Hydraulics Research
Wallingford

FLOW IN CULVERTS

Interim Review

Report No SR 189
December 1988

Registered Office: Hydraulics Research Limited,
Wallingford, Oxfordshire OX10 8BA.
Telephone: 0491 35381. Telex: 848552

CONTENTS

FIGURES

PLATES

PLATES (Contd)

PREAMBLE

Hydraulics Research Ltd. are carrying out a series of investigations of the performance of river structures. This research is sponsored by the Ministry of Agriculture Fisheries and Food (MAFF). One of these investigations concerns the performance of culverts. The stimulus for this investigation was the apparent lack of information on the roughness values to be used for modern sectional pre-cast concrete culverts. The preliminary stage to the investigation was a literature search and collection of prototype evidence.

The literature search showed that there was an immense body of work on the subject of culverts but that much of it was fragmented. The available information on culverts is therefore being collected together in an attempt to relate the various threads of research and ascertain whether other questions arise on the performance of culverts than the one originally posed.

This interim report reviews the general analysis of culverts and some of the research into culvert entries. A bibliography is also included of reseach sources not yet reviewed.

1. INTRODUCTION

Culverts can be described in general terms as relatively short pipes used to pass flood plain flows or open water courses through obstructions such as a road or rail embankment. Flow through a culvert may be free surface or full pipe flow or may change from one to the other within the discharge range.

The type of flow depends on a number of factors - the headwater and tailwater levels, the length, the slope, the roughness and the inlet geometry. Consequently, the flow characteristics can be very complex. In some cases, the culvert capacity can be calculated accurately; in others, laboratory investigations may be necessary to determine the stage/discharge characteristics.

2. TYPES OF CULVERT FLOW

Research into culvert flow has identified six principal types of flow. These are illustrated in Fig 1. The flow types are identified by the following descriptions.

Type 1: The inlet is not submerged, bed slope is steep enough to maintain supercritical flow throughout the culvert length and tailwater is not high enough to submerge the outlet. The control section is then at the inlet or just inside the inlet where critical depth occurs, assuming that the approach flow is subcritical (the usual case). Equating energy levels at the control section and a section in the approach, allowing for head losses at the culvert entry, will give the headwater level. This may be above the culvert entry soffit but research has shown that with a conventional entry geometry, the water surface will not touch the soffit for headwater levels up to 1.2 times the height of the culvert entry or, in some cases, up to 1.5 times the height of the culvert entry.

Type 2: For this type of flow, the tailwater level at the culvert outlet is below the critical depth line but the bed slope is not great enough to sustain critical flow down the culvert and the water surface is therefore above the critical depth line. The control section is therefore at the culvert outlet at the point of critical depth. Unlike Type 1, the roughness of the culvert becomes a factor in determining the headwater level to discharge relationship.

Type 3: This is a similar condition to Type 2 but the tailwater is above the critical depth line and the control section is downstream of the culvert outlet.

Type 4: Both inlet and outlet are submerged and the culvert runs full. The headwater to discharge relationship is controlled by the tailwater level.

Type 5: In this type of flow the inlet is submerged while tailwater is below the crown of the outlet. The control section is at the inlet where the flow pattern is similar to that downstream of a sluice gate and the discharge is determined by the upstream head level above the culvert inlet and the area of the contracted flow. Whether this flow condition will persist depends on the slope, length and roughness of the culvert. As the flow is retarded by the roughness it will expand at a rate influenced by the slope. If the water surface touches the crown of the culvert before the outlet then the flow will extract the air upstream of the seal and the pipe will run full.

Type 6: This type of flow is the alternative to Type 5; the inlet is submerged and the tailwater is below the crown of the outlet but the pipe runs full. In this condition the operating head is the height from the headwater level to the tail of the culvert and the discharge is higher than for Type 5 flow.

Although this list covers the principal types of flow, it is not exhaustive. For example, if the culvert is steep and the tailwater level high the inlet may be unsubmerged while the lower end of the culvert runs full or, a variation of Type 6 flow, the water surface may fall below the crown at a point upstream of the outlet. Further variations occur if the culvert has a break in slope midway along its length.

3. CALCULATION OF CULVERT FLOW

For Type 1 flow, critical depth at the entry is assumed and therefore minimum specific energy. At this point:

$$Q^2/g = A^3/B \qquad (1$$

where Q = discharge

g = acceleration due to gravity

A = cross-sectional area of flow at critical depth

B = water surface width at critical depth

To relate the headwater level to discharge an energy balance is carried out between the entry of the culvert and a section in the approach:

$$d_c + V_c^2/2g = h + V^2/2g - h_f - h_e \qquad (2$$

where d_c = critical depth

V_c = critical velocity

h = upstream water surface level above culvert invert

V = velocity in approach section

h_f = friction head between approach section and entry

h_e = head loss at entry

These two equations are solved by successive approximations. Friction head will normally be small and not easy to calculate in this condition of rapidly varying flow and is therefore commonly omitted. In all culvert calculations the determination of the entry loss can be difficult. This is referred to later.

