THE UNIVERSITY OF NEW SOUTH WALES

WATER RESEARCH LABORATORY

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Notes on the Design

of

Culverts with Outlet Scour Control

by

H. R. Vallentine and B. A. Cornish

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PREFACE

This publication, prepared for the designing engineer concerned with culverts, presents an approach to the design of a pipe culvert with a cheap but effective provision for the control of scour at the outlet. The scour protection is provided by a mattress of broken stone enclosed in a wire mesh basket, covering a layer of stone at the culvert outlet.

The details of the gabion technique given here are based upon an experimental study recently completed by the Water Research Laboratory for the New South Wales Department of Public Works. The study, which was one phase of a long term programme of investigations with culverts and causeways, included the testing of over 60 conditions of flow and scour protection with a 4-inch diameter culvert model. The stability criteria developed were then checked on an 8-inch diameter model and found to give consistent results. The technique is now presented as a relatively cheap and effective method of protection of culvert outlet structures against undermining by scour action.

It is not generally recognised that culverts frequently operate under part-full conditions, even when there is a considerable surcharge at the inlet. The gabion data presented here are based upon tests with part-full flow in a single pipe culvert with 45° wing-walls and a downstream bed of fine sand. For full details of the tests, reference should be made to W. R. L. Report No. 48 "Hydraulic Model Investigation of Gabion Protection of Culvert Outlets" by Hattersley and Cornish.

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1. INTRODUCTION

Culvert design involves the fixing of the location, length, grade and size of the conduit or conduits, and the form of the inlet and outlet structures, for the conveyance of surface runoff from a drainage area.

The location and length are determined normally from consideration of the local topography and the form and dimensions of the embankment through which the culvert passes; the grade is generally fixed at, or in excess of, a value adequate for the maintenance of a self-cleansing velocity of flow; the inlet and outlet structures (the headwalls, wingwalls and aprons) are commonly based upon a standard design of a State Highway Authority.

There remain two aspects of culvert design in which the designer has had to rely on judgment, experience and rule-of-thumb. These are, first, the determination of the conduit size, that is pipe diameter or box dimensions; and second, the protection necessary to ensure that the outlet structure does not collapse from the effects of scour.

The conduit size depends upon the peak flow rate to be accommodated by the culvert without the permissible surcharge of water over the culvert inlet being exceeded. The flow rate having been estimated by one of the several available approaches, it is possible to estimate the pipe diameter necessary to provide for a particular mode of culvert flow. This approach is treated in Section 3 below.

Protection of the outlet walls from the effects of scour has engaged the attention of a number of engineers and research workers in recent years. Outlet structures in the form of dissipators have been proposed (Ref. 2) and some have been used to a limited extent, with success. In general, such structures have been far too expensive for general adoption. The cheapest forms of protection so far suggested involve broken stone lining, sometimes referred to as "armour-plating". Of these, a form which is kept stable by the weight of an overlying mattress of broken stone in a basket of wire mesh has performed very effectively in laboratory tests. This technique, commonly called "gabion" protection, is dealt with from the designer's view point in Sections 4, 5 and 6.

2. CULVERT HYDRAULICS

For a culvert of specified size and grade, the capacity or rate of flow which is sustained by a given depth of approach flow depends upon whether or not the culvert flows full. This is not always easy to predict, especially when the designer has little reliable information on flow conditions downstream of the culvert.

If consideration is limited to a single circular pipe culvert of diameter D with an upstream depth or headwater h, and a downstream depth or tailwater t, it is evident that the pipe will flow full if the inlet and outlet are submerged, that is if $h > D$ and $t > D$ (See Fig. 1a).

With the inlet well submerged, say $h > 2D$, a short culvert on a mild slope, with a free outlet, may flow part full with the flow depth increasing downstream; but it will flow full, if it is long enough for the backwater effect to fill the pipe. (See Figs. 1b and 1c). For example, a pipe on a slope of 1 in 100 might behave as a short pipe, flowing part-full if the length L is less than about 30 diameters but as a long pipe flowing full if L is appreciably greater than 30D.

If the inlet is not well submerged, vortex action admits air to the culvert sufficiently to prevent or seriously interfere with full bore flow. Laboratory experiments indicate that such effects occur if $h < 2D$ and that the capacity is reduced by 20 pc. or more, unless hoods or other devices are installed to prevent the vortex action.

