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Efficient Pipe-Culvert Exit Transitions

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SUMMARY The basic concepts and practical factors governing design of hydraulically and economically efficient exit transitions for small pipe culverts are briefly outlined. Head-loss and scour tests on models (scales 1:9 and 1:3) led to the development of culvert exit transitions (pipe diameter d) of minimum length 3d, with a longitudinally horizontal obvert and essentially elliptical outlet section 2d wide and $\frac{2}{3}$d high, requiring no headwall, apron or training walls; and having a total head loss of 40 to 50% of the pipe velocity head and a very low erosion potential.

1 INTRODUCTION

Low-capacity pipe culverts, siphons and subways constitute a fairly large proportion of irrigation and drainage structures. Consequently, their hydraulic efficiency, low scour potential, and first-cost and maintenance economy are of primary importance. Where channel grades and available heads are small, a low head loss at such structures is usually required.

Considerable research has improved the hydraulic efficiency and minimized the channel scour downstream of large structures of this type, involving pressure- and/or free-flow transitions and often incorporating aprons, sills, walls, etc. However for small-capacity pipe structures, geometrically complicated transitions are not justified (Simmons, 1964), and end structures should preferably be eliminated, or simplified in shape and construction (Collett, 1965).

The inlet (converging, accelerated flow) zone usually requires relatively simple shaping to achieve an acceptably low total energy loss and scour potential, and is not considered in this paper. On the other hand, the outlet zone poses a greater problem because a low scour potential and a reasonable head recovery in a short distance are required, notwithstanding the unfavourable conditions created by the sudden expansion in waterway area.

A natural energy-dissipating basin often forms where no exit transition is provided but, of course, does not resolve the problem of minimizing head losses or maintenance costs. Extension walls can successfully limit batter erosion downstream of some control structures (Carr, 1960) ; bed scour is often inhibited by placing beaching in an excavated dished profile (Murley, 1970).

Hydraulic model tests initiated earlier by the author, aimed at improving the performance and reducing the size of standard end structures for drainage subways (Tadgell, 1962), showed that for minimum head loss, the entry and exit walls should spring directly from the sides of the pipe (i.e. without any offset) and be splayed at respectively 30° and 15° to the pipe axis; the outlet to be provided with long fillet transitions from the lower quadrant of the pipe to the wall/apron corner. A short outlet hood achieved a further improvement, but its construction would be expensive. These results indicated that for such outlet structures, the optimum total horizontal angle of divergence is about 30° and that the transition from the pipe should preferably be smooth (i.e. without any lateral offsets).

2 BASIC CONCEPTS

The foregoing considerations led to the following two basic design concepts:

I Introduction of an expanding closed-conduit transition to reduce the exit velocity smoothly and substantially closer to channel velocity, preferably to less than 75% of the pipe velocity.

II Minimization of scour of channel bed and batters by limiting and/or controlling the turbulence generated by the sudden expansion from transition exit to channel waterway.

Furthermore, observation of the performance of various hydraulic structures and models had indicated to the author that channel scour is governed not only by the magnitude of the exit velocity and erodibility of the soil, but also by the shape of the outlet jet, its divergence angle, and the waterway configuration downstream. In the subject case, the following additional concept was therefore proposed:

III "Flattening" of the transition exit shape to conform generally with the channel section downstream, and with a lateral total angle of transition divergence of about 30°.

The specification for the research study thus envisaged a gradual closed-conduit exit transition from a circular inlet (pipe diameter d) to an elliptical outlet (horizontal axis 2d to 3d, vertical axis not less than $\frac{1}{2}$d), with a minimum length of 3d, preferably requiring no end structure and little or no beaching.

In practice, any given hydraulic efficiency has to be balanced against costs, i.e. the head loss and channel scour should be minimal consistent with an acceptable level of capitalized cost of the pipeline, transition, end structure (if any), and maintenance including the adjoining channel. In some cases, a larger pipe diameter may lower overall cost as well as increase hydraulic efficiency, as it may require no end structures.

