curves.

** Surface roughness is the equivalent sand roughness discussed in the Hydraulics Research Paper No. 1 "Resistance of fluids flowing in channels and pipes", HMSO, 1958. The original experiments on friction were made with pipes artificially roughened with sand particles and the flow equations were related to sand grain size. The equivalent sand roughness is a measure of the surface texture, but it must be emphasised that depth is not the only factor affecting friction; other important factors are the roughness spacing, angularity and distribution.

According to a relation given in the HRS Paper No. 1, an equivalent sand roughness of 0.6 mm is equal to a Manning roughness coefficient of 0.011 (see Section 7).

The HRS concluded from this investigation:—

"(a) The outlet spacing just to prevent channel overflow increases with the cross-sectional area of the channel and decreases with increasing rainfall intensity. The effect of the longitudinal slope is not so well defined. This is due to the complicated balance between frictional, gravitational and momentum forces. In general, the larger channel sizes show an increase in outlet spacing with increasing slope while the smallest channel size (76 mm deep and 102 mm wide at the bottom) shows a decrease in outlet spacing with increasing slope (see Table 1). Systematic variations occur within these limits.

(b) The maximum slope considered was 0.20 per cent (1 in 500). Flows in the larger channels at this slope were near critical, (ie with Froude numbers near unity), thus conditions would alter radically at steeper slopes and this would call for major changes in the computation techniques and in the models considered. Further research would be necessary to extend the work into this region of steeper slopes.

(c) Calculations based on a surface roughness of 3.0 mm indicated that the outlet spacings should be reduced by about 10 per cent at slopes of less than 0.10 per cent (1/1000) and by about 15 per cent at steeper slopes. Road grit entering the drains would produce this degree of roughness and, if this is likely, the outlet distances should be reduced. Large accumulations of debris in the channels would produce a further reduction in capacity due to the reduction of cross-sectional area".

3. EXPERIMENTAL WORK BY BEIJ

Beij[2] measured the depth of water at various points along horizontal gutters fed by water running off a roof. The water supply was metered and controlled and was uniformly distributed along the length of the roof. Most of the tests were made with gutters of rectangular or semi-circular cross-sectional shape. The rectangular gutters were 76 mm (3 in) and 152 mm (6 in) wide and were studied in lengths of up to 9.6 m (31.6ft). The semi-circular gutters were 102 mm (4 in) or 152 mm (6 in) wide and were investigated in lengths of up to 12.6 m (41.5 ft). Empirical curves, which were a good fit to the experimental results, were obtained for each of the two main types of gutter.

Although Beij did not make a comprehensive study of gutters of trapezoidal cross-section, he suggested that gutters of any cross-section might be taken as equal in performance to either a rectangular or a semi-circular gutter of equal cross-sectional area. The proposal was confirmed by tests made with the moulded copper gutters. Details are given in Fig. 1 for calculating the dimensions of the rectangular cross-section equal in area to a trapezoidal channel.

Appendix 2 (equation (3)) of this report gives a formula based on Beij's experimental data for computing the outlet spacing for a channel of zero longitudinal gradient and having a trapezoidal cross-section, viz:—

$$J = \frac{0.235\,(S + \tfrac{1}{2}Kh_o)^{12/13}\,h_o^{16/13}}{(IW)^{10/13}} \qquad (1)$$

where J = outlet spacing in metres

S = width of the channel bottom in millimetres

K = constant factor by which the width of the trapezoidal cross-section increases with vertical distance above the channel bottom.

h_o = depth of the channel in millimetres

I = rainfall intensity in mm/h

W = width of the road in metres (for the motorway considered, this is the width of a carriageway plus the hard shoulder).

It should be noted that K = the sum of the cotangents of the two angles of inclination of the sides of the trapezoidal channel (see Fig. 1(a)). For the channel considered in detail in this report, which has sides at 30° and 45° to the horizontal,

$$K = 2.732, \text{ and thus:--}$$

$$J = \frac{0.235\,(S + a.366\,h_o)^{12/13}\,h_o^{\,16/13}}{(IW)^{10/13}} \qquad (2)$$

4. COMPARISON BETWEEN OUTLET SPACINGS FOR TRAPEZOIDAL CHANNELS COMPUTED BY THE HRS AND FROM BEIJ'S EXPERIMENTAL DATA

Table 2 compares the outlet spacings for trapezoidal channels computed for longitudinally level roads by the HRS and those given by the equation (2) which was derived from Beij's experiments. In the table, there are four columns for each rainfall intensity. The first two columns give the outlet spacings in metres calculated respectively by equation (2) and by HRS. The third column gives the value computed by equation (2) expressed as a percentage of that calculated by the HRS, and the fourth column gives the smallest spacing calculated by the HRS for any one of the four longitudinal gradients considered (see Table 1 for details). This minimum value will be compared with that derived from Beij's experiments later in Section 5.

Table 2 shows that the outlet spacings derived from equation (2) are between 4 and 11 per cent less than those computed by the HRS. The experimental work, which was executed with smooth channels, gives a slightly closer outlet spacing than the theoretical treatment which allowed for roughness of the channel – a difference expected to lead to the experimental work giving a wider spacing than the theoretical treatment. However, the difference between the two sets of values is not great and, if the Beij values were used in practice, they would probably provide a small factor of safety.

The ratios between the HRS theoretical and Beij's experimental values are independent of the rainfall intensity within the range considered and decrease only slightly with increase of the depth of the channel and the width of its bottom.

5. EFFECT OF LONGITUDINAL GRADIENTS ON OUTLET SPACING FOR TRAPEZOIDAL CHANNELS

Section 2 shows that, in general, the outlet spacing decreases initially with increase of the slope from zero and then increases again. The outlet spacing required for a gradient of 0.20 per cent (1/500) is usually greater than that needed at zero slope.

Because of the way the outlet spacing has been found to vary with change of longitudinal gradient over the range of slopes investigated (0 to 0.20 per cent), engineers may find it convenient to take a minimum value of the outlet spacing and to use it throughout their designs regardless of slope within the range of gradients investigated. Table 2 shows minimum values of outlet spacing taken from the HRS data given in Table 1 and compared with those computed for longitudinally level roads by the formulae based on Beij's experiments. The two sets of values of outlet spacing are in reasonable agreement and only small differences of spacing occur at some values of the gradient as a result of using Beij's data throughout the whole range of gradients from zero up to 0.20 per cent (1/500).

6. WATER FLOWING ALONG THE HARD SHOULDER – COMPUTER DATA

The flow condition is shown in Fig. 1(b) and was described as case (2) in Section 1.

The computer program described in Appendix 1, paragraph (6) was used to calculate the spacing needed between the drainage outlets to restrict to specified values the maximum width of flow of the surface water along the left hand edge of the hard shoulder. The carriageway and hard shoulder were assumed to have a constant crossfall over the whole width and this overall width was used in the calculations.

The parameters selected for the calculations were:–

(a) Road width .... 5.43, 9.30, 11.70 and 14.0 m.

(b) Crossfall .... 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0 per cent.

(c) Longitudinal gradient .... Zero, 0.05, 0.10, 0.20, 0.30, 0.40 and 0.50 per cent.

(d) Maximum width of flow along left hand edge .... 0.5, 0.75, 1.0, 2.0 and 3.0 m.

(e) Rainfall intensity .... 38.1, 44.5, 51.0 and 57.0 mm/h.

As in the earlier work on channels, the surface over which the water flowed was assumed to have an equivalent sand roughness of 0.6 mm (equivalent to a Manning roughness coefficient "n" of 0.011).

The road widths and some of the values of crossfall and longitudinal gradient were specified in requests for drainage design data from several of the Road Construction Units during 1972/3 and others have been added to complete the ranges likely to be of interest to highway engineers.

Typical results derived from the HRS/TRRL computer program are given in Table 3. In all, 3825 calculations of outlet spacing were made. Because the computer program became unstable, it was not possible to obtain values of the outlet spacing for the cases where wide flow widths were associated with steep crossfalls and longitudinal gradients (see Table 3).

In general, when all other parameters were held constant, increase of the longitudinal gradient from zero caused first a small decrease in the outlet spacing needed to restrict the flow near to the left hand boundary to a specified width, followed by an increase in this spacing. Typical results are shown in Fig. 2 which shows that the later increase in outlet spacing usually greatly exceeded the initial decrease. The scatter in the results is caused by the numerical techniques used to integrate the equations. It is explained in Appendix 3 that the initial reduction in outlet spacing was neglected when analysing the data to devise an empirical formula covering all of the parameters studied. Curves based on this formula are given in Fig. 2–6 to demonstrate the effects of the various parameters on the outlet spacing.

Fig. 2 shows that increase of the road crossfall affected not only the magnitude of the outlet spacing but also the rate at which it increased with increase of the longitudinal gradient. Increase of the flow width also increased the outlet spacing and its rate of increase with increase of the longitudinal gradient (see Fig. 3).

Increase of the road width (Fig. 4) and of the rainfall intensity (Figs 5 and 6) reduced both the outlet spacing and the rate at which it increased with increase of the horizontal gradient. Road width and rainfall intensity would be expected to behave similarly in their effect on outlet spacing because an increase in either has the effect of increasing the amount of water flowing along the road by the left hand edge.

It is impossible to derive a general formula for outlet spacings from the basic equations and hence regression analyses were carried out on the data given by the computer programs to give a usable general formula. From these analyses it was found that:–

$$J = 545 \left(\frac{N^3}{IW}\right)^{\frac{3}{4}} C^{23/16} \left[1 + \frac{BN^{7/4} \quad Y^{w}}{(IW)^{\frac{7}{8}}}\right] \qquad (3)$$

where J = outlet spacing in metres

N = maximum flow width in metres

I = rainfall intensity in mm/h

W = overall width of hard shoulder and road in metres

C = crossfall (expressed as a percentage)

B = coefficient depending on the crossfall (see Appendix C for values)

Y = longitudinal gradient (expressed as a percentage)

w = index depending on the crossfall and is given by

$w = 2.32 - 0.13C$

Appendix 3 shows that this empirical formula fits the computer results with a standard deviation of 7.3 per cent which reduces to 6.7 per cent if the results applicable to a crossfall of 0.5 per cent are omitted. Tables 4–6, which are based on the empirical formula, facilitate the calculation of outlet spacings for any given set of parameters within the range studied.

7. FLOW ALONG THE HARD SHOULDER – RELATION WITH DATA GIVEN IN THE LABORATORY REPORT NO. LR 277

It was mentioned in Section 1 that the Laboratory Report No. LR 277 provided data for estimating the outlet spacings on kerbed roads having crossfalls ranging from 1.67 to 6.67 per cent and longitudinal gradients ranging from 0.33 to 1.67 per cent. The Tables 3(a), (b) and (c) of that Report give the drained areas associated with widths of flow along the kerb of 0.5, 0.75 and 1.0 m.

Appendix 4 of the present report extends Appendix 1 of LR 277 and provides formulae for computing the outlet spacing assuming a hydraulic efficiency of 100 per cent for each gulley grating. The equation (6) of Appendix 4 shows the outlet spacing to be proportional to the value assumed for the Manning roughness coefficient "n". In much of the data published in LR 277, a value of "n" of 0.010 was assumed, but the calculations made for the present report by the HRS/TRRL computer programme assumed an equivalent sand roughness of 0.6 mm, which is equivalent to a value of "n" of 0.011 (see footnote to Section 2). Changing "n" from 0.010 to 0.011 reduces the outlet spacing by 10 per cent.

It was stated in LR 277 that measurements of the values of "n" at the edges of roads gave results varying between 0.002 and 0.012, with values below 0.007 being very rare and confined to very smooth surfaces free from debris. There was no consistent variation in the value of the roughness coefficient with the type of road surface, ie. concrete, bituminous carpet or surface dressing, and the texture depth gave little indication of the value of the roughness coefficient. The mean of nearly 200 values of the Manning coefficient "n" was 0.0095. The Fig. 2 of LR 277 shows flow plotted against longitudinal gradient for a crossfall of 2.5 per cent and a flow width of 0.75 m. The experimental points lie between curves obtained by using values of "n" of 0.010 and 0.015 indicating the coefficient in these experiments to be possibly somewhat greater than the value of 0.010 used in the calculations leading to the tables of results. For this reason, a coefficient of 0.011 has been used in connection with Appendix 4 of the present report to calculate outlet spacings by the formulae developed from LR 277, thus keeping these calculations in line with those made by the HRS/TRRL computer program.

The Figs. 7 and 8 of the present report show outlet spacings for a crossfall of 2.5 per cent calculated by the formulae derived from LR 277 and using n = 0.011 together with curves based on the empirical formula derived from the HRS/TRRL computer program.