For practical purposes, with grades between 1 pc. and 2 pc., the following guides to the likely form of culvert flow can be used.

Outlet Condition	Inlet Condition	Culvert Length	Flow Condition
Submerged	$h > D$	Any length	Full
Free	$h > 2D$	$L > 30D$	Full
Free	$2D < h < 3D$	$L < 20D$	Probably part full
Free	$h < 2D$	Any length	Part full

3. DETERMINATION OF CULVERT DIAMETER

(i) Full Pipe Flow

If available data indicate that the culvert will flow full for the design flow rate, the necessary pipe diameter can be determined from normal pipe flow charts or formulae (Figs, 1a and 1c). The headwater can be fixed from a knowledge of the permissible surcharge over the inlet. The drop in level from the upstream surface to the surface of the water at the pipe outlet is equated to the sum of the entrance loss, the exit loss and the pipe resistance losses.

$$\Delta H = K_i \frac{V^2}{2g} + K_o \frac{V^2}{2g} + \frac{fL}{D} \frac{V^2}{2g} = \frac{V^2}{2g} (K_i + K_o + \frac{fL}{D})$$

$$\therefore \Delta H = \frac{Q^2}{2g(\frac{\pi}{4})^2 D^4} (K_i + K_o + \frac{fL}{D})$$

With appropriate values being adopted for the entrance coefficient K_i, the exit coefficient K_o and the resistance coefficient f, (of the order of magnitude 0.25, 1.0 and 0.015 respectively) a solution for D can be found.

(ii) Part-full Pipe Flow

The pipe size necessary to convey a given flow rate, when the culvert is flowing part full without a submerged entrance, can be determined by application of normal open channel flow formulae.

For peak design flow conditions, a pipe culvert is usually designed for submergence of the entrance. The necessary pipe size in such a case can be estimated with the aid of a chart relating headwater, flow rate and pipe size (Fig. 3). Alternatively, the chart may be based upon surcharge flow rate and pipe size (Fig. 2). These charts have been derived from experiments in the range of upstream headwaters from h = D to h = 3D, the pipe being sufficiently short for the flow to be part full. Extrapolation of the charts is not recommended.

4. THE PRINCIPLE OF THE GABION

The scouring action of water discharging from a culvert over an erodible bed can be reduced by means of a protective layer of broken stone in the vicinity of the outlet. A properly proportioned stone layer prevents the development of scour holes which might undermine the outlet head and wing-walls. The flow velocity is reduced as the issuing stream spreads so that the scouring action downstream of the layer is of reduced intensity and, in any case, is harmless as far as the outlet structure is concerned.

The stability of the layer and of the underlying bed material for a given outlet velocity depends on the size and grading of the stone and on the thickness of the layer. Each surface stone must be heavy enough to resist the transporting force of the water, while the grading and thickness of the layer must prevent the high velocity discharge from penetrating the layer and washing out the underlying material.

With velocities in excess of about ten feet per second, the required size of surface stones is excessive. However, stability is obtained with stones of convenient size provided that their movement is restrained. Suitable restraint can be applied by the use of wire mesh which totally encloses the upper layer of the stone so as to form a rock mattress or gabion (Fig. 4).

The gabion stone should be fairly uniform and about twice the size of the wire mesh opening. The underlying stone which, with the gabion, makes up the total thickness of the protective layer, can be of mixed size with a small percentage of fines.

Adequate total thickness is essential for stability for, if bed scour is able to occur under the stone layer at all, it progresses rapidly and complete collapse and failure of the rock layer result.

5. GABION DIMENSIONS

Dimensions recommended for gabions on the basis of scale model tests with a sand bed channel are:-

Stone size	9"
Mesh size	4" x 4" x 12½ S.W.G. galv.
Thickness of mat	15"
Width " "	5 diameters
Length " "	2½ to 3½ diameters downstream from the outlet. The larger values are recommended for shallow tailwater conditions in wide channels.

If the headwater and tailwater depths for the design flow can be estimated, the appropriate minimum dimensions can be taken from the following table:-

Tailwater Depth	Headwater Depth	Length of Gabion	Total Thickness of Stone Layer
1/4D	$1\frac{1}{2}$D	$2\frac{1}{2}$D*	$\frac{1}{2}$D
	$1\frac{1}{2}$ to $2\frac{1}{2}$D	3D*	$\frac{1}{2}$D x
1/4D to $\frac{1}{2}$D	2D	$2\frac{1}{2}$D	$\frac{1}{2}$D
	2 to $2\frac{1}{2}$D	3D	$\frac{1}{2}$D
$\frac{1}{2}$D to D	1 to $2\frac{1}{2}$D	$2\frac{1}{2}$D	$\frac{1}{2}$D

* Increase by 20 pc. for channels over 10D in width
x Increase by 50 pc. for channels over 8D in width.