3 PRACTICAL FACTORS

The closed-conduit transition unit should, of course possess not only the desired hydraulic efficiency but also adequate strength and freedom from sharp profile changes (these act as stress concentrators). Small-sized rigid prefabricated units of fairly complex shapes can be mass-produced in standard sizes at relatively low cost, using the wider range of strong and durable materials now available, including moulded fibre-reinforced plastics and epoxy-strengthened compounds (e.g. epoxy cement).

Investigations encompassing applications of such materials are necessary, including surface roughness, joint details, ease of fabrication, lightness for transport, rapidity of installation, and inexpensive maintenance.

Channel shaping downstream, aimed at creating "buffer zones" of dead water, may be initially cheaper than a concrete headwall or end structure achieving the same reduction in scour, but such (nonrigid) earthworks may lose their shape or symmetry by rain scour, operation of channel-cleaning plant, or unusually or accidentally high flows, with consequent erosion and heavy repair costs.

4 HYDRAULIC MODEL TESTS

4.1 General

The prototype channel was assumed to have a bed width of 1.8 m to 2.4 m, 1:2 (V:H) batters, and a water depth of 0.6 m to 1 m. Pipe diameters could range between 450 mm and 1200 mm, and the transition proportions had been outlined as indicated earlier. The design discharge was fixed at 0.39 $m^3 s^{-1}$.

A pilot (1:9 scale) indoor model was first tested for overall performance and best setting of the initially proposed transition. A larger (1:3) scale was then used for an outdoor series with a sand-lined channel downstream, varying the transition length and exit shape to evaluate their effects. All these tests were for (prototype) values of: pipe diameter, 900 mm; submergence of outlet, 150 mm; and channel bed width, 2 m. Parallel testing of a standard (transitionless) culvert with a triangular box-type end structure provided a reference base for assessing performance of the various alternatives. The principal model proportions are presented in Fig. 1. Model A was introduced merely to check the validity of concept III.

4.2 Methodology

4.2.1 Head-loss coefficient

The head-loss coefficient K was defined in terms of the mean pipe velocity v_1, as follows:

$$K\,(v_1^2/2g) = (v_1^2/2g) + h_1 - (v_2^2/2g) + h_2,$$

where v_2 = mean channel velocity, m s^{-1};

g = acceleration due to gravity, 9.8 m s^{-2}.