When Type 2 flow occurs, Equation 1 still applies but the friction loss along the culvert has to be included in Equation 2.
In effect, a backwater calculation has to be carried out along the culvert from the estimated critical depth at the outlet to establish the depth at the culvert inlet and repeated until the equations are satisfied. This is an extremely tedious process to carry out by hand but is relatively simple with the aid of a microcomputer or programmable calculator. A simplified method using graphical aids is given by Carter (Ref.2).

Computation of Type 3 flow follows the same process as that for Type 2 flow except that the estimated discharge/tailwater level relationship in the latter is determined by the critical flow condition while in the former it is by a backwater calculation from a control section in the tailwater channel.

For Type 4 flow, calculation of the headwater level/discharge relationship is a straightforward solution of the energy equation between the headwater and tailwater sections. In this case, head loss due to friction poses no problems since the cross-sectional area and hydraulic mean depth are constant.

If Type 5 flow occurs, calculation of the headwater level /discharge relationship is apparently a single step application of an orifice equation. However, occurence of this type of flow depends upon a number of factors that are difficult to evaluate. Length, slope and roughness all play a part and the inlet geometry is a particularly influential factor. Carter (Ref.2) has prepared charts which may be used to distinguish roughly between Type 5 and Type 6 flow for concrete or corrugated metal culverts with strictly defined entry geometry. The chart for concrete pipes is reproduced in Fig 2.

When Type 5 flow is identified, the discharge is calculated from the standard orifice equation:

$$Q = C\ A\sqrt{2gh} \qquad (3$$

where C = Coefficient of discharge

A = Cross sectional area of inlet

g = acceleration due to gravity

h = upstream head

Discharge calculations for Type 6 flow are carried out as for Type 4 flow except that tailwater level is taken as the crown of the outlet on the assumption that critical depth is at or close to the crown. This may not be the case, however; the pipe may still run full even though the critical depth is measurably below the crown. In this situation, tailwater level above the invert can be approximated as half the sum of critical depth and culvert height.

4. ENTRY LOSSES AT CULVERTS

Entry geometry can have a dramatic effect on the performance of a culvert; a more efficient entry design may allow the use of a culvert of smaller area with significant cost savings. Each design of entry must however be laboratory or field tested to confirm its performance. Since there are innumerable permutations of design features and because tests are often carried out for a specific application it is extremely difficult to generalise on the subject of entry losses.

Entry loss coefficients are commonly expressed in two ways, as a fraction of the reference velocity head (say K) or as a coefficient of discharge C applied to the energy equation in the form:

$$Q = C \times \text{Area} \times \sqrt{2g \times \text{Effective head}} \qquad (4$$

The relation between the two forms is:

$$K = 1/C^2 - 1 \qquad (5$$

For the simple case of a circular pipe set flush into a vertical wall the entry loss coefficient will range from 0.15 when the pipe is running half full to 0.5 when on the point of submergence. These values will fall to half or less if the entry is rounded to a radius of between 10 and 15 percent of the entry diameter.

The coefficient of discharge for the equation for

Type 5 flow will vary from 0.45 to 0.6 as head rises if the head is measured from the invert. However, for relatively low heads it is preferable to measure the head to the centre of the orifice when the coefficient will remain virtually constant at 0.6 when the entry has a square edge. Rounding the edges of the entry will raise this value to 0.75.

More detailed information on entry losses and friction coefficients can be found in references 1 to 8.

5. FIELD DATA

Initial enquiries to Water Authorities on the subject of culvert studies elicited a positive response from Yorkshire Water Authority who had set up a water level monitoring system on Batley Beck in Dewsbury. This Beck runs through a heavily built-up area and passes through numerous culverts, particularly under roads.

An initial inspection of the culverts was made and a location plan is shown in Fig. 3. Photographs of all culverts within a selected reach are shown in Plates 1 to 30.

Not all the culverts are suitable for investigation. A number will be selected and studied more fully on the basis of prototype data on head losses and flows.

A certain amount of water level data has already been acquired and further data is awaited.

6. LABORATORY TESTS

A laboratory investigation specifically aimed at determining losses at culvert barrel steps and discontinuities is at the planning stage for construction during 1989.