These dimensions are appropriate for a fine sand bed. For less erodible material some reduction in dimensions may be possible.

6. GABION CONSTRUCTION PROCEDURE

The bed of the channel downstream of the outlet structure is excavated to the depth and extent of the required stone protection. Into this excavation is dumped ungraded rock fill to bring the upper surface to approximately 1'3" below the pipe invert level. The dumped rock is levelled to a surface upon which a layer of 4" x 4" mesh $12\frac{1}{2}$ S.W.G. galvanised 'pig' wire is laid. ('Pig' wire is a woven wire mesh with all the wire intersections securely tied). This net is to be the shape of the required gabion with a selvedge or trim wire turn up for tying to the upper layer of wire. "Mattress ties" of 12 S.W.G. galvanised tie wire connected to mesh intersections should be attached at approximately 1'4" x 1'4" centres and left upright for fixing to the upper layer of wire mesh.

Selected stone of uniform average size 9 inches is placed on the wire to bring the finished surface up to the culvert invert level. A top layer of 'pig'wire is then placed over the rock and tied firmly around the edges to the lower layer. The intermediate ties are then firmly fastened.

7. COSTS

It has been estimated that gabion protection would increase the initial cost of a culvert installation by up to twentyfive per cent, under average conditions. Figure 5 gives an indication of the estimated costs of the components of a gabion-protected culvert. The figure is based upon the following costs:-

Concrete headwalls	£30 per cu. yd.
Concrete pipe, 60 ft. long	current (1962) contract prices.
Gabion (stone and mesh) in place	£3 per cu. yd.

The relatively small increase of cost involved in the provision of scour protection makes gabion construction in erodible soils an attractive proposition.

REFERENCES

1. Hattersley R. T., and Cornish B. A. "Hydraulic Model Investigation of Gabion Protection Culvert Outlets. Water Research Laboratory Report No. 48, October, 1961.

2. Argue J. R. - New Structure for Roadway Pipe Culverts, Jnl. Inst. Engineers, Aust. Vol. 32 No. 6 June 1960.

APPENDIX

DESIGN EXAMPLES

1. Culvert with Restricted Surcharge

A flow of 80 cubic feet per second is to pass through a single-pipe culvert 80 feet long with a headwater surcharge of not more than 1 ft. 3 in. The culvert discharges onto the flat bed of a channel 20 ft. wide in sandy loam. The tailwater is estimated to be about 1 ft. 6 in. for this flow.

(a) Pipe Size. For a conservative estimate, assume that the flow is part-full. From Fig. 2, with S = 1-1/ 4 and Q = 80, the required pipe size is 48 in. The value of $\frac{L}{D}$ is 20, hence the flow is probably part full as assumed.

(b) Gabion Dimension. Since the inlet headwater h = D+S= 4+ 1 = 5 $1\frac{1}{2}$D, and the channel width is 20 ft.< 8D, the required gabion length is $2\frac{1}{2}$D or 10 ft. and the required depth of stone is $\frac{1}{2}$D or 2 ft.

2. Culvert with Restricted Headwater

A single pipe culvert 75 feet long is to carry a flow of 100 cubic feet per second with a headwater measured above the pipe invert, of not more than 8 feet. The culvert discharges into a flat-bottom channel 36 feet wide, with an estimated tailwater of 10 in.

(a) Pipe Size. If the flow is part-full, Fig. 3 yields D = 42 in., with a headwater of 6. 2 ft. The ratio $\frac{L}{D}$ is 21, so that the culvert probably will flow part-full.

(b) Gabion Dimensions. Since the headwater h (6. 2 ft.) exceeds $1\frac{1}{2}$D, the channel width (36 ft.) exceeds 10D, and the tailwater (10 in.) is less than 1/ 4D, the required length of gabion is 3D + 20 pc., i. e. 12. 6 ft. with a stone thickness of $\frac{1}{2}$D + 50 pc. or 2. 6 ft.