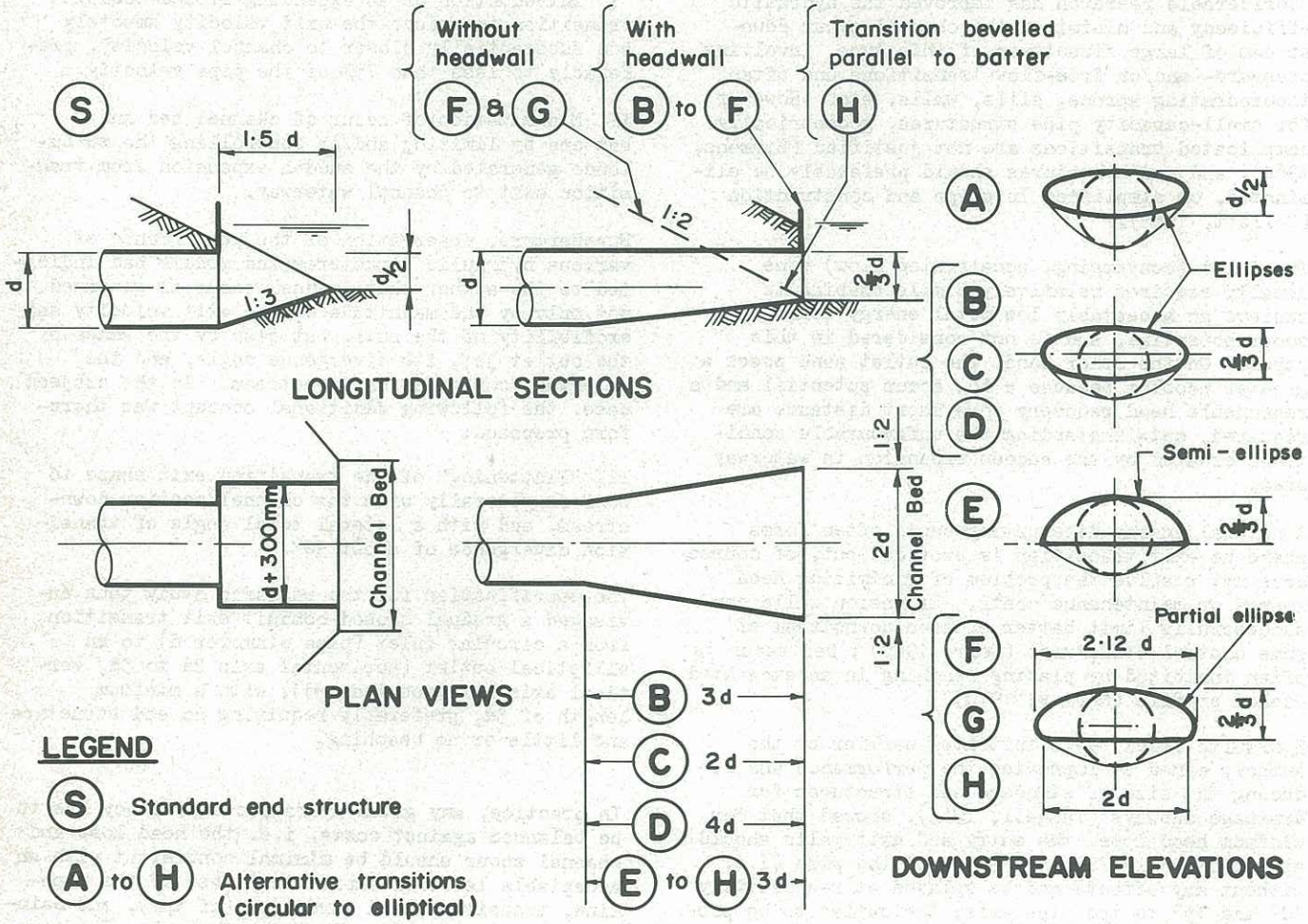

Figure 1

Principal proportions of exit transitions

h_1 = piezometric head in the pipe, just upstream of the transition (average of three readings of manometers tapped into its circumference), m;

h_2 = piezometric head (measured by manometer) in the channel 2.8 m downstream of the transition, m.

Because at fairly low model discharges the manometers could not be measured accurately, and to cover higher possible design discharges, tests were also conducted at much higher discharges (up to $3Q_d$).

4.2.2 Channel scour

The test results of even large-scale Froude-number hydraulic models involving scour of soils, cannot be directly scaled up to evaluate prototype erosion because the dynamic-similitude criteria for the soils (size, cohesion, resistance to displacement) are different and cannot be achieved simultaneously.

However, past experience with similar studies had shown that, under steady discharge conditions, a stable bed-scour pattern is developed in about one hour (Collett, 1965), thus enabling comparisons of the bed-scour potential of different models. The conditions governing batter erosion are different in that soil cohesion and particle stability on a slope, are involved.

In the subject study, these two scour zones were observed to have the following specific characteristics:

a) Channel bed - Sand removed downstream of the transition, forming a typical dished pit which eventually approached a stable shape. b) Batters - Erosion caused by the horizontal side eddies generated at the sudden expansion to the channel waterway, manifested mainly at or near the water surface, progressing with time and, at large discharges, causing sloughing and collapse. Batter erosion (progressive) is obviously more important than bed scour (self-stabilizing): The former has freedom to develop, whereas the latter eventually forms a sediment-replacing reverse roller.