The drained areas calculated using Manning's empirical formula (LR 277) took account only of the effect of road crossfall and longitudinal gradient, neglecting the true hydraulic gradient, giving zero flow at a zero gradient. The HRS/TRRL computer program takes the true hydraulic gradient into account and hence can calculate the effect of the additional head generated by the flow, giving some flow at zero gradient. Also, Manning's formula assumes that the flow is in the rough-turbulent region with a Froude number greater than unity whereas for the slack gradients the flow is likely to be smooth with a Froude number of less than unity over most of the length of the channel. At these gradients the Froude number increases to unity at the outlets. Hence, for these two reasons it cannot be expected that the two approaches will give similar results.

If the longitudinal gradient is less than 0.2 per cent the flow will almost certainly be sub-critical ie with Froude number less than unity and in this case the data in this report should be used to estimate gulley spacings. If the longitudinal gradient is greater than 0.5 per cent the flow will almost certainly be super-critical ie with a Froude number greater than unity and hence for these gradients the LR 277 data should be used. In the transition range it is not easy to decide whether the flow will be super or sub-critical. If the flow is shallow it is likely to be super-critical. When the flow becomes deeper it is likely to be sub-critical. It is possible to see this effect in Figs. 7 and 8 where the transition point A occurs at steeper gradients with greater (and hence probably deeper) flows.

Thus, in the transition range of gradients the engineer should construct the two curves for his chosen rainfall and take note of the gradient at which the change in flow regime occurs. However, in this connection, it must be remembered that the experiments on which LR 277 was based dealt with flow widths up to 1 metre and there could be danger in extrapolating it to greater widths.

8. ESTIMATION OF THE CAPACITY OF THE DRAIN OUTLETS

8(a) General

The Appendix 5 outlines the calculations of the drainage capacity needed for the outlets of the proposed systems while Table 7 gives the outlet capacity needed for a range of outlet spacings and for the road widths studied in this report. Capacities for other outlet spacings or road widths can be obtained by simple proportion. Where the hydraulic efficiency of an outlet is known (see LR 277), the outlet spacing should be reduced in proportion to the hydraulic efficiency in order to take it into account.

8(b) Outlet capacities for trapezoidal channels

The Table 8 gives the outlet spacings recommended earlier for the various types of trapezoidal channel and the capacities required at these outlets. A high hydraulic efficiency would be expected at each outlet because they are likely to be placed across the whole width of the bottom of the channel.

8(c) Outlet capacities for drainage along the hard shoulder

The information given in this reports shows that large outlet spacings are adequate to restrict flow widths to 2 or 3 metres when the crossfall and longitudinal gradient approach the upper limits of the ranges studied. Reference to Table 7 then shows that such outlets need to have a capacity well above the flow rate of 15 litres per second which was the maximum employed in the tests of hydraulic efficiency recorded in the Report LR 277. There is no information available, therefore, relating to these greater flows other than the warning given in that report that the flow width should not exceed 1.5 times the width of any gulley grating which might be used. These limits of flow width are certain to be exceeded with normal gratings when flow widths as great as 2 or 3 metres are permitted and special outlets will be required. Another complicating factor is that, with flow along the hard shoulder, the position of the maximum flow width moves towards the lower outlet as the longitudinal gradient is raised above zero and coincides with it at gradients above about 0.20 per cent.

9. CONCLUSIONS

9(a) Longitudinal drainage channel

1. For constructional reasons, some engineers prefer the drainage channel to be of constant depth and of trapezoidal cross-section. With a longitudinally level road, the maximum depth of water in the channel will occur midway between the outlets, while increase of the gradient causes the point of maximum depth to move towards the lower outlet. The design problem is to determine the dimensions of the channel and the outlet spacing so that the water just does not overflow from the channel under a specified rainfall intensity.

2. With a longitudinal drainage channel, the magnitude of the crossfall of the road is unimportant. For longitudinal gradients from zero up to 0.20 per cent (the maximum studied), the outlet spacing can be deduced by the empirical formula:—

$$J = \frac{0.235\,(S + \tfrac{1}{2}Kh_o)^{12/13}\,h_o^{16/13}}{(IW)^{10/13}}$$

where J = outlet spacing in metres

S = width of the bottom of the trapezoidal channel in millimetres

K = factor by which the width of the trapezoidal cross-section increases with increase of the vertical distance from the bottom (This means that K = sum of the cotangents of the angles of inclination of the channel sides).

h_o = maximum depth of water permitted in the channel so that it just does not overflow (ie h_o = depth of the channel)

I = rainfall intensity in mm/h

W = width of the road in metres (width of carriageway plus the hard shoulder).

3. The report gives details of the outlet capacities needed for the proposed design of trapezoidal channel and, because each outlet is likely to be placed across the whole width of the channel bottom, its hydraulic efficiency would be expected to be high.

9(b) Drainage along the hard shoulder

1. With a longitudinally level road, the greatest width of flow or depth of water close to the left hand boundary occurs midway between the outlets. Increase of the longitudinal gradient causes the point of maximum depth of water (or width of flow) to move towards the lower outlet and to approach or coincide with it at slopes of the order of 0.2 per cent. The design problem is to determine the outlet spacing needed to restrict the flow width or water depth to specified values under a given rainfall intensity, road width, crossfall and longitudinal gradient.

2. A computer program developed by the Hydraulic Research Station and modified by the TRRL has been used to calculate the outlet spacings needed to limit the flow width within the range from 0.5 to 3.0 m, for crossfalls from 0.5 to 5.0 per cent, longitudinal gradients up to 0.50 per cent and road widths up to 14 m. Analysis of the results shows that the outlet spacing can be calculated with a standard deviation of about 7 per cent by the empirical formula:—

$$J = 545\left(\frac{N^3}{IW}\right)^{\frac{3}{4}} C^{23/16}\left[1 + \frac{B\,N^{7/4}\,Y^{W}}{(IW)^{\frac{7}{8}}}\right]$$

where J = outlet spacing in metres

N = maximum flow width in metres

I = rainfall in mm/h

W = overall width of hard shoulder and carriageway in metres

C = crossfall expressed as a percentage

Y = longitudinal gradient expressed as a percentage

w = index depending on crossfall and given by $w = 2.32 - 0.13C$

B = coefficient depending on crossfall (see table 11)

Tables are given in the report which facilitate the calculation of outlet spacings by this formula.

3. Curves based on values of the outlet spacing computed by this empirical formula intersect curves based on the Laboratory Report No. LR 277 using a roughness coefficient "n" of 0.011. The latter report gives data for flow widths of 0.5, 0.75 and 1.0 m and, over this range, the curves based on the new empirical formula intersect those derived from LR 277 at longitudinal gradients near to zero and up to the intersection, while data from LR 277 may be preferred at higher slopes.

4. At gradients exceeding about 0.3 per cent and flow widths greater than a metre, normal gulley gratings will be incapable of handling the large amounts of water without considerable loss of hydraulic efficiency and special designs of outlet may be needed.

9(c) Danger from grit

1. Unless it is certain that the longitudinal channel or hard shoulder will remain free from grit or other debris, the outlet spacings computed by any of the methods outlined in this report should be reduced by 15 per cent.

10. ACKNOWLEDGEMENTS

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12. APPENDIX 1

THEORETICAL TREATMENT OF FLOW OF WATER IN CHANNELS

12.1 Equation for spatially variable steady flow

The incremental changes in depth of water along a channel with lateral inflow are derived by considering continuity and energy balances for a short length of channel. The differential equation which is obtained when the momentum changes due to lateral inflow are taken into account is:—

$$\frac{dh}{dx} = \frac{Y - i - 2aQq/gA^2}{1 - Fr^2} \qquad (1)$$

where dh/dx = change in depth of water per unit length of channel

Y = longitudinal slope of channel

i = hydraulic gradient (see paragraph 12.2 below)

a = Coriolos energy coefficient

Q = flow of water at the point under consideration

q = lateral inflow per unit length of channel

g = acceleration due to gravity

A = cross-sectional area of water at point under consideration

Fr = Froude number (see paragraph 12.3).

12.2 Hydraulic gradient

The hydraulic gradient "i" is given by:—

$$i = GQ^2/8gLA^2 \qquad (2)$$

where G = friction factor

and L = hydraulic mean depth

also $L = A/P$ (3)

where P = perimeter of the wetted portion of the channel cross-section.

Using the Colebrook-White equation applicable to the transitional flow regime

$$\frac{1}{\sqrt{G}} = -2 \log_{10} \left[\frac{k_s}{14.8L} \right] + \frac{2.51}{R_e \sqrt{G}} \qquad (4)$$

(5)

where k_s = equivalent sand grain roughness

R_e = Reynold's number = 4QL/vA

v = kinematic viscosity of the fluid

Equations (2), (3), (4) and (5) provide the value of "i" in equation (1) from the basic flow parameters. A successive approximation technique is, however, necessary.

12.3 Froude number

The Froude Number is the ratio of the inertial and gravitational forces:—

$$Fr = \sqrt{\frac{aQ^2}{ga^2 f}} \qquad (6)$$

and $f = A/T$ (7)

where f = mean depth of water

A = cross-sectional area of the water flow

T = width of the water surface

12.4 Coriolos energy coefficient

As a result of non-uniform velocity distributions over a channel section, the velocity head is generally greater than the value computed according to the expression $V^2/2g$ where V is the mean velocity. When the energy principle is used in computations, the true velocity head may be expressed as $aV^2/2g$, where "a" is the Coriolis coefficient. The coefficient varies with the physical properties of the channel, but an average value of 1.15 is found applicable to regular channels, flumes and spillways. This figure is used in the present investigation.

12.5 Longitudinal water surface profiles

The shape of the longitudinal water surface profile is shown in Fig. 9 and is obtained by integrating equation (1). This can only be done for most practical cases by using numerical approximation techniques. The basic method is to replace the differential coefficient dh/dx by the differentials $\Delta h/\Delta x$ where Δh and Δx are small but finite changes in h and x. A value of Δx is assumed and the corresponding change Δh is calculated from equation (1) and its associated equations. The calculated value of Δh is then added to a known value of h to give a new value of $h + \Delta h$. This process is continued until the complete profile is produced.

To start the process, it is necessary to find an initial value of h and, while it is continuing, precautions must be taken to ensure that the approximations remain reasonable. The starting value is given by the point D in Fig. 9 where the water surface is parallel to the bed of the channel. At this point

$$Y = I + 2aQq/gA^2 \qquad (8)$$

giving $dh/dx = o$

By the well-known theory of maximum and minimum values this is the point of maximum depth of water and, of course, it cannot exceed the maximum depth of the channel without overflow occurring.

The calculation is carried out in three parts. Firstly from the point D down the slope to the outlet B. Secondly, from D up the slope to point C and then from C continuing up the slope to A, the upper outlet.

From D to C, the rate of flow decreases until it is zero at C. At this point, equation (1) becomes:—

$$\frac{dh}{dx} = \frac{Y - 0 - 0}{1 - 0} = n \qquad (9)$$

Zero flow thus occurs at the point where the longitudinal water surface profile is horizontal. The point C is the highest point on the water surface profile and hence water apparently flows uphill to the point A which is, in fact, lower than C although, of course, higher than the lower outlet B.

The positions of the outlets A and B are given by the points at which the Froude Number, Fr, becomes unity. At these points the water surface is vertical, ie. the water is flowing straight down over some form of weir.

As the longitudinal gradient of the road or channel is decreased, the point D moves up the slope and C moves downwards until, when the channel bed is horizontal, the two points coincide in the middle, midway between the outlets.

12.6 Computer programs for calculating surface profiles

The Hydraulic Research Station prepared two computer programs for calculating surface water profiles. Both were written in Algol for an ICL 1903 computer and details are given in their Report DE.2[3]. The first program carries out the integration of equation (1) for the case of horizontal longitudinal bed slopes. The second carries out the process for the more complicated case of bed slopes with some longitudinal gradient.

As the integration processes are basically similar for longitudinally level beds and those having a slight slope, a single program can be written to carry out the integration for both cases provided precautions are taken to ensure that the program starts and stops at the correct places. The precautions are concerned solely with the technicalities of the mathematical procedures and not with the hydraulics of the problem. Consequently, a single program based on that originally devised by the HRS was written in Fortran by TRRL for use on an ICL.4/70 computer to calculate the outlet spacings given in this Report for flow over the hard shoulder of a motorway.

The main differences between the TRRL and HRS programs are:–

(a) the calculations of the hydraulic characteristics of the channel, eg. hydraulic mean depth, are carried out using sub-routines so that different channel shapes can be easily investigated while using the same basic program.

(b) the friction factor, G, in equations (2) and (4) is evaluated using a Newton iterative technique rather than the "reducing interval" technique employed by the HRS.

(c) the program can cope with both zero and non-zero longitudinal bed slopes, as already mentioned.