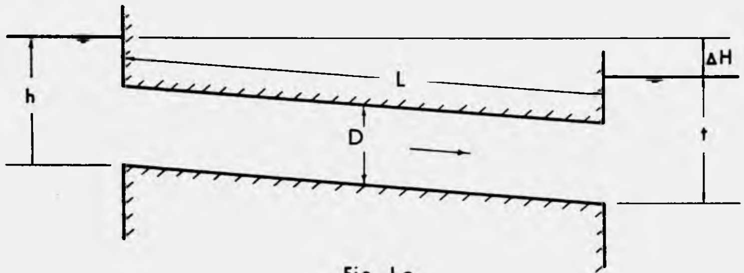

Fig. 1a.

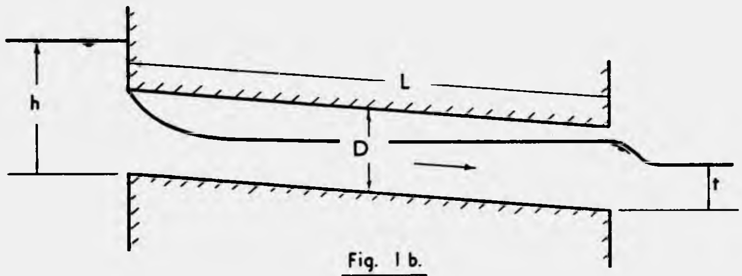

Fig. 1b.

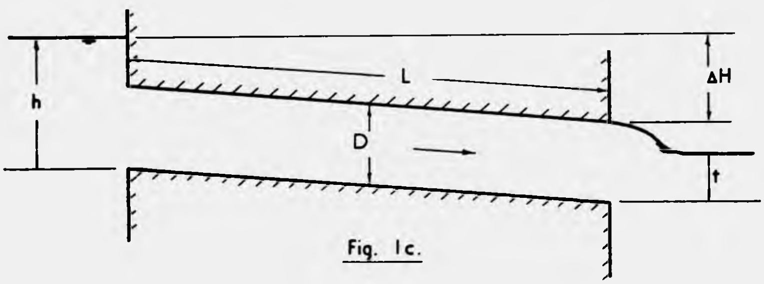

Fig. 1c.

FIGURE No. 1.

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The Dept. of Public Works - Project E 877	Scale: -	Date: 28 - 3 - 62
TYPES OF CULVERT FLOW	Drawn: B.A. Cornish Traced: P. A. Checked:	CE-E-2527