The scour rating system developed (Aughton, 1980) to compare the performance of different models was based on measured depths of both bed and batter scour, with a scale of 0 (no scour) to 10 (failure or destruction). Each test rating was a weighted combination of the two scour measurements (model scale): a) Bed scour: 0 (0 mm), 1-5 (0-50 mm), 4-7 (50-60 mm) and 5-10 (60-70 mm); b) batter scour: 0-4 (0 mm) and 5-10 (0-40 mm). Similar methods have been used previously: Visual ratings (Simmons, 1964), particle-displacement velocity (Collett, 1965), and a smaller-scale rating (Mills, 1970). The subject system, though arbitrary, nevertheless enabled scour potential to be compared.

Because scour magnitudes and differences were very difficult to measure at the (small) design discharge Q_d, tests were run at up to 3 Q_d (as for head loss). Of course, the scour at such high discharges does not necessarily represent long-term values at Q_d, but this procedure enabled a better estimation of the latter and covered possible higher values of design discharge.

Following the first-stage scour tests with a well-graded sand containing clay particles, a second series was run with a gap-graded sand (1-2 mm), aimed at achieving uniform and repeatable scour patterns, and making more accurate comparisons between alternative transitions and with the Commission's current standard end structure S. The reduction in "cementing" of the sand by washing out of the fines first, had been observed earlier (Collett, 1965).

4.3 TEST RESULTS

4.3.1 Head-Loss coefficient

The head-loss test results for the various transitions as developed, are presented graphically in Fig.2

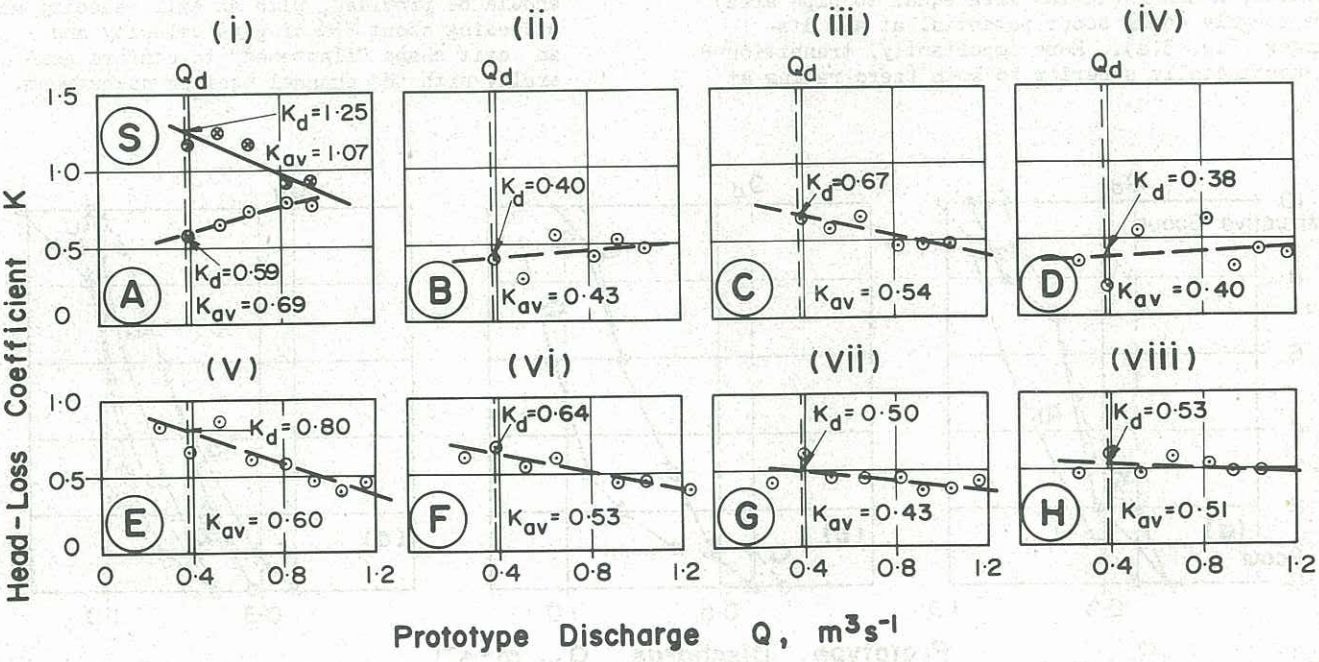

Figure 2

Comparison of head-loss coefficients for different transitions and discharges.