The TRRL programme also contains additional statements to enable it to be used to cover somewhat steeper slopes (0.20 to 0.50 per cent) than the range from zero up to 0.20 per cent covered by the HRS. As longitudinal gradients are increased, the technical problems associated with the mathematical procedures increase rapidly until it becomes impractical to deal with them. The theory outlined by Chow[4], on which the HRS work is based, does not impose any limitations on longitudinal slope, they arise solely on the computer side. However, if the gradient is such that the Froude Number of the flow exceeds unity, ie. the flow becomes super-critical, then an alternative theory is required leading to sets of equations that cannot be readily programmed for a computer.

The accuracy of the integrations naturally depends mainly on the size of the interval Δx. This is varied for each combination of slope, rainfall intensity and flow depth (or width in the case of hard shoulder drainage). When the likely outlet spacing is large, it is necessary to use large intervals in the integration process to ensure that the computation is done in reasonable time. The slight scatter of the points shown in Fig. 2 and Table 3 is due to this.

13. APPENDIX 2

CALCULATION OF OUTLET SPACING FROM BEIJ'S EXPERIMENTAL DATA

Beij's experiments on level roof gutters lead to the empirical equation:–

$$b = 0.0106\, m^{-4/7} \left(\tfrac{1}{2}J\right)^{3/28} (IE)^{5/14} \qquad (1)$$

where b = width of the rectangular gutter in feet

h_o = maximum depth of water in the gutter (in feet), ie. the depth the gutter must have in order not to overflow.

m = h_o/b

$\frac{1}{2}J$ = distance (in feet) from the outlet to the point where maximum depth of water in the gutter occurs.

I = intensity of the rainfall in inches per hour

E = area of roof (in square feet) discharging into the gutter

= $\frac{1}{2}JW$ square feet

W = width of roof or road in feet

J = distance between outlets in case of road drainage channel.

Converting equation (1) to metric units and rearranging gives:–

$$J = \frac{0.235\, b^{12/13}\, h_o^{16/13}}{(IW)^{10/13}} \qquad (2)$$

In equation (2)

J and W are in metres

b and h_o are in millimetres

I is in millimetres per hour

When the drainage channel has a trapezoidal cross-section (see Fig. 1a), it is necessary to find the rectangle of equal area:–

Let K = factor by which the width of the trapezoidal cross-section increases with vertical distance from the bottom of the channel.

= sum of the cotangents of the angles of inclination of the two sides of the trapezium (see Fig. 1).

S = width of the flat bottom of the trapezoidal channel in mm.

Thus for the required rectangle:–

$b = S + \frac{1}{2}Kh_o$ where h_o is the depth of the channel as before.

Equation (2) then becomes:—

$$J = \frac{0.235\,(S + \tfrac{1}{2}Kh_o)^{12/13}\,h_o^{16/13}}{(IW)^{10/13}} \qquad (3)$$

14. APPENDIX 3

DRAINAGE OF KERBED HARD SHOULDER – ANALYSIS OF DATA DERIVED FROM HRS/TRRL COMPUTER PROGRAM

14.1 Outlet spacings for draining roads having hard shoulders with a vertical left hand boundary were computed by means of the HRS/TRRL program for the following parameters:—

(a) Road widths .... 5.43, 9.30, 11.70 and 14.00 metres

(b) Crossfall .... 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0 per cent

(c) Longitudinal gradients .... Zero, 0.05, 0.10, 0.20, 0.30, 0.40 and 0.50 per cent

(d) Rainfall intensities .... 38.1, 44.5, 51.0, and 57.0 mm/h

(e) Maximum width of flow along edge of road by kerb of 0.5, 0.75, 1.0, 2.0 and 3.0 metres

The road width included the hard shoulders and it was assumed that the road had a constant crossfall across its whole width. In the calculations an equivalent sand roughness of 0.6 mm was assumed (equal to a Manning roughness coefficient of 0.011). Results are given in Table 3 for rainfall intensities of 38.1 and 57 mm/h and road widths of 9.30 and 14.0 m and for the other parameters listed above.

14.2 Analysis of data to derive a statistical formula for outlet spacings

From the above it can be seen that outlet spacings are derived as a function of five variables. The effect of each of these was examined to show how they should be arranged to give the best fit. This was done in three stages:—

(a) to give the spacings for roads of zero longitudinal gradient,

(b) to give a factor to allow for other longitudinal gradients for a fixed rate of rainfall (38.1 mm/h),

(c) to give a factor to allow for other rates of rainfall.

The formula finally derived is

$$J = 545 \left(\frac{N^3}{IW}\right)^{\frac{3}{4}} C^{23/16} \left[1 + \frac{BN^{7/4}\; Y^W}{(IW)^{\frac{7}{8}}}\right] \qquad (1)$$

where J = outlet spacing in metres

N = maximum flow width in metres

I = rainfall intensity in mm/h

W = width of road plus shoulder in metres

C = crossfall – per cent

B = coefficient depending on the crossfall

Y = longitudinal gradient – per cent

w = index depending on the crossfall and is given by

$w = 2.32 - 0.13\,C$

Values of the coefficient B and the index w are given in Table 11.

14.3 Use of the formula to calculate outlet spacings

The formula can, of course, be used directly to give outlet spacings but tables have been prepared to facilitate its evaluation. These are based on the three factors mentioned in section 2 of this appendix. Using these the outlet spacing, J, is expressed as

$$J = J_o \times (1 + F(R - 1))$$

where J_o is the outlet spacing for a zero gradient for the chosen values of road and flow width, crossfall and rainfall intensity.

R is a factor to adjust for the specified gradient.

F is a factor to adjust R for the specified values of rainfall and road widths.

The values of J_o, R and F are given in tables 4, 5 and 6.

14.3.1 Example of use of tables 4, 5 and 6

It is required to determine the outlet spacing for the following conditions:–

Roadwidth (W)	=	9.3 metres
Crossfall (C)	=	3.0 per cent
Longitudinal gradient (Y)	=	0.40 per cent
Flow width (N)	=	1.0 metres
Rainfall (I)	=	51 mm/h

Table 4 gives J_o as 26.0 m.

Table 5 gives R = 1.29 for a longitudinal gradient of 0.40 per cent.

Table 6 gives the factor F as 1.108 for the specified values of rainfall intensity, 51 mm/h, and road width, 9.3m. Thus J, the required spacing is given by

$$J = 26.0 \times (1 + 1.108\,(1.29 - 1)$$

$$= 26 \times 1.32 = 34.3 \text{ metres}$$

14.4 Quality of fit of outlet spacings provided by formula

14.4.1 To determine the quality of fit of the data provided by the empirical formula, it was used to calculate the outlet spacing for every set of conditions for which the HRS/TRRL computer program had been employed, providing a total of 3825 pairs of results. The value of spacing derived from the formula was divided by the corresponding value obtained from the computer program and variation of the result around unity was examined statistically. Full details of the results of the analysis are given in Table 9.

14.4.2 When all 3825 results were considered together the standard deviation was 7.3 per cent and the mean value was unity, ie. the value of outlet spacing calculated from the statistical formula will usually be within 7.3 per cent of the actual value derived from the computer program.

14.4.3 When the outlet spacing is small the error introduced by the necessary choice of a finite steplength, Δx, (Appendix 1) increases. To see how much this contributed to the scatter of the results derived from the formula, Table 9 shows separate deviations for the values obtained for a crossfall of 0.5 per cent and for the remainder. The standard deviation was higher for the data applicable to a crossfall of 0.5 per cent and their omission reduced the scatter of the remainder of the data. The overall standard deviation fell from 7.3 per cent to 6.7 per cent. Apart from the significant effect of the scatter associated with the smallest crossfall and flow width, the value of the flow width did not appear significantly to affect the standard deviation.

14.4.4 It will be noticed from Table 3 that results were not obtained from the computer program for the higher values of longitudinal gradient and the greater crossfalls at flow widths of 2.0 and 3.0 m and these omissions are reflected in Table 9 by reductions of the numbers of pairs of results. The omission of data in this region was caused by the computer program becoming unstable when considerable flow widths were associated with steep crossfalls and steep gradients. This is probably unimportant because, as Table 7 indicates, it would be necessary in this area to copy with very considerable quantities of water and little information is available for outlets and gulleys of such high capacity.

15. APPENDIX 4

CALCULATION OF OUTLET SPACING FOR WATER FLOWING ALONG THE HARD SHOULDER BY FORMULAE GIVEN IN THE LABORATORY REPORT NO. LR 277

According to Appendix 1 of LR 277, the amount of water flowing along the edge of a kerbed road can be calculated by Manning's empirical formula:—

$$Q = \left(\frac{D}{n}\right) AM^{2/3} \quad Y^{\frac{1}{2}} \qquad (1)$$

where Q = flow per second

D = a constant of proportionality which is equal to unity when the unit of length is a metre.

n = roughness coefficient

A = cross-sectional area of the flowing water

M = hydraulic radius taken as the ratio of the cross-sectional area of the flowing water to the wetted perimeter.

Y = longitudinal gradient (expressed as a fraction).

From equation (1) it was deduced that the flow per second along the edge of a kerbed road is:–

$$Q \quad \frac{D}{n}\left[\tfrac{1}{2}N\,(NC + 2d)\right]^{5/3}\left[\frac{1}{d + NC + N\,(1 + C^2)^{\frac{1}{2}}}\right]^{2/3} Y^{\frac{1}{2}} \qquad (2)$$

where N = width of flow of the water along the kerb

d = thickness of the water film (in metres) on the road on the average except, of course, in the path of the flowing water.

C = crossfall (expressed as a fraction).

when D = 1

and Q^1 = flow in cubic metres per hour = 3600 x Q

Equation (2) becomes:–

$$Q^1 = \frac{3600}{n} \times 0.31498\left[N\,(NC + 2d)\right]^{5/3}\left[\frac{1}{d + NC + N\,(1 + C^2)^{\frac{1}{2}}}\right]^{2/3} Y^{\frac{1}{2}} \qquad (3)$$

Now when

J = distance between outlets (in metres)

W = width of the road (carriageway plus shoulder) in metres

I = rainfall intensity in mm/h

Q^1 = JWI/1000 cubic metres per hour and hence (4)

J = 1000 Q^1/WI (5)

The outlet spacing would have to be reduced by multiplying it by the percentage hydraulic efficiency of the gulley grating employed divided by 100. The Tables published in LR 277 show that for a crossfall of 1/40 and a longitudinal gradient of 1/300, the efficiencies of heavy duty and medium duty gratings were 100 per cent at flow widths of 0.5 and 0.75 m and between 91 and 97 at a flow width of 1.0 m. For the flatter gradients studied in the present report, therefore, it has been assumed that the efficiency is 100 per cent at flow widths up to 1.0 m.

From equations (3) and (5):–

$$J = \frac{1.1339 \times 10^6}{WIn} \left[N(NC + 2d) \right]^{5/3} \left[\frac{1}{d + NC + N(1 + C^2)^{\frac{1}{2}}} \right]^{2/3} Y^{\frac{1}{2}} \qquad (6)$$

It was stated in LR 277 that "d" depends on the rate of the rainfall and the width of the road, but, under normal circumstances, it is likely to be of the order of 0.001 m.

In the present paper, the HRS/TRRL computer programs were based on an equivalent sand roughness of 0.6 mm and it can be estimated that this is equivalent to a value of Manning's "n" of 0.011. Much of the information published in LR 277 was based on n = 0.010 and the change to 0.011 reduces the outlet spacing by 10 per cent. If it is assumed that the crossfall is 1/40 (= 0.025) and the road width is 14 m equation (6) gives:–

$$J = \frac{7.363 \times 10^6}{I} \left[(0.025\, N^2 + 0.002\, N) \right]^{5/3} \left[\frac{1}{0.001 + 1.025312\, N} \right]^{2/3} Y^{\frac{1}{2}} \qquad (7)$$

The Table 10 gives values of the outlet spacing in metres for flow widths of 0.5, 0.75 and 1.0 m, a longitudinal gradient of 1/100 (0.01) and for the rainfall intensities employed throughout this report.

Values of other longitudinal gradients (Y) can be derived from those in the Table by multiplying by $(Y/0.01)^{\frac{1}{2}}$.

Curves based on equation (7) are given in Figs. 7 and 8.

16. APPENDIX 5

CALCULATION OF CAPACITY OF DRAIN OUTLETS

The quantity of water flowing to each outlet of a longitudinal drainage channel

= rainfall intensity (I) x road width (W) x distance between outlets (J)

= IWJ

where I is in mm/h and W and J are in metres.