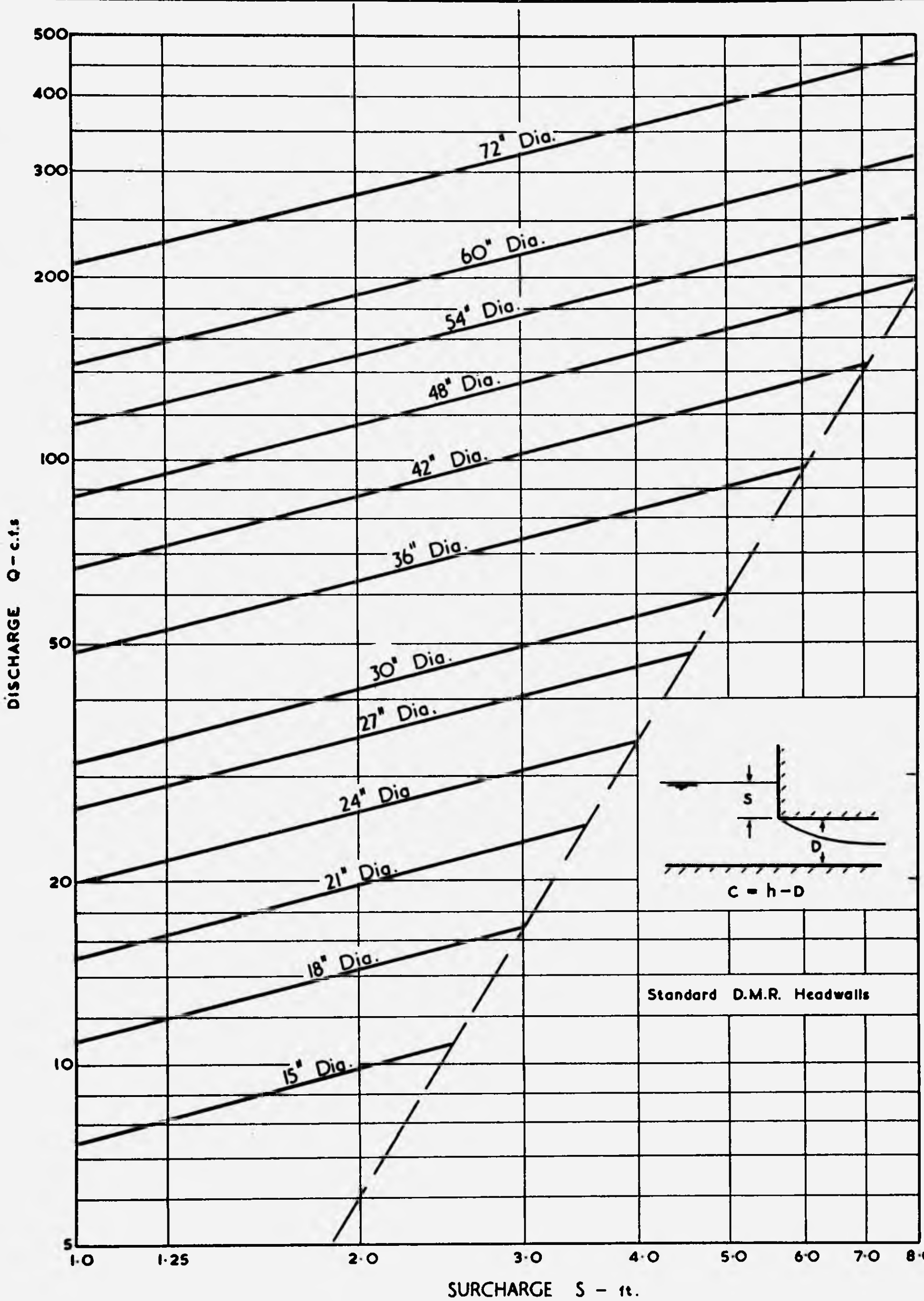

FIGURE No. 2.

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The Department of Public Works - Project E877	Scale: —	Date: 9·3·62
CULVERT COVER – DISCHARGE RELATIONSHIPS	Drawn: B.A.Cornish. Traced: P. A. Checked:	CE-E-2490