At design discharge Q_d, the circular-to-elliptical "shape only" transition A (equal end areas) has about half the head-loss coefficient K_d of the standard end structure S (Fig. 2.i), thus verifying basic concept III. The difference diminishes with discharge, the K values converging to 0.8 at about $2\frac{1}{2}Q_d$.

Figures 2.ii to 2.iv show that K diminishes with length of the circular-to-elliptical transition (exit:entry area ratio of 4:3), with a greater incremental improvement for the length increase from 2d (C) to 3d (B) than 3d(B) to 4d(D). This trend was noted earlier, for circular-to-rectangular transitions with lengths up to 6d and exit:entry area ratio of 2.55:1 (Simmons, 1964). Pending economic comparisons, transition length in the subject study was limited to 3d in all subsequent alternatives tested.

The semi-elliptical flat-floor outlet transition E, which was aimed at limiting spreading of the upper part of the outflow (Aughton, 1980) and thus inhibiting batter scour by back eddies, has a K_d of 0.80, i.e. double that of transition B (Fig. 2.v), dropping to equal value (0.47) at $2\frac{1}{2}Q_d$.

The results for transitions F, G and H (partially elliptical, flat-floor exit shape) are shown in Figs. 2.vi to 2.viii. For arrangement F (with a headwall, as in all previous transitions), K_d is 0.64, i.e. 60% higher than for transition B, but the K values coincide (0.46) at $2\frac{1}{2}Q_d$. With the end batter shifted back to the transition-exit invert and dispensing with the headwall (arrangement G), K_d is reduced to 0.50, i.e. still 25% above that for transition B, although the K values are equal (0.45) at about $1.6Q_d$. If the transition is then bevelled to coincide with the end batter (arrangement H), the material cost is reduced but K_d increases slightly to 0.53, and K values for H and B merge (0.47) at $2\frac{1}{2}Q_d$.

4.3.2 Scour potential

The scour ratings obtained in the second test series are compared in Fig. 3. As might have been expected, A and S (outlet area equal to pipe area) have roughly equal scour potential at all discharges (Fig. 3.a). More importantly, transition B is substantially superior to both (zero rating at Q_d and about half their ratings at higher discharges), thus validating the author's hypothesis.

The second comparison (Fig. 3.b) shows that at Q_d the shortest transition (C) has a very low rating, and longer transitions have a zero rating. At higher discharges, the longest transition (D) has about one-third the ratings of transitions B and C.

Finally, Fig. 3.c shows that the transition with a partially-elliptical outlet shape, whether with or without a headwall (arrangements F and G respectively) has the smallest scour potential over the whole discharge range, and a zero rating up to $1.6Q_d$. When 3d long, it compares favourably with transition D of length 4d; its superiority over transitions B and H is outside the adopted design limits, and it is only slightly better than transition E. Transition B was not tested without a headwall, but even if only a slight improvement in performance were obtained (compare G with F), there would also be the same economic advantage of dispensing with the headwall.

Presented in Fig. 4 are photographs of the standard end structure S and the circular to partially epliptical, flat-floor transition G, respectively before (a and c) and after (b and d) a test run at 0.52 m^3s^{-1}, to illustrate and compare a typical set of scour results.

4.3.3 Basis for Comparison

The adopted value of design discharge Q_d corresponds to the fairly low pipe and channel velocities applicable where the available heads and channel grades are small. Where the latter are substantially greater, the results for appropriately higher values of Q_d would be used to provide the proper basis for comparing the performance of alternative transitions.