The outlet capacity is normally required in litres per second (p), thus

$$p = \frac{I}{3600} \times \frac{1}{1000} \times WJ \times 1000 = \frac{IWJ}{3600} \text{ litres per second}$$

TABLE 1

Outlet spacings for trapezoidal channels computed by the Hydraulics Research Station

Dimensions of trapezoidal drainage channel				Distance between drainage outlets in metres to deal with a rainfall intensity of															
				38 mm/h				44.5 mm/h				51 mm/h				57 mm/h			
Width of base		Vertical depth		when slope (%) is				when slope (%) is				when slope (%) is				when slope (%) is			
mm	in	mm	in	Zero	0.05	0.10	0.20	Zero	0.05	0.10	0.20	Zero	0.05	0.10	0.20	Zero	0.05	0.10	0.20
102	4	76	3.0	55	56	54	54	49	50	50	46	43	42	45	40	39	39	40	37
		89	3.5	73	–	–	–	64	–	–	–	57	–	–	–	52	–	–	–
		102	4.0	91	–	–	–	81	–	–	–	73	–	–	–	65	–	–	–
		114	4.5	118	111	109	116	102	97	97	100	91	89	88	88	81	81	81	81
		152	6.0	196	181	184	214	173	162	164	184	154	146	147	163	141	135	135	146
203	8	76	3.0	82	80	78	79	73	71	70	70	65	64	63	61	59	59	59	58
		89	3.5	105	–	–	–	93	–	–	–	84	–	–	–	75	–	–	–
		102	4.0	130	–	–	–	115	–	–	–	104	–	–	–	94	–	–	–
		114	4.5	162	151	148	170	143	134	133	148	128	122	120	131	116	112	108	118
		152	6.0	265	243	250	306	235	208	221	266	211	196	198	234	191	180	183	207
305	12	76	3.0	106	99	100	100	94	87	88	95	84	80	80	85	77	73	75	77
		89	3.5	135	–	–	–	119	–	–	–	107	–	–	–	97	–	–	–
		102	4.0	167	–	–	–	147	–	–	–	132	–	–	–	120	–	–	–
		114	4.5	204	187	193	233	181	166	170	200	163	152	155	176	147	136	142	159
		152	6.0	325	297	305	394	289	264	272	342	261	239	247	302	238	220	226	272

TABLE 2

Trapezoidal drainage channels – Comparison between outlet spacings computed from Beij's data and value obtained by HRS

Dimensions of trapezoidal drainage channel				Outlet spacings to deal with a rainfall intensity in mm/h of															
				38				44.5				51				57			
Width of base		Vertical depth		For zero longit. grad			Min. from HRS calcs	For zero longit. grad			Min. from HRS calcs	For zero longit. grad			Min. from HRS calcs	For zero longit. grad			Min. from HRS calcs
				Beij	HRS	Beij/HRS		Beij	HRS	Beij/HRS		Beij	HRS	Beij/HRS		Beij	HRS	Beij/HRS	
mm	in	mm	in	m	m	%	m	m	m	%	m	m	m	%	m	m	m	%	m
102	4	76	3.0	53	55	96	54	47	49	96	46	43	43	100	40	39	39	100	37
		89	3.5	69	73	95	–	61	64	95	–	55	57	96	–	51	52	98	–
		102	4.0	87	91	96	–	78	81	96	–	70	73	96	–	64	65	98	–
		114	4.5	108	118	92	109	96	102	94	97	86	91	95	88	79	81	98	81
		127	5.0	130	–	–	–	116	–	–	–	104	–	–	–	95	–	–	–
		152	6.0	182	196	93	181	161	173	93	162	146	154	95	146	133	141	94	135
203	8	76	3.0	77	82	94	78	68	73	93	70	62	65	95	61	56	59	95	58
		89	3.5	98	105	93	–	87	93	94	–	78	84	93	–	72	75	96	–
		102	4.0	121	130	93	–	107	115	93	–	97	104	93	–	89	94	95	–
		114	4.5	146	162	90	148	130	143	91	133	117	128	91	120	107	116	92	108
		127	5.0	174	–	–	–	155	–	–	–	139	–	–	–	127	–	–	–
		152	6.0	236	265	89	243	210	235	89	208	189	211	90	196	173	191	91	180
305	12	76	3.0	100	106	94	99	89	94	95	87	80	84	95	80	73	77	95	73
		89	3.5	126	135	93	–	112	119	94	–	101	107	94	–	92	97	95	–
		102	4.0	154	167	92	–	137	147	93	–	123	132	93	–	113	120	94	–
		114	4.5	184	204	90	187	164	181	91	166	148	163	91	152	135	147	92	136
		127	5.0	217	–	–	–	193	–	–	–	174	–	–	–	159	–	–	–
		152	6.0	290	325	89	297	257	289	89	264	232	261	89	239	212	238	89	220

TABLE 3

Flow along kerbed hard shoulder – Typical results provided by main computer programme

Cross. fall	Long. Grad.	Drain outlet spacing (metres) to restrict maximum flow width to																			
		0.5m under rainfall of				0.75m under railfall of				1.0m under rainfall of				2.0m under rainfall of				3.0m under rainfall of			
		38.1 mm/h & road width		57mm/h & road width		38.1 mm/h & road width		57 mm/h & road width		38.1 mm/h & road width		57 mm/h & road width		38.1 mm/h & road width		57 mm/h & road width		38.1 mm/h & road width		57 mm/h & road width	
%	%	9.30m	14.0m	9.30m	14.0m	9.30m	14.0m	9.30m	14.0m	9.30m	14.0m	9.30m	14.0m	9.30m	14.0m	9.30m	14.0m	9.30m	14.0m	9.30m	14.0m
0.5	Zero	0.5	0.5	–	–	1.5	1.1	1.1	0.5	2.5	2.0	2.0	1.5	11.0	8.5	8.5	6.5	28.0	22.0	22.0	16.0
	0.10	0.6	0.3	–	–	1.4	0.9	0.9	0.7	2.3	2.0	2.0	1.3	10.5	7.7	7.9	6.1	29.0	20.5	20.6	14.7
	0.20	0.4	0.4	–	–	1.3	0.8	0.8	0.8	2.5	1.8	1.8	1.5	12.1	8.4	8.4	6.0	35.1	24.3	24.4	17.1
	0.30	0.4	0.4	–	–	0.9	0.9	0.9	0.8	2.2	1.8	1.8	1.4	13.7	9.5	9.5	6.4	42.3	27.4	28.0	18.4
	0.40	0.5	0.4	–	–	1.1	0.8	0.8	0.8	2.5	1.7	1.7	1.3	15.6	10.5	10.8	7.2	49.5	32.2	31.7	21.3
	0.50	0.3	0.3	–	–	1.2	0.8	0.8	0.6	2.8	1.7	1.7	1.1	17.5	11.5	11.5	7.7	54.1	35.6	35.7	24.2
1.0	Zero	1.6	1.0	1.0	1.0	3.5	2.5	2.5	2.0	7.0	5.0	5.0	3.5	31.0	23.0	23.0	17.0	76.0	58.0	58.0	44.0
	0.10	1.3	1.1	1.1	0.8	3.5	2.7	2.7	2.0	6.5	4.8	4.8	3.6	30.4	22.0	22.0	16.2	83.6	59.0	59.1	41.7
	0.20	1.6	1.3	1.3	0.8	3.5	2.4	2.4	1.9	6.4	4.9	4.9	3.5	37.7	25.6	25.4	17.5	110.7	74.6	74.8	51.0
	0.30	1.5	1.0	1.0	1.0	3.5	2.8	2.8	2.0	7.1	5.2	5.2	3.7	44.7	29.8	29.6	19.9	133.2	88.3	89.2	58.1
	0.40	1.1	1.0	1.1	0.9	4.0	2.6	2.6	1.9	7.7	5.4	5.5	3.8	51.0	33.6	33.7	22.2	–	102.8	102.2	67.2
	0.50	1.3	1.2	1.2	0.9	4.0	2.7	2.7	2.1	8.7	5.8	5.8	3.9	59.5	39.0	40.1	24.5	–	–	–	–
2.0	Zero	4.0	3.0	3.0	2.0	10.0	7.0	7.5	5.5	18.5	13.5	13.5	10.0	85.0	63.0	63.0	46.5	208.0	156.0	156.0	116.0
	0.10	3.8	2.7	2.7	2.3	9.4	6.9	7.2	5.0	17.5	13.0	13.0	9.5	90.3	62.7	62.9	44.6	256.3	174.4	174.9	120.6
	0.20	3.8	3.0	3.0	2.2	9.7	7.0	7.1	5.0	19.6	13.5	13.5	9.6	118.9	78.4	78.6	52.7	346.1	229.3	230.0	153.6
	0.30	3.9	2.8	2.8	2.2	10.5	7.2	7.2	5.1	22.2	14.8	14.8	10.2	141.7	93.5	93.8	61.7	–	–	–	182.5
	0.40	4.2	2.9	2.9	1.9	11.7	7.8	7.8	5.3	25.0	16.5	16.5	11.0	–	107.3	108.3	70.0	–	–	–	–
	0.50	4.5	3.0	3.0	2.1	12.8	8.5	8.6	5.7	27.4	18.3	18.4	11.8	–	–	–	–	–	–	–	–
3.0	Zero	7.0	5.0	5.5	4.0	17.5	13.0	13.0	9.5	33.5	24.5	24.5	17.5	153.5	113.5	113.5	83.5	374.0	280.0	280.0	208.0
	0.10	6.9	5.0	5.0	3.9	16.7	12.3	12.3	9.0	31.9	23.2	23.2	17.1	173.7	117.6	117.9	82.0	490.0	331.0	332.0	225.0
	0.20	7.6	5.0	5.0	3.7	18.0	12.7	12.5	9.0	37.0	25.0	25.3	17.6	228.3	151.5	153.0	100.8	–	448.8	450.2	295.3
	0.30	7.2	5.1	5.1	3.7	20.2	13.7	13.7	9.4	43.0	28.6	28.6	19.2	276.5	183.1	183.7	120.3	–	–	–	355.1
	0.40	7.7	5.5	5.5	3.6	22.4	15.0	15.0	10.0	48.7	32.0	32.2	20.9	–	–	–	144.7	–	–	–	–
	0.50	8.4	5.6	5.6	4.0	24.8	16.2	16.3	10.4	54.0	35.3	35.5	23.3	–	–	–	–	–	–	–	–
4.0	Zero	11.0	8.0	8.0	5.6	26.5	19.5	19.5	14.0	50.5	37.0	37.0	27.0	232.5	172.0	172.5	126.5	566.0	422.0	422.0	314.0
	0.10	10.5	7.6	7.6	5.9	25.4	18.5	18.6	13.5	48.8	35.2	35.2	25.9	272.7	186.4	187.0	129.8	777.3	523.0	524.6	354.1
	0.20	10.5	7.5	7.6	5.5	28.2	19.4	19.4	13.7	58.7	39.5	39.5	27.1	367.2	242.7	243.7	161.6	1066	706.6	708.9	470.9
	0.30	11.3	8.0	8.0	5.5	32.2	21.5	21.5	14.6	–	45.7	45.9	30.0	–	–	–	–	–	–	–	–
	0.40	12.3	8.1	8.3	5.7	36.3	23.7	23.8	15.9	–	51.2	51.3	33.8	–	–	–	–	–	–	–	–
	0.50	13.3	8.7	8.7	5.9	39.9	26.1	25.9	17.1	–	–	–	36.9	–	–	–	–	–	–	–	–
5.0	Zero	15.0	11.0	11.0	7.5	37.0	26.5	27.0	19.5	69.5	51.0	51.0	37.0	320.5	237.0	237.5	174.5	776.0	580.0	587	435.0
	0.10	14.4	10.4	10.4	8.1	34.9	25.5	25.5	18.7	68.2	48.5	48.6	35.2	387.6	263.4	264.1	181.5	1108	742.3	–	–
	0.20	14.8	10.3	10.6	7.4	39.8	27.0	27.0	18.9	83.7	55.8	56.0	38.1	–	345.9	347.0	230.6	1533	1014	–	–
	0.30	15.8	10.9	10.9	7.6	46.0	30.5	30.6	20.3	99.1	65.1	65.3	43.1	–	–	–	275.9	–	–	–	–
	0.40	17.6	11.8	11.8	7.9	52.9	33.9	34.3	22.4	–	70.0	–	48.1	–	–	–	–	–	–	–	–
	0.50	19.2	12.7	12.7	8.3	–	–	37.6	24.3	–	–	–	–	–	–	–	–	–	–	–	–

TABLE 4

Outlet spacings for zero longitudinal gradient derived from simplified formula:– $J_o = 545 \left(\frac{N^3}{IW} \right)^{\frac{3}{4}} C^{23/16}$