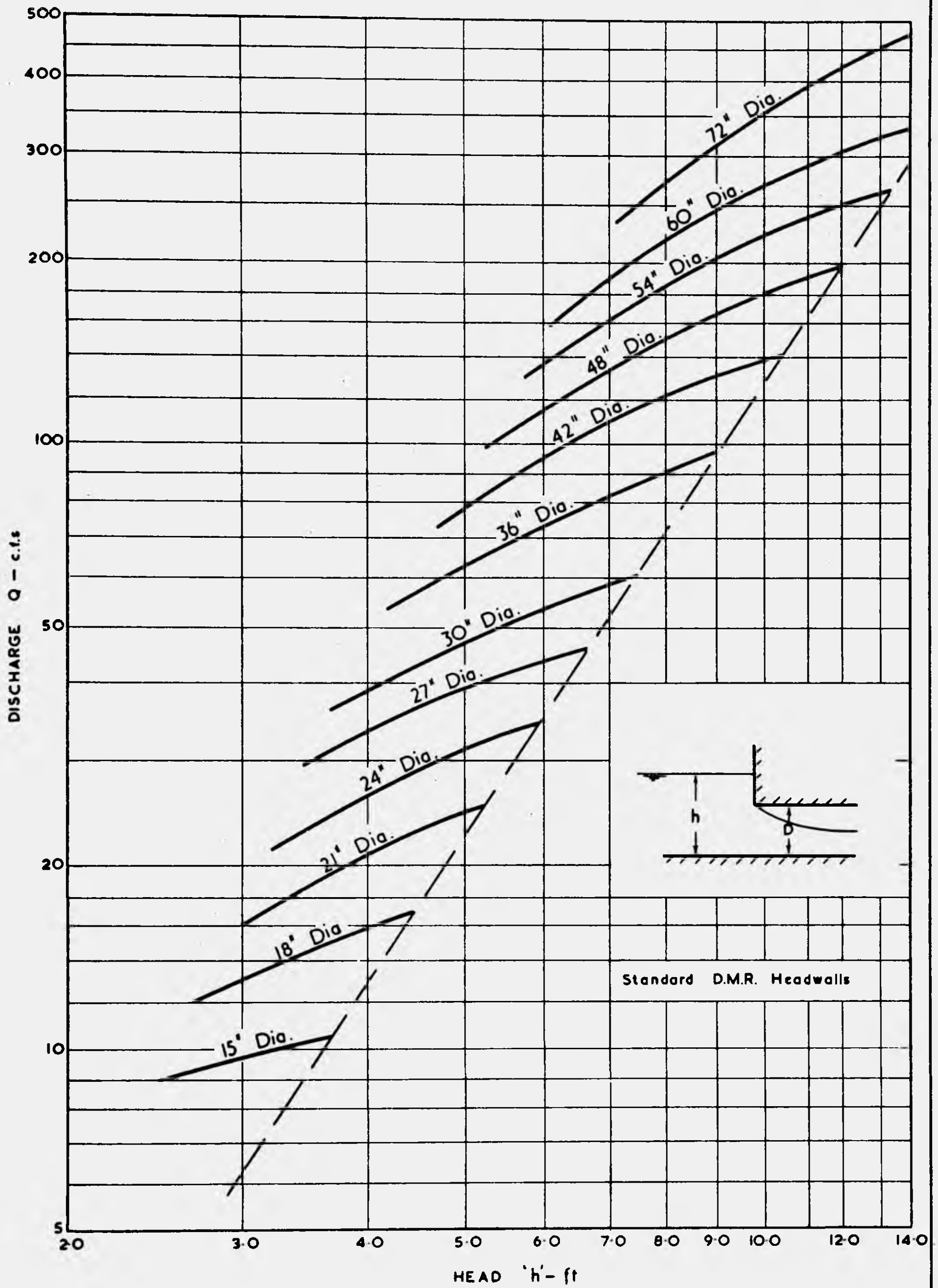
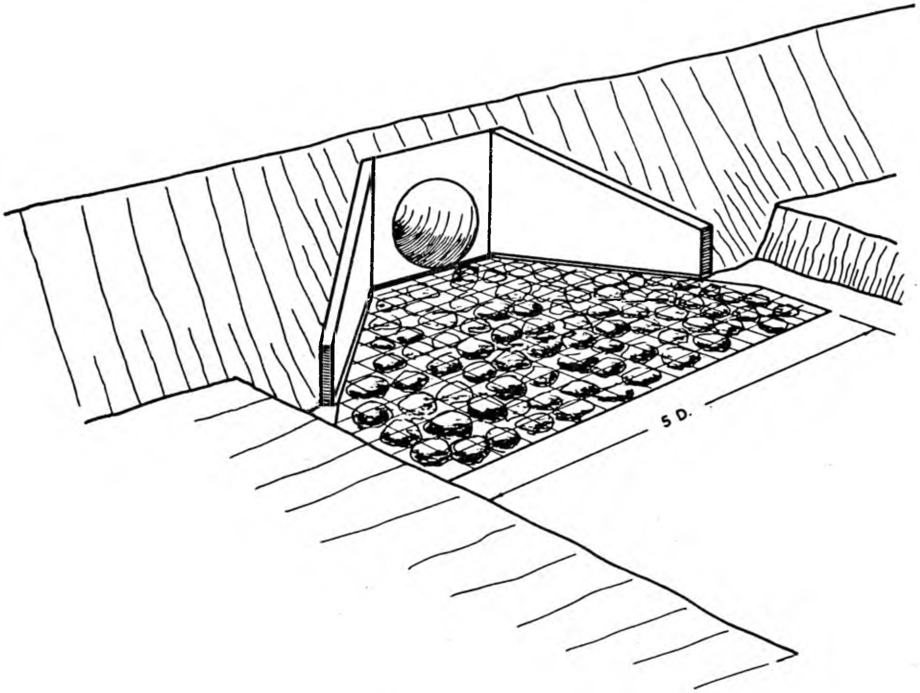
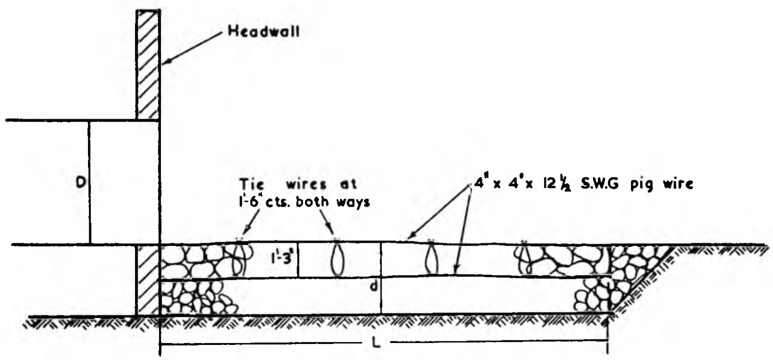


FIGURE No. 3.