5 CONCLUSIONS

The hydraulic research study led to the following conclusions :

(i) A closed-conduit expanding outlet transition should be provided, with an exit velocity not exceeding about 75% of pipe velocity and an exit shape "flattened" to conform generally with the channel section downstream.

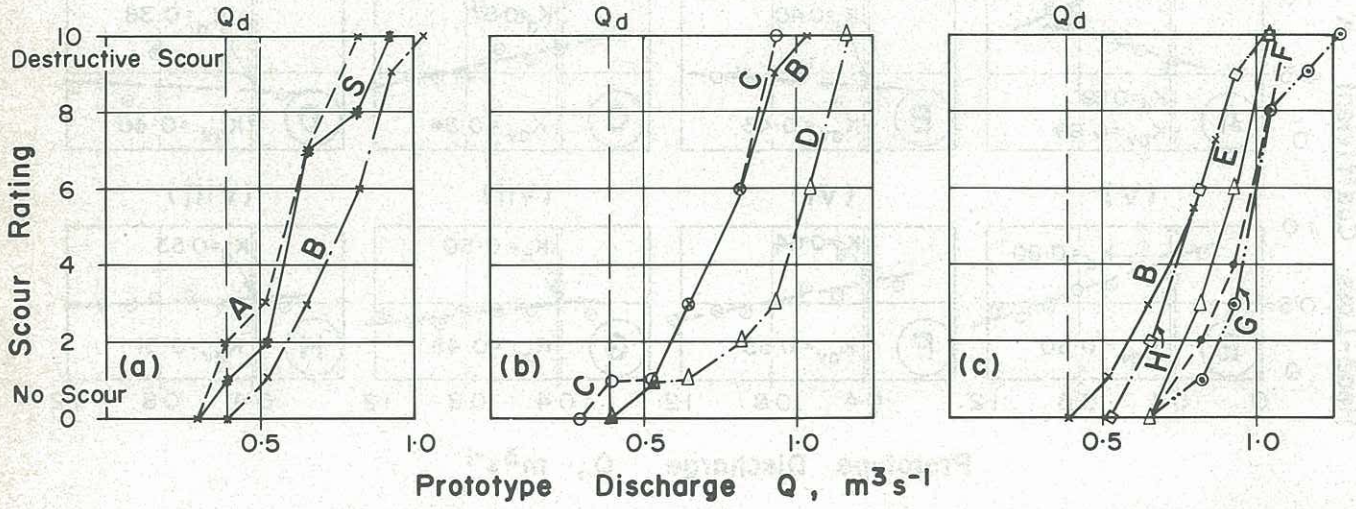

Figure 3
Comparison of scour ratings for different transitions and discharges.