Rainfall intensity	Cross-fall	Drain outlet spacing (metres) to limit maximum flow width to																			
		0.5m When road width (m) is				0.75m When road width (m) is				1.0m When road width (m) is				2.0m When road width (m) is				3.0m When road width (m) is			
mm/h	Per cent	5.43	9.3	11.7	14.0	5.43	9.30	11.7	14.0	5.43	9.3	11.7	14.0	5.43	9.3	11.7	14.0	5.43	9.3	11.7	14.0
38.1	0.5	0.8	0.5	0.4	0.4	2.0	1.3	1.1	1.0	3.6	2.5	2.1	1.8	17.5	11.7	9.9	8.7	43.7	29.3	24.5	21.5
	1.0	2.1	1.4	1.2	1.0	5.2	3.4	3.0	2.6	10.0	6.7	5.6	4.9	47.5	31.8	26.7	23.4	118	79	67	58
	1.5	3.7	2.6	2.1	1.9	9.4	6.3	5.2	4.6	17.9	11.9	10.0	8.8	85	57	47.9	41.9	212	142	119	104
	2.0	5.7	3.8	3.2	2.8	14.2	9.5	8.0	7.0	27.1	18.1	15.2	13.3	129	86	72	63	320	214	180	157
	2.5	7.9	5.2	4.4	3.8	19.5	13.0	10.9	9.6	37.3	24.9	21.0	18.3	177	119	100	87	442	295	248	217
	3.0	10.2	6.8	5.7	5.0	25.3	17.0	14.3	12.5	48.5	32.4	27.3	23.8	231	154	130	113	574	384	323	282
	4.0	15.4	10.3	8.7	7.6	38.3	25.6	21.6	18.8	73	49.0	41.2	36.1	349	233	196	171	868	580	488	427
	5.0	21.3	14.2	11.9	10.4	52.9	35.4	29.8	26.0	101	67	57	49.7	480	321	270	236	1196	799	673	588
44.5	0.5	0.7	0.5	0.4	0.3	1.7	1.2	1.0	0.9	3.3	2.2	1.9	1.6	15.6	10.4	8.8	7.7	38.9	26.0	21.9	19.1
	1.0	1.9	1.3	1.1	0.9	4.6	3.2	2.7	2.3	8.9	5.9	5.0	4.3	42.3	28.3	23.8	20.8	105	70	59	52
	1.5	3.4	2.3	1.9	1.7	8.4	5.6	4.7	4.1	16.0	10.6	9.0	7.8	76	51	42.7	37.3	189	126	106	93
	2.0	5.0	3.4	2.9	2.5	12.6	8.4	7.1	6.2	24.0	16.1	13.5	11.8	115	76	64	56	285	191	160	140
	2.5	7.0	4.6	3.9	3.5	17.3	11.6	9.8	8.6	33.2	22.2	18.6	16.4	158	105	89	78	393	263	221	193
	3.0	9.1	6.0	5.1	4.4	22.6	15.1	12.7	11.1	43.2	28.8	24.2	21.2	205	137	115	101	511	341	287	251
	4.0	13.7	9.2	7.7	6.7	34.2	22.8	19.2	16.8	65	43.6	36.7	32.0	310	207	174	153	773	516	435	380
	5.0	18.9	12.6	10.6	9.3	47.1	31.4	26.5	23.2	90	60	51	44.2	428	286	240	210	1065	711	599	523
51.0	0.5	0.6	0.4	0.4	0.3	1.6	1.0	0.9	0.8	3.0	2.0	1.7	1.5	14.1	9.5	7.9	6.9	35.1	23.5	19.7	17.2
	1.0	1.7	1.1	1.0	0.8	4.2	2.8	2.4	2.1	8.0	5.3	4.5	3.9	38.1	25.5	21.5	18.7	95	63	54	46.7
	1.5	3.1	2.0	1.7	1.5	7.5	5.0	4.2	3.7	14.4	9.6	8.1	7.1	68	45.7	38.4	33.6	170	114	96	84
	2.0	4.5	3.1	2.6	2.3	11.3	7.6	6.4	5.6	21.8	14.5	12.2	10.6	103	69	58	51	258	172	145	127
	2.5	6.3	4.2	3.5	3.1	15.7	10.4	8.9	7.7	30.0	20.0	16.9	14.7	143	95	80	70	355	237	200	174
	3.0	8.2	5.5	4.6	4.0	20.4	13.6	11.4	10.1	38.9	26.0	21.9	19.1	185	124	104	91	461	308	259	227
	4.0	12.4	8.3	7.0	6.1	30.8	20.6	17.3	15.2	59	39.3	33.1	29.0	280	187	157	138	698	466	392	343
	5.0	17.0	11.4	9.6	8.4	42.5	28.4	23.8	20.9	81	54	45.6	39.9	386	258	217	190	961	642	541	473
57.0	0.5	0.6	0.4	0.3	0.3	1.4	1.0	0.8	0.7	2.8	1.8	1.6	1.4	13.0	8.7	7.3	6.4	32.3	21.6	18.1	15.9
	1.0	1.6	1.0	0.9	0.8	3.8	2.6	2.2	1.9	7.4	4.9	4.1	3.6	35.1	23.5	19.7	17.2	87	58	49.2	43.0
	1.5	2.8	1.9	1.6	1.4	6.9	4.6	3.9	3.4	13.2	8.9	7.4	6.5	63	42.0	35.4	30.9	157	105	88	77
	2.0	4.2	2.9	2.4	2.1	10.4	7.0	5.9	5.1	20.0	13.4	11.2	9.9	95	64	54	46.8	237	158	133	116
	2.5	5.8	3.8	3.3	2.9	14.4	9.7	8.1	7.1	27.6	18.4	15.5	13.5	131	88	74	64	327	218	184	160
	3.0	7.5	5.0	4.2	3.7	18.7	12.5	10.5	9.3	35.9	23.9	20.1	17.6	170	114	96	84	424	283	239	209
	4.0	11.4	7.6	6.4	5.6	28.4	18.9	16.0	13.9	54	36.2	30.5	26.6	258	172	145	127	642	429	361	315
	5.0	15.7	10.4	8.9	7.7	39.1	26.1	22.0	19.2	75	50	42.0	36.7	355	237	200	175	885	591	497	435

TABLE 5

Multiplication factor (R) to obtain outlet spacings at specified gradients and crossfalls

Note:– *the factors below apply to a rainfall intensity of 38.1 mm/h and a road width of 14.0 metres.*

Flow width m	Longitudinal gradient Per cent	Factors appropriate to a crossfall (per cent) of							
		0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0
0.5	0.05	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	0.10	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.01
	0.20	1.00	1.01	1.01	1.01	1.02	1.02	1.03	1.04
	0.30	1.01	1.02	1.02	1.03	1.04	1.05	1.06	1.07
	0.40	1.02	1.03	1.05	1.06	1.07	1.09	1.11	1.12
	0.50	1.03	1.05	1.07	1.10	1.12	1.13	1.16	1.17
0.75	0.05	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01
	0.10	1.00	1.00	1.00	1.01	1.01	1.01	1.02	1.02
	0.20	1.01	1.01	1.02	1.03	1.04	1.05	1.06	1.08
	0.30	1.02	1.03	1.05	1.07	1.08	1.10	1.12	1.15
	0.40	1.04	1.06	1.09	1.12	1.15	1.18	1.21	1.24
	0.50	1.06	1.10	1.15	1.19	1.23	1.27	1.32	1.35
1.0	0.05	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.01
	0.10	1.00	1.00	1.01	1.01	1.02	1.02	1.03	1.04
	0.20	1.01	1.02	1.04	1.05	1.06	1.08	1.10	1.13
	0.30	1.03	1.06	1.08	1.11	1.14	1.17	1.21	1.25
	0.40	1.06	1.10	1.16	1.20	1.25	1.29	1.35	1.40
	0.50	1.10	1.17	1.25	1.32	1.39	1.45	1.53	1.58
2.0	0.05	1.00	1.00	1.01	1.01	1.01	1.02	1.03	1.04
	0.10	1.01	1.02	1.03	1.04	1.05	1.07	1.10	1.13
	0.20	1.04	1.08	1.12	1.16	1.21	1.26	1.34	1.43
	0.30	1.11	1.19	1.28	1.38	1.47	1.56	1.71	1.84
	0.40	1.21	1.35	1.52	1.68	1.84	1.98	2.19	2.35
	0.50	1.34	1.58	1.84	2.08	2.31	2.51	2.78	2.96
3.0	0.05	1.00	1.00	1.01	1.02	1.03	1.03	1.05	1.09
	0.10	1.02	1.03	1.05	1.08	1.11	1.14	1.20	1.27
	0.20	1.09	1.16	1.24	1.34	1.42	1.53	1.70	1.87
	0.30	1.22	1.38	1.57	1.77	1.96	2.14	2.44	2.70
	0.40	1.42	1.72	2.06	2.39	2.71	3.00	3.42	3.75
	0.50	1.68	2.17	2.70	3.19	3.67	4.07	4.61	4.98

TABLE 6

Adjustment of multiplication factors to other rainfalls and road widths

The ratio (R) given above in Table 5 can be adjusted to any other rainfall (I) or road width (W) by multiplying (R–1) by $(38.1\mathrm{x}14.0=533.4)/(IW)^{\frac{7}{8}}$. Values of this adjusting factor are given below for the rainfalls and road widths considered in this report.

Rainfall intensity	Adjustment factor, F, when road width (in metres) is			
mm/h	5.43	9.30	11.70	14.0
38.1	2.290	1.430	1.170	1.000
44.5	1.999	1.249	1.021	0.873
51.0	1.775	1.108	0.907	0.896
57.0	1.610	1.005	0.822	0.703

TABLE 7

Capacity of drain outlets

Outlet spacing	Outlet capacity in litres per second for a rainfall intensity of															
	38.1 mm/h and a road width (metres) of				44.5 mm/h and a road width (metres) of				51 mm/h and a road width (metres) of				57 mm/h and a road width (metres) of			
metres	5.43	9.30	11.70	14.0	5.43	9.30	11.70	14.0	5.43	9.30	11.70	14.0	5.43	9.30	11.70	14.0
10	0.57	0.98	1.24	1.48	0.67	1.15	1.45	1.73	0.77	1.32	1.66	1.98	0.86	1.47	1.85	2.22
20	1.15	1.97	2.48	2.96	1.34	2.30	2.89	3.46	1.54	2.64	3.32	3.97	1.72	2.95	3.71	4.43
30	1.72	2.95	3.71	4.44	2.01	3.45	4.34	5.19	2.31	3.95	4.97	5.95	2.58	4.42	5.56	6.65
40	2.30	3.94	4.95	5.92	2.68	4.60	5.79	6.92	3.08	5.27	6.63	7.93	3.44	5.89	7.41	8.87
50	2.87	4.92	6.19	7.40	3.36	5.75	7.23	8.65	3.85	6.59	8.29	9.92	4.30	7.36	9.26	11.1
60	3.45	5.91	7.43	8.89	4.03	6.90	8.68	10.4	4.62	7.91	9.95	11.9	5.16	8.84	11.1	13.3
80	4.60	7.87	9.91	11.9	5.37	9.20	11.6	13.8	6.15	10.5	13.3	15.9	6.88	11.8	14.8	17.7
100	5.75	9.84	12.4	14.8	6.71	11.5	14.5	17.3	7.69	13.2	16.6	19.8	8.60	14.7	18.5	22.2
200	11.5	19.7	24.8	19.6	13.4	23.0	28.9	34.6	15.4	26.4	33.2	39.7	17.2	29.5	37.1	44.3
300	17.2	29.5	37.1	44.4	20.1	34.5	43.4	51.9	23.1	39.5	49.7	59.5	25.8	44.2	55.6	66.5
400	23.0	39.4	49.5	59.3	26.8	46.0	57.9	69.2	30.8	52.7	66.3	79.3	34.4	58.9	74.1	88.7
500	28.7	49.2	61.9	74.1	33.6	57.5	72.3	86.5	38.5	65.9	82.9	99.2	43.0	73.6	92.6	111
600	34.5	59.1	74.3	89.0	40.3	69.0	86.8	104	46.2	79.1	99.5	119	51.6	88.4	111.1	133
700	40.2	68.9	86.7	104	47.0	80.5	101	121	53.8	92.2	116	139	60.2	103	130	155
800	46.0	78.7	99.1	119	53.7	92.0	116	138	61.5	105.4	133	159	68.8	118	148	177
900	51.7	88.6	111	133	60.4	103	130	156	69.2	118.6	149	178	77.4	133	167	200
1000	57.5	98.4	124	148	67.1	115	145	173	76.9	132	166	198	86.0	147	185	222
1200	69.0	118	149	178	80.5	138	174	208	92.3	158	199	238	103	177	222	266
1400	80.5	138	173	207	94.0	161	202	242	108	184	232	278	120	206	259	310
1600	91.9	157	198	237	107	184	231	277	123	211	265	317	138	236	296	355

Engineers may wish to know that 28.317 litres per second = 1 cubic foot per second (1 cusec).