THE UNIVERSITY OF NEW SOUTH WALES WATER RESEARCH LABORATORY		
The Department of Public Works – Project E877 CULVERT HEAD – DISCHARGE RELATIONSHIPS	Scale: — Drawn: B.A.Cornish Traced: P.A. Checked:	Date: 12·3·62 CE-E-2491





CROSS SECTION

FIGURE No. 4.

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The Dept. of Public Works. Project E877	Diagrammatic.	Date : 29·3·62
DIAGRAM OF GABION	Drawn : B.A.Cornish	CE-E-2528
	Traced : P. A.	
	Checked :	

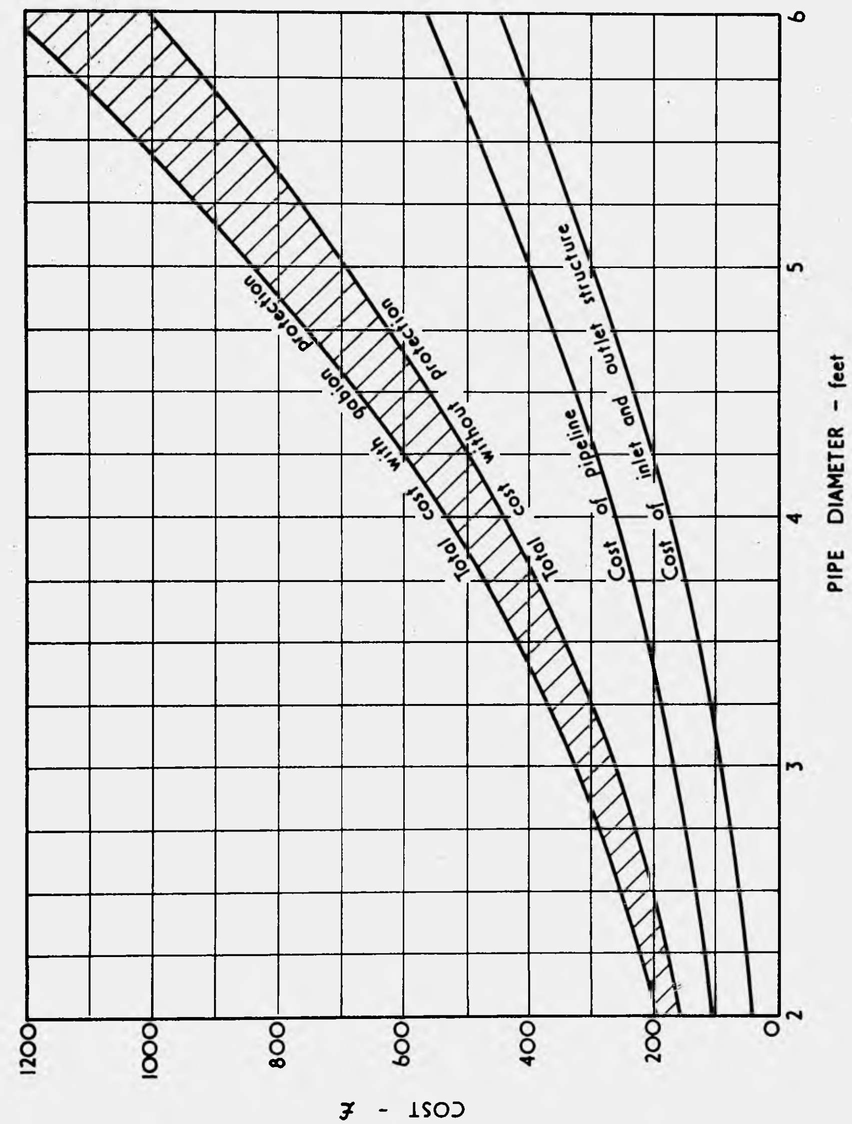

FIGURE No. 5.

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The Department of Public Works - Project E877	Scale: —	Date: 28·3·62
COST OF GABION PROTECTION	Drawn: B.A.Cornish	CE-E-2526
	Traced: P. A.	
	Checked:	