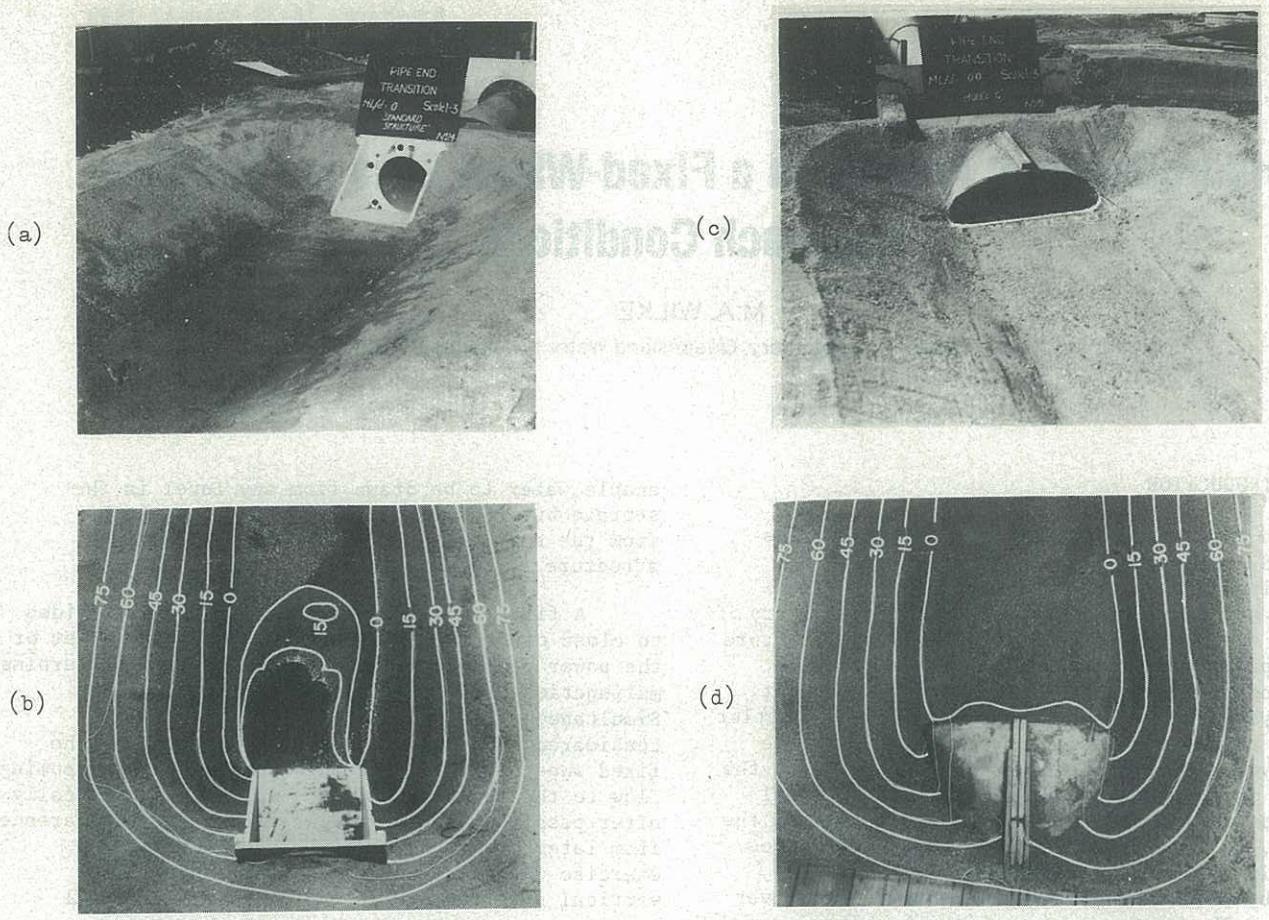

Figure 4 Comparison of scour pattern (b) of standard end structure S (a) with that of (d) of partially-elliptical flat-floor transition G (c), after test run at 0.52 m^3s^{-1}.

(ii) A suitable transition from a pipe of diameter d, which meets the above requirements, has a longitudinally horizontal obvert, set at least d/6 below tailwater; a minimum length of 3d; and a gradually changing section to an outlet profile which is essentially elliptical with a width 2d and height $\frac{2}{3}$d.

(iii) The transition from circular to fully elliptical profile (B) is of relatively simple form, and has the smallest head-loss coefficient K_d at design discharge Q_d; but the transition from circular to partially elliptical profile (G), although more complex because of its flat floor, has a better performance for discharges exceeding $2Q_d$.

(iv) Likewise, transition B has a zero scour rating at Q_d and would be just adequate where discharge is controlled, as in irrigation systems; but transition G has a much lower scour potential in general, and thus would be advantageous, particularly in drains, where the discharge can sometimes greatly exceed Q_d.

(v) Transition G (and possibly B) can be installed without a headwall, thus achieving considerable economy in construction.

(vi) Research in this field should be continued, aimed at further improvements in transition design and reduction in scour potential. Prototype structures of identical proportions should be tested for comparison and correlation with the developed models, to confirm their head-loss coefficients and, especially, to verify their scour potential.

6 ACKNOWLEDGEMENTS

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