TABLE 8

Outlet capacities needed for trapezoidal drainage channel

Dimensions of trapezoidal drainage channel				Outlets to deal with a rainfall intensity (mm/h) of 38			44.5			51			57		
Width of base		Vertical depth		Spacing	Capacity		Spacing	Capacity		Spacing	Capacity		Spacing	Capacity	
mm	in	mm	in	m	litres per sec.	Cusecs	m	litres per sec.	Cusecs	m	litres per sec.	Cusecs	m	litres per sec.	Cusecs
102	4	76	3.0	53	7.8	0.28	47	8.1	0.29	43	8.5	0.30	39	8.6	0.31
		89	3.5	69	10.2	0.36	61	10.6	0.37	55	10.9	0.39	51	11.3	0.40
		102	4.0	87	12.9	0.45	78	13.5	0.48	70	13.9	0.49	64	14.2	0.50
		114	4.5	108	16.0	0.56	96	16.6	0.59	86	17.1	0.60	79	17.5	0.62
		127	5.0	130	19.2	0.68	116	20.1	0.71	104	20.6	0.73	95	21.1	0.74
		152	6.0	182	26.9	0.95	161	27.9	0.98	146	29.0	1.02	133	29.5	1.04
203	8	76	3.0	77	11.4	0.40	68	11.8	0.42	62	12.3	0.43	56	12.4	0.44
		89	3.5	98	14.5	0.51	87	15.1	0.53	78	15.5	0.55	72	16.0	0.56
		102	4.0	121	17.9	0.63	107	18.5	0.65	97	19.2	0.68	89	19.7	0.70
		114	4.5	146	21.6	0.76	130	22.5	0.79	117	23.2	0.82	107	23.7	0.84
		127	5.0	174	25.7	0.91	155	26.8	0.95	139	27.6	0.97	127	28.2	0.99
		152	6.0	236	34.9	1.23	210	36.3	1.28	189	37.5	1.33	173	38.3	1.35
305	12	76	3.0	100	14.8	0.52	89	15.4	0.54	80	15.9	0.56	73	16.2	0.57
		89	3.5	126	18.6	0.60	112	19.4	0.68	101	20.0	0.71	92	20.4	0.72
		102	4.0	154	22.8	0.80	137	23.7	0.84	123	24.4	0.86	113	25.0	0.88
		114	4.5	184	27.2	0.96	164	28.4	1.00	148	29.4	1.04	135	29.9	1.06
		127	5.0	217	32.1	1.13	193	33.4	1.18	174	34.5	1.22	159	35.2	1.24
		152	6.0	290	42.9	1.51	257	44.5	1.57	232	46.0	1.62	212	47.0	1.66

TABLE 9

Flow along kerbed hard shoulder – Check on quality of fit of empirical formula

Flow width	Comparison of values calculated for all crossfalls by formula and by computer programme		Comparison of values calculated for 0.5 per cent crossfall by formula and by computer programme		Comparison of values omitting those obtained for 0.5 per cent crossfall	
	Number of pairs of results	Standard deviation	Number of pairs of results	Standard deviation	Number of pairs of results	Standard deviation
metres		Per cent		Per cent		Per cent
0.5	848	9.2	Values derived from computer programme not entirely satisfactory		–	–
0.75	880	7.1	112	14.8	768	4.2
1.0	831	7.7	112	9.8	719	7.1
2.0	695	4.5	112	5.2	583	4.1
3.0	571	6.4	112	7.3	459	6.1
All flow widths taken together	3825	7.3	448	10.1	3377	6.7

TABLE 10

Spacing derived from LR 277

Rainfall intensity (I) in mm/h	Outlet spacing in metres to restrict flow width (metres) to 0.5	0.75	1.0
38	8.18	22.32	46.16
44.5	7.01	19.11	39.52
51	6.11	16.67	34.48
57	5.47	14.92	30.85

Table 10 shows good agreement between the two sets of ratios.

TABLE 11

Values of "B" and "w" needed for empirical formula to calculate spacing

Crossfall – per cent	Coefficient B	Inded w
0.5	117	2.26
1.0	190	2.19
1.5	265	2.125
2.0	326	2.06
2.5	380	1.995
3.0	416	1.93
4.0	448	1.80
5.0	448	1.67

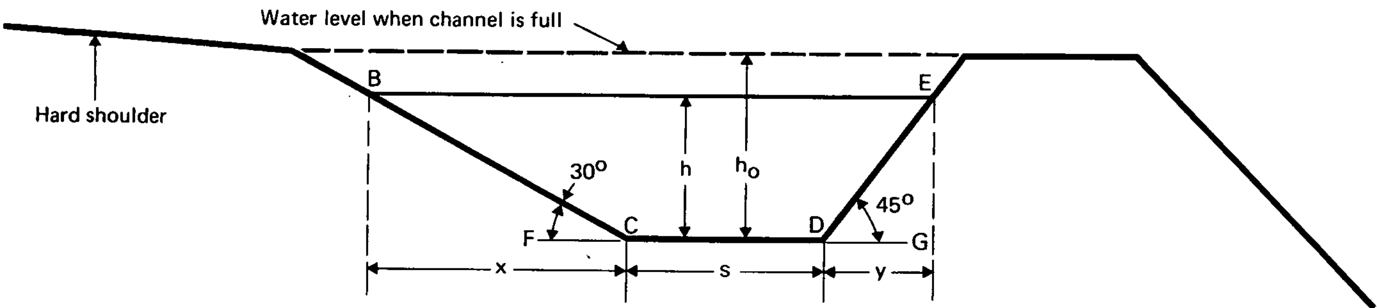


Fig.1(a) CROSS-SECTION OF TRAPEZOIDAL CHANNEL

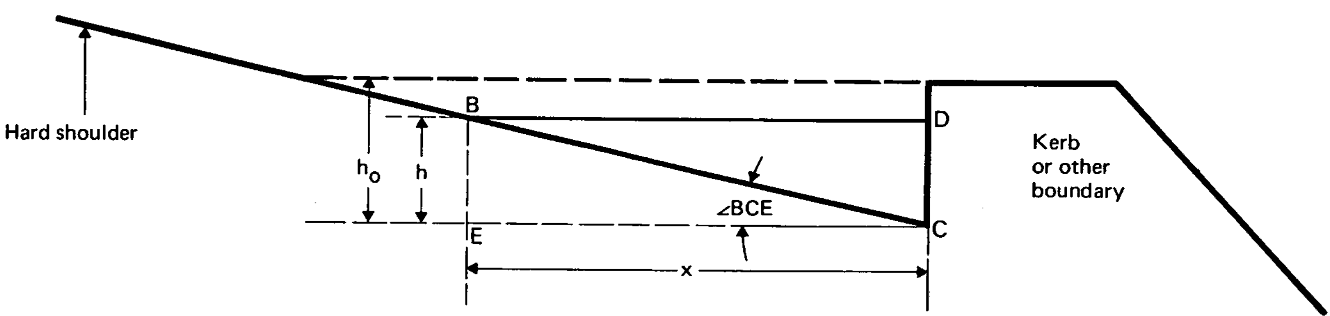
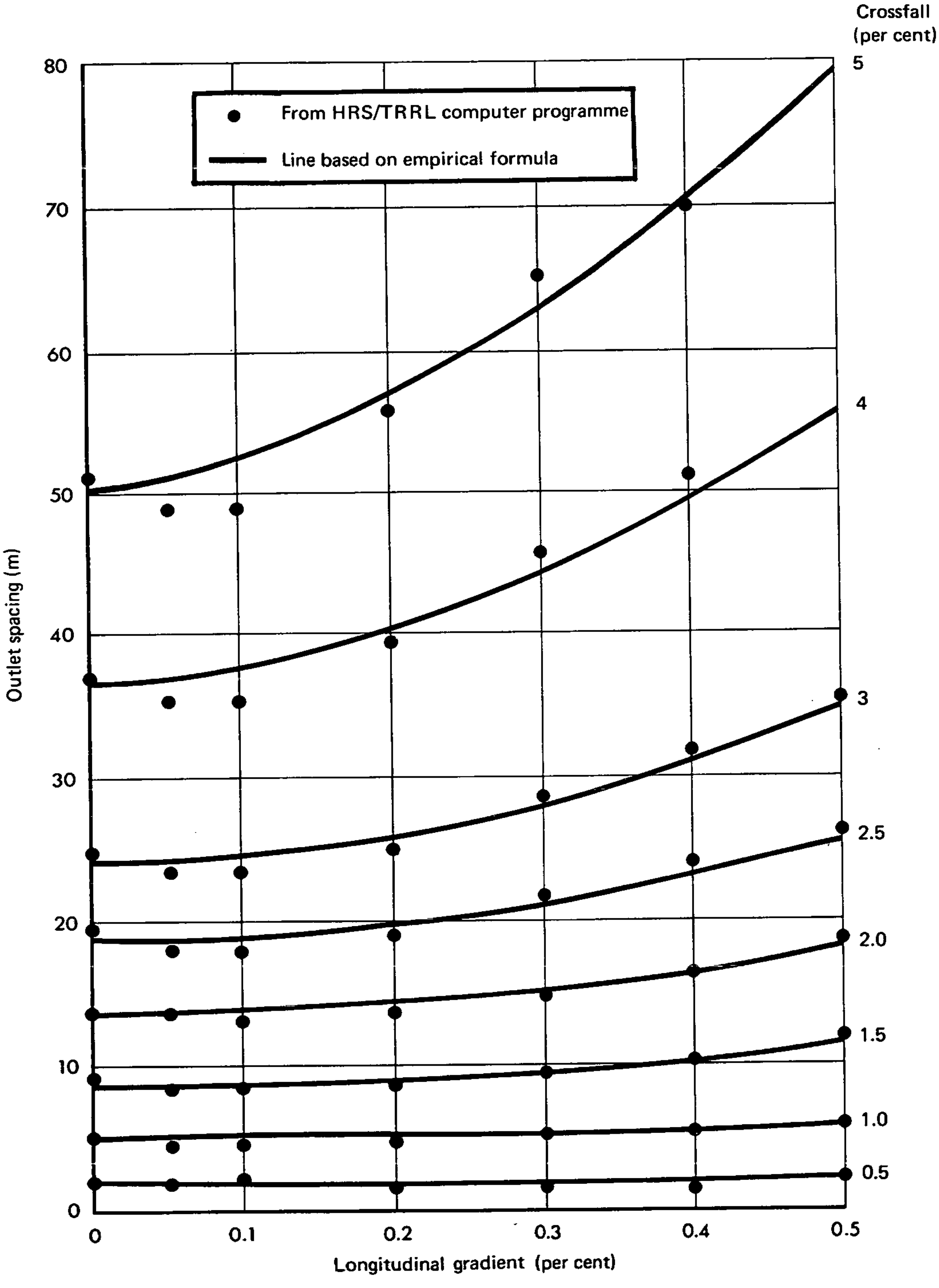


Fig.1(b). LONGITUDINAL CHANNEL FORMED BY HARD SHOULDER AND KERB



Road width = 14.0 m Flow width = 1.0 m Rainfall intensity = 38.1 mm/h

Fig.2. TYPICAL RESULTS SHOWING RELATION BETWEEN OUTLET SPACING, LONGITUDINAL GRADIENT AND CROSSFALL

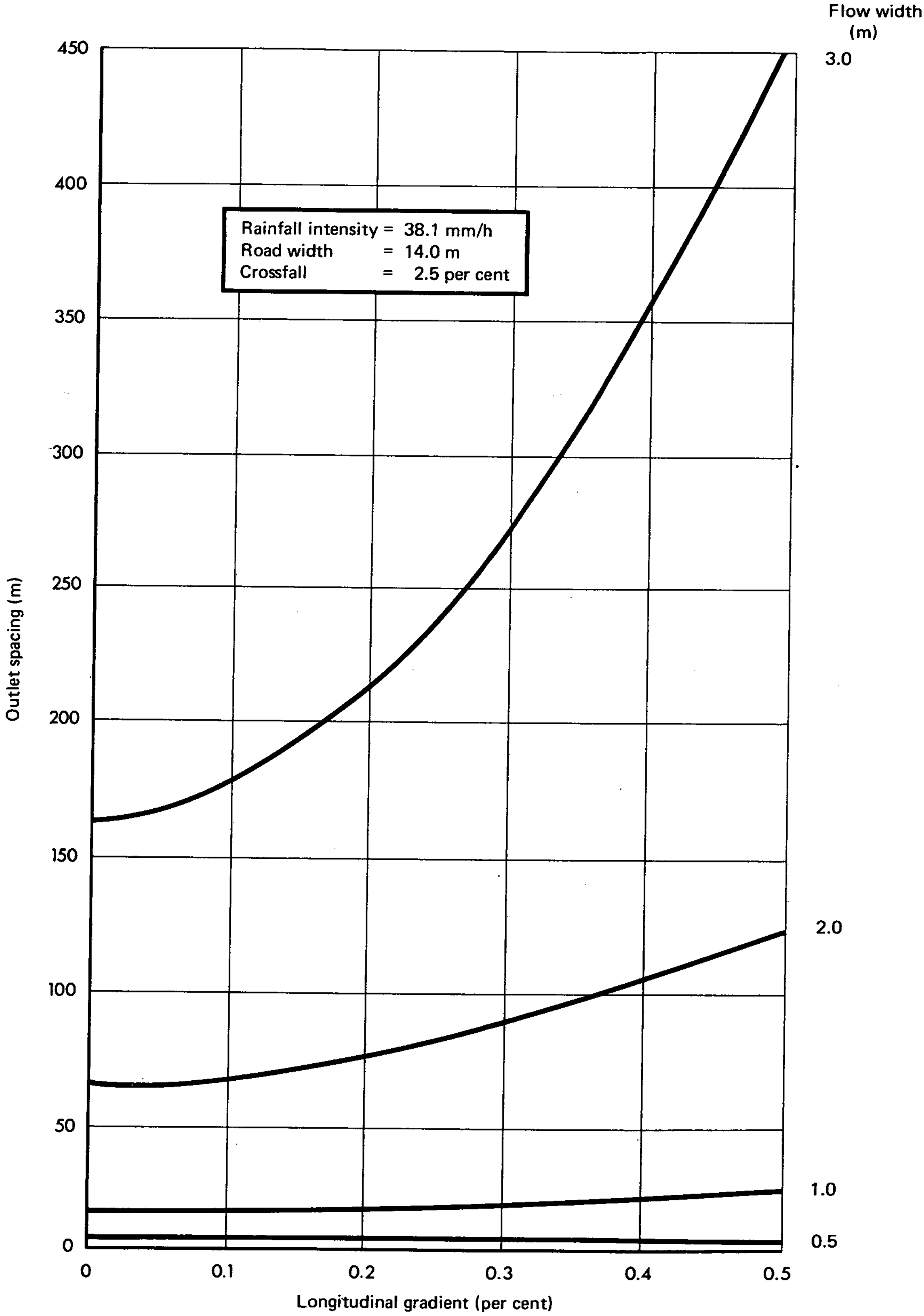


Fig.3. EFFECT OF FLOW WIDTH ON RELATION BETWEEN OUTLET SPACING AND LONGITUDINAL GRADIENT

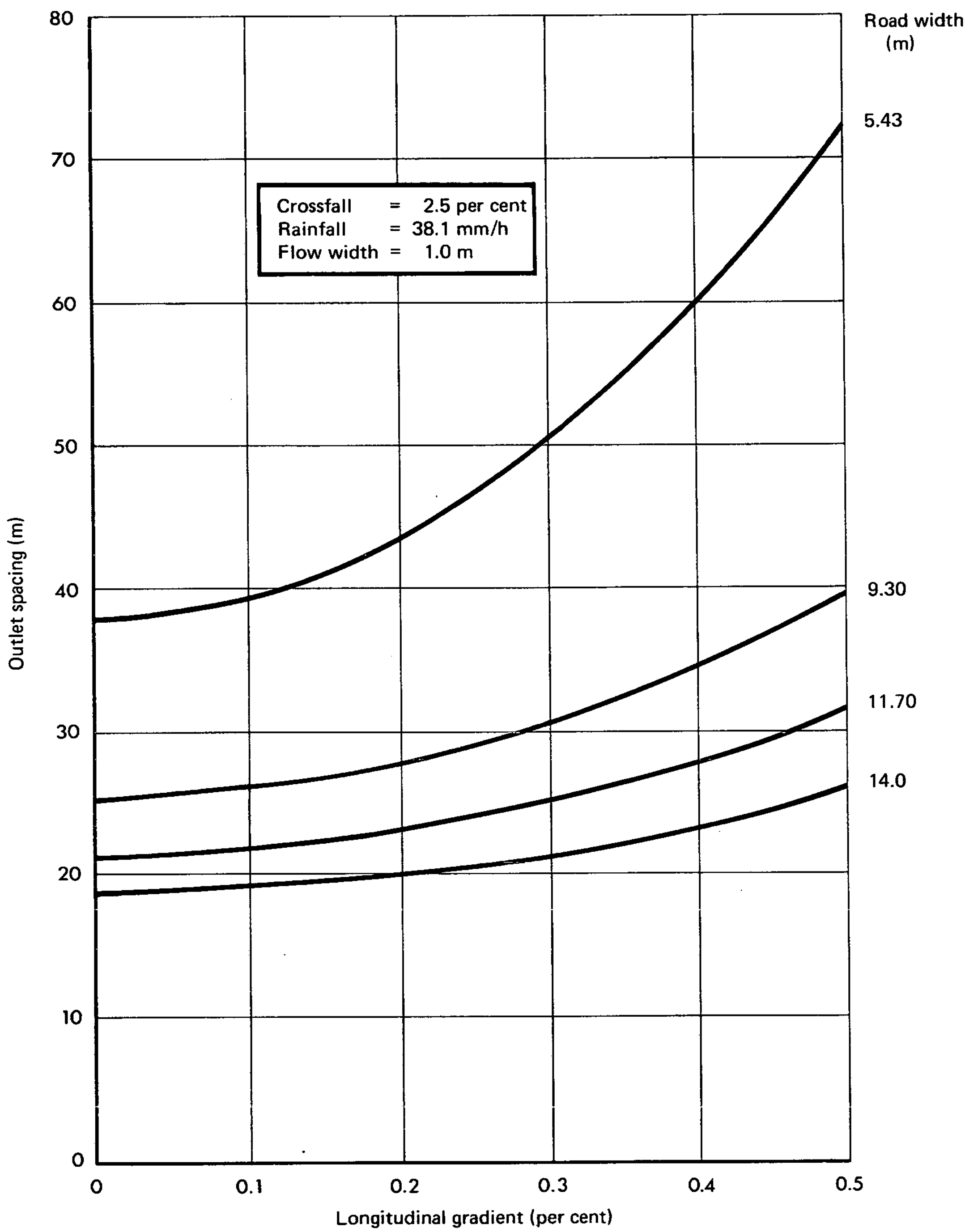


Fig.4. EFFECT OF ROAD WIDTH ON RELATION BETWEEN OUTLET SPACING AND LONGITUDINAL GRADIENT

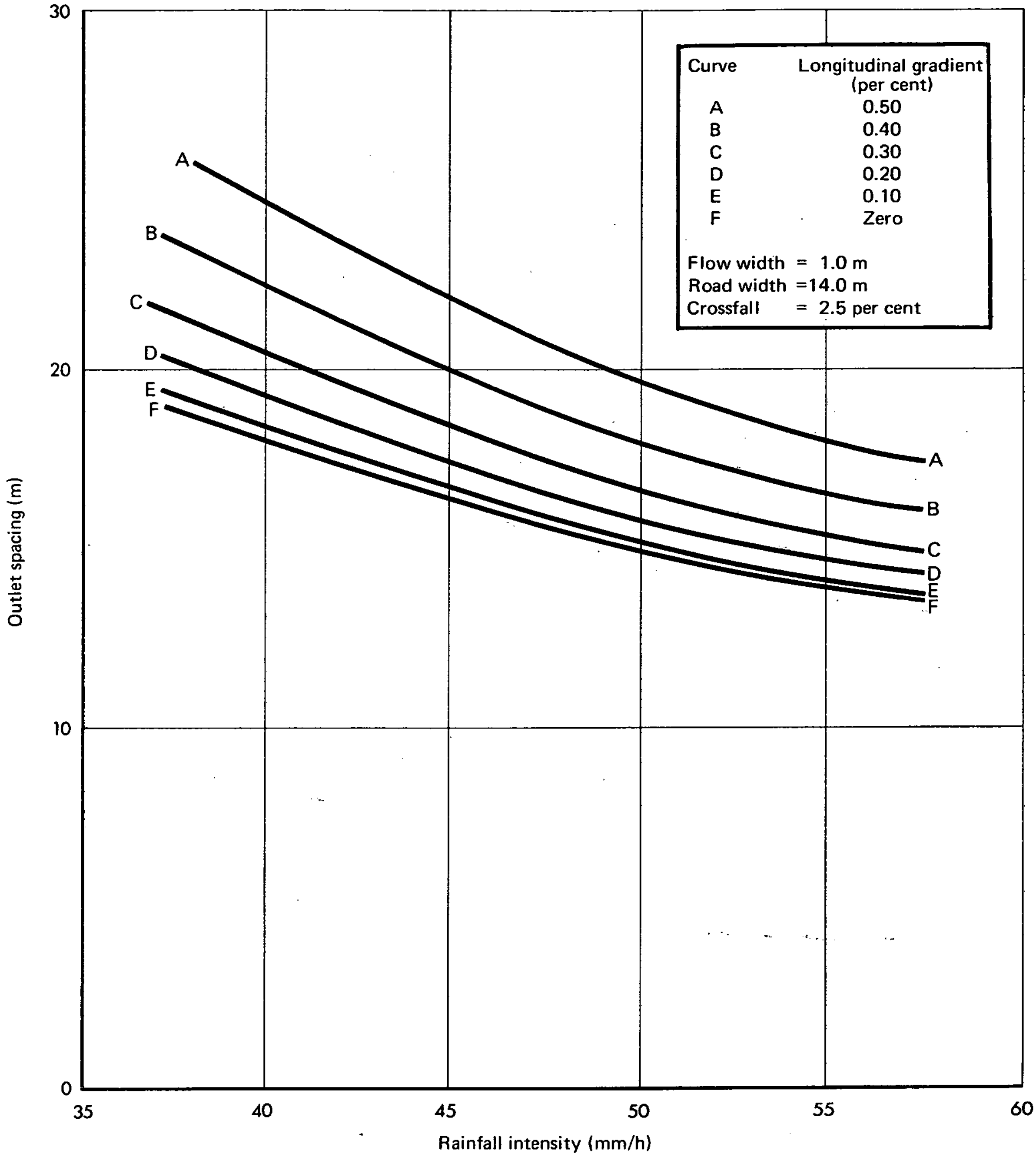


Fig. 5. TYPICAL RELATION BETWEEN OUTLET SPACING AND RAINFALL INTENSITY

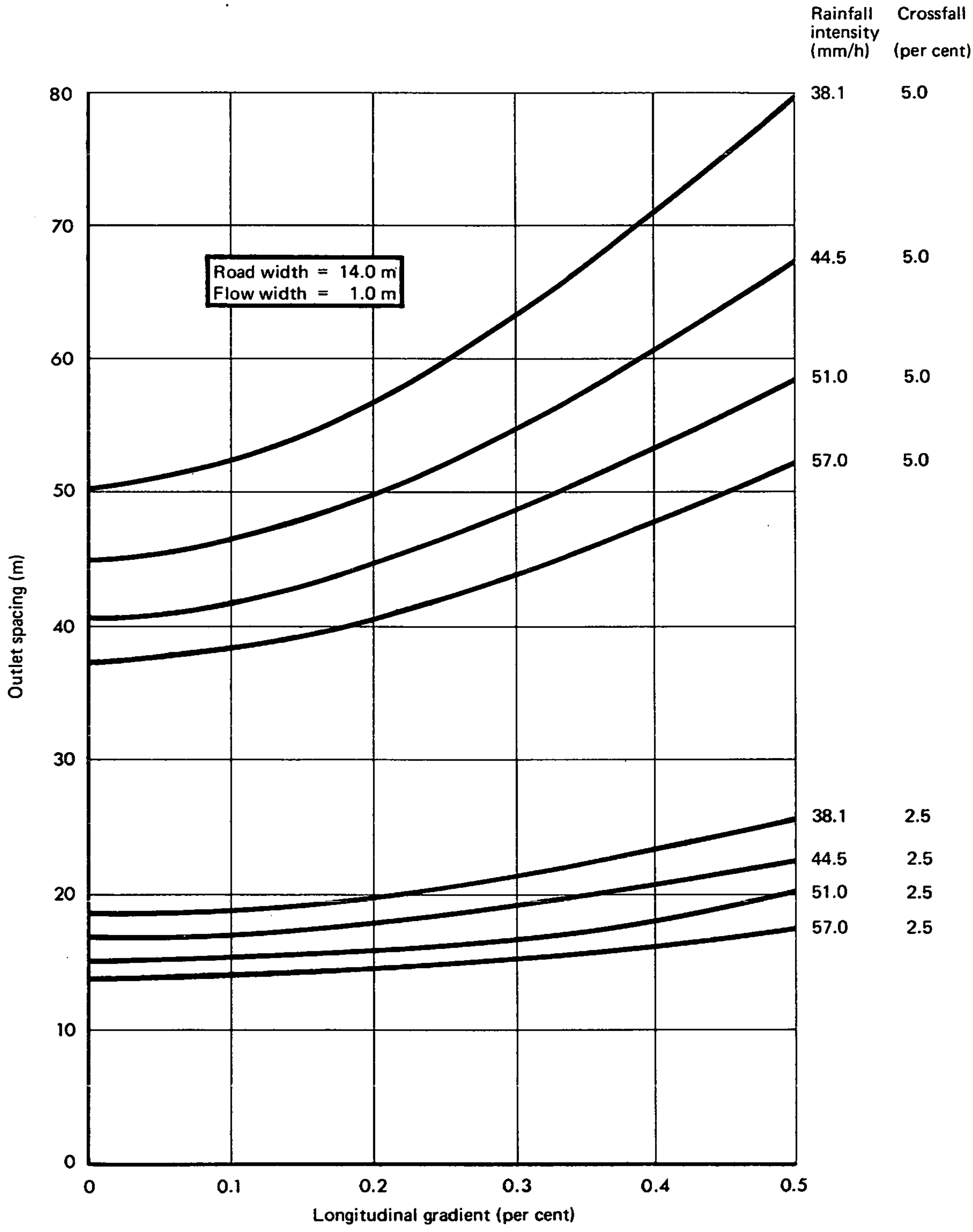
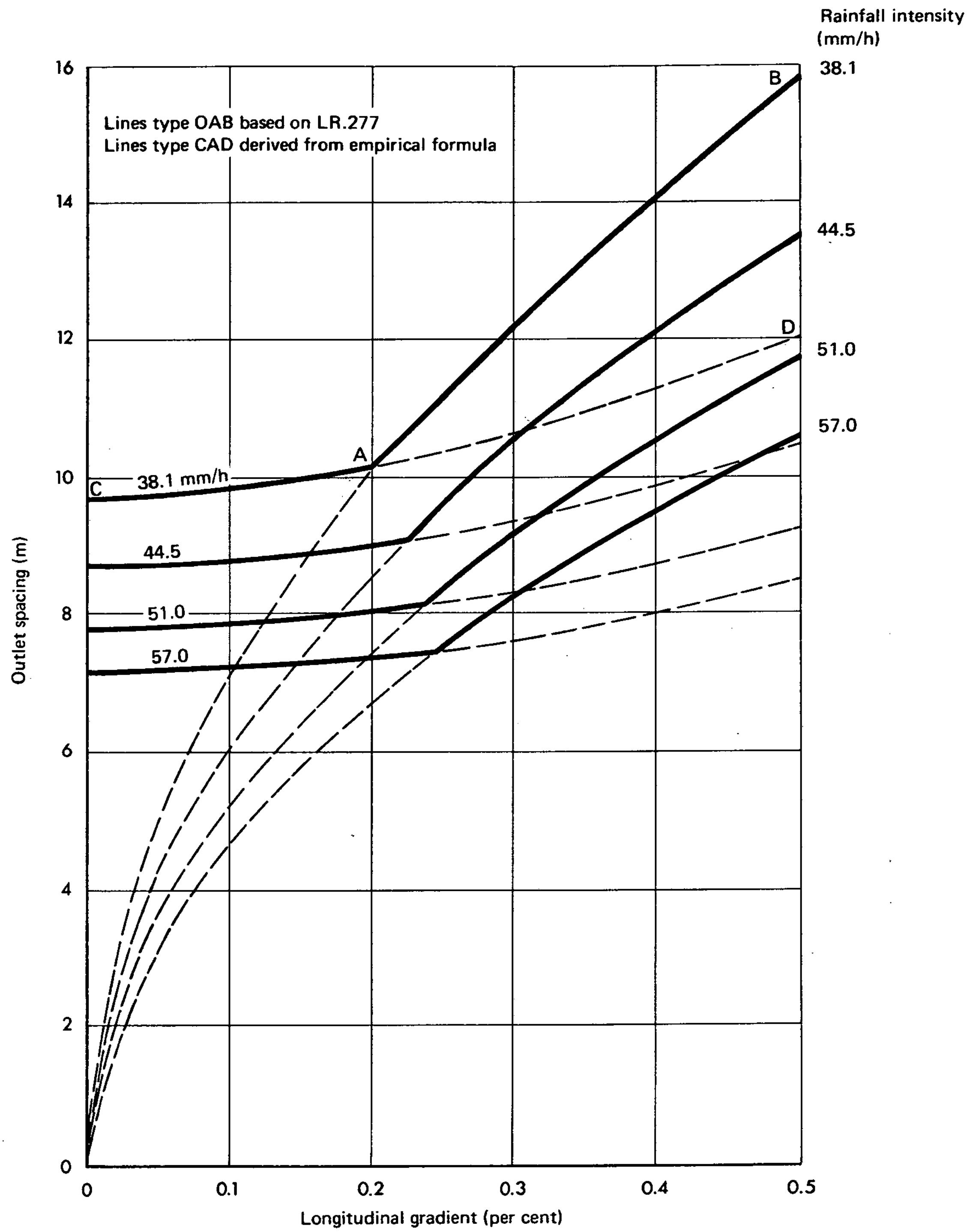
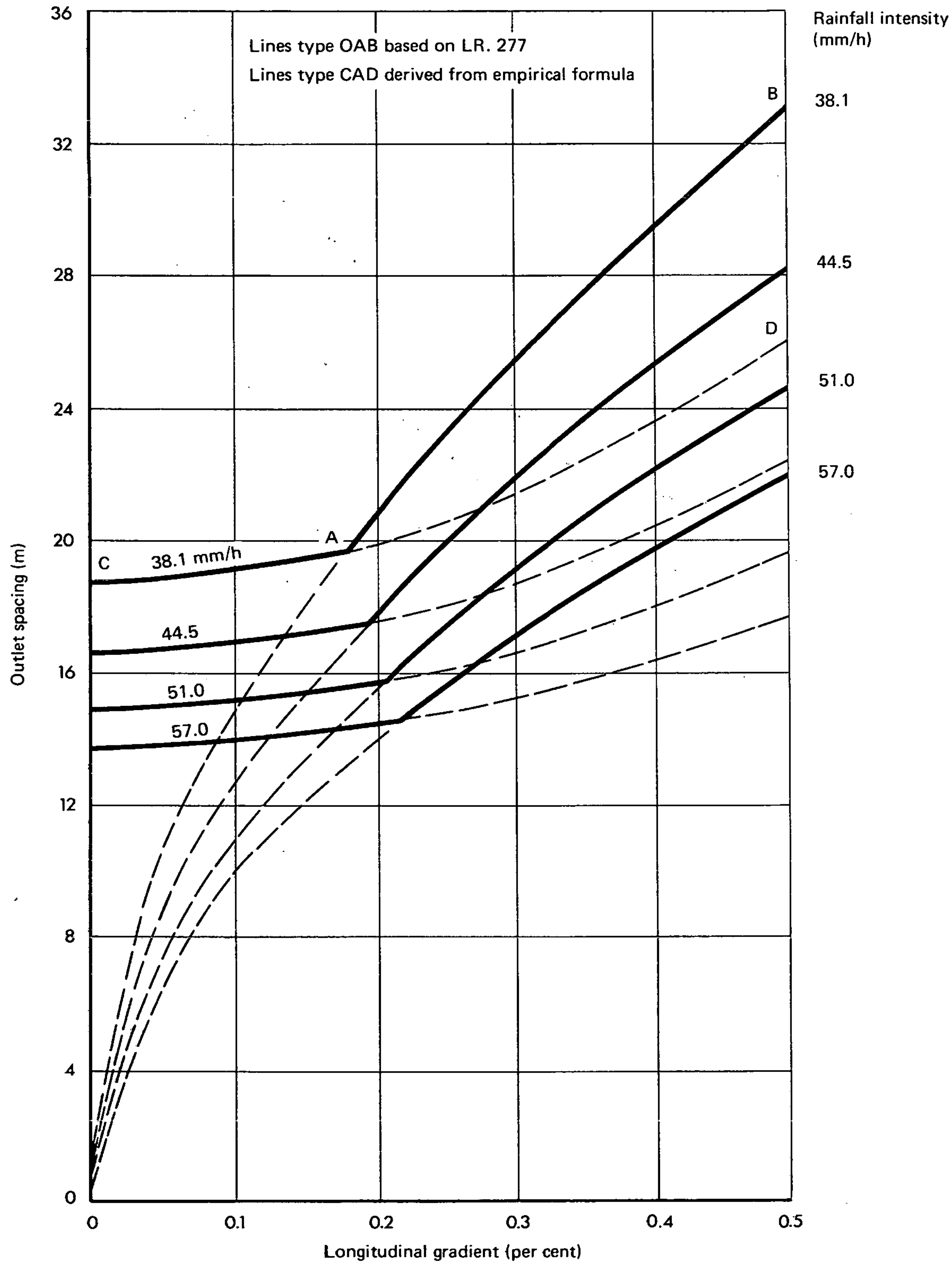


Fig.6. TYPICAL CURVES SHOWING RELATION BETWEEN OUTLET SPACING, LONGITUDINAL GRADIENT, RAINFALL INTENSITY AND CROSSFALL



Flow width = 0.75 m   Road width = 14.0 m   Crossfall = 2.5 per cent

Fig.7. OUTLET SPACINGS TO RESTRICT FLOW WIDTH TO 0.75m AT A CROSSFALL OF 2.5 per cent – COMPARISON WITH LABORATORY REPORT LR.277



Flow width = 1.0 m. Road width = 14.0 m Crossfall = 2.5 per cent

Fig.8. OUTLET SPACINGS TO RESTRICT FLOW WIDTH TO 1.0m AT A CROSSFALL OF 2.5 per cent – COMPARISON WITH LABORATORY REPORT LR.277

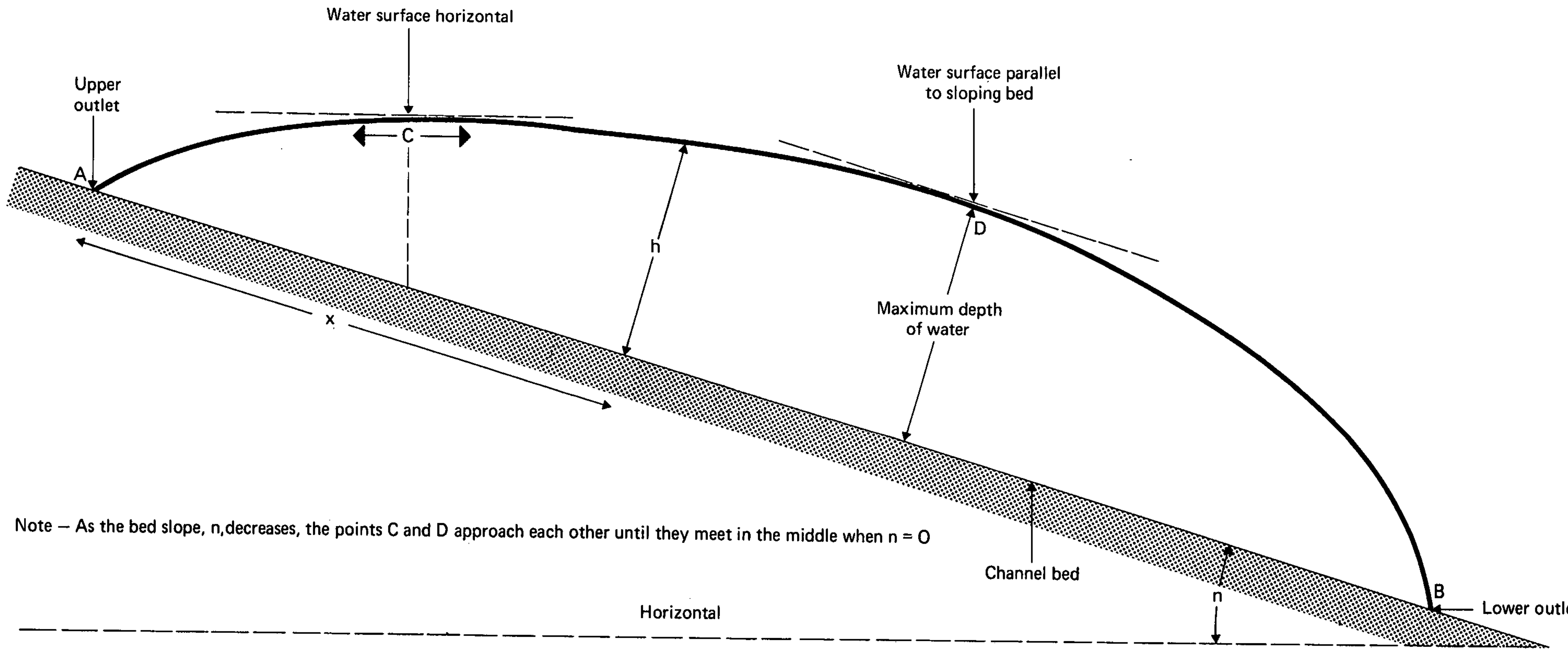


Fig.9. SURFACE PROFILE OF WATER

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ABSTRACT

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1. a channel of constant depth along the lower edge with outlets at regular intervals and

2. a channel formed by a raised kerb again with outlets at regular intervals.

The results in the report are based mainly on theoretical considerations though these are co-ordinated with practical measurements. They apply mainly to level or nearly level roads and supplement the results given in an earlier report LR 277 "The hydraulic efficiency and spacing of road gulleys".

The theoretical equations are comparatively complex and not suitable for use in design offices and so the results have been analysed statistically to give a simpler formula. Tables are provided which give the solutions of this latter formula for a wide variety of conditions.

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