7. REFERENCES

1. BLAISDELL F.W., Hood inlet for closed conduit spillways, Proc. ASCE, Vol 86, HY 5, May 1960

2. CARTER R.W., Computation of peak discharge at culverts, US Geological Survey Circular 376, 1968

3. NEILL C.R., Hydraulic tests on pipe culverts, Research Council of Alberta, Alberta Highway Research Report 62-1, 1962

4. NORMANN J.M.,HOUGHTALEN R.J.,JOHNSTON W.J., Hydraulic design of highway culverts, US Dept of Transportation, Federal Highway Administration, Hydraulic Design Series No.5, Sept 1985

5. NORMANN J.M.,BOSSY H.G., Hydraulic flow resistance factors for corrugated metal conduits, US Dept of Transportation, Federal Highway Administration, Sept 1970

6. ROSSMILLER R.L.,DOUGAL M.D., Tapered inlet design using specific energy curves, Proc.A.S.C.E, Vol 108, HY1, Jan 1982

7. SHOEMAKER R.H.,CLAYTON L.A., Model studies of tapered inlets for box culverts, US Highway Research Board, Research Report 15-B, 1953

8. STRAUB L.G.,ANDERSON A.G.,BOWERS C.E., Importance of inlet design on culvert capacity, US Highway Research Board, Research Report 15-B, 1953

BIBLIOGRAPHY

1. ABT S.R and RUFF J.R Estimating culvert scour in cohesive material
Proceedings American Society of Civil Engineers
Vol.108 No.HY1, January 1982 p.25-34

2. ABT S.R, KLOBERDANZ R.L and MENDOZA C Unified culvert scour determination
Journal of Hydraulic Engineering (American Society of Civil Engineers) Vol.110 No.10, October 1984 p.1475-1479

3. ABT S.R et al Influence of culvert shape on outlet scour
Journal of Hydraulic Engineering (American Society of Civil Engineers) Vol.113 No.3, March 1987 p.393-400

4. BLAISDEL F.W Flow in culverts and related design philosophies
Proceedings of the American Society of Civil Engineers Vol 92, HY 2, March 1966, p.19-31

5. BODHAINE G.L Measurement of peak discharge at culverts by indirect methods
United States Geological Survey 1968
Techniques of water resources investigations of the U.S.G.S. Book 3 Chapter A3

6. BOHAN J.P Erosion and riprap requirements at culvert and storm-drain outlets, Hydraulic laboratory investigation
United States Army Engineer Waterways Experiment Station, Vicksburg, Research Report H-70-2, January 1970

7. BOONKIRD V. Culverts as flow measuring devices
CUSUS WASH Council of U.S. Universities for Soil and Water Development in Arid and Sub-humid areas. Water Management Technical Report No. 17, February 1972

8. BROWN C.B Forces on rigid culverts under high fills
Proceedings of the American Society of Civil Engineers
93, ST 5, October 1967, p.195-215

9. CARTER R.W Computation of peak discharge at culverts
U.S Geological Survey Circular 376, Washington 1957

BIBLIOGRAPHY (contd)

10. CIVIL ENGINEERING AND PUBLIC WORKS REVIEW Flow in rectangular culverts and channels
C.E.P.W.R. 64. No.760, November 1969,p.1150.

11. ESCRITT L.B Drainage and sewerage
National Salt Glazed Pipe Manufacturers' Association

12. FLETCHER B.P and GRACE J.L Practical guidance for estimating and controlling erosion at culvert outlets
United States Army Engineer Waterways Experiment Station Vicksburg, Miscellaneous Paper H-72-5, May 1972

13. FRENCH J.L and BOSSY H.G Tapered box culvert inlets with fall concentration in the inlet structure
U.S. National Bureau of Standards, Seventh Progress Report on Hydraulics of Culverts 9528, July 1967

14. FRENCH J.L Hydraulics of improved inlet structures for pipe culverts
U.S. National Bureau of Standards, Fourth Progress Report on Hydraulics of Culverts 7178, August 1961

15. FRENCH J.L Tapered box culvert inlets
U.S National Bureau of Standards, Sixth Progress Report on Hydraulics of Culverts 9355, June 1966

16. FRENCH J.L Non-enlarged box culvert inlets
U.S. National Bureau of Standards, Seventh Progress Report on Hydraulics of Culverts 9327, June 1966

17. GEORGE J.F Filling and emptying system, Walter Bouldin lock, Coosa River waterway, Alabama. Hydraulic model investigation
United States Army Waterways Experiment Station, Vicksburg Technical Report HL-84-8, September 1984

18. HATTERSLEY R.T and CORNISH B.A Hydraulic model investigation of gabion protection for culvert outlets
University of New South Wales Water Research Laboratory Report No.48, October 1961

19. HERR L.A and BOSSY H.G Hydraulic charts for the selection of highway culverts
U.S. Bureau of Public Roads. Hydraulic Engineering Circular No.5, April 1969

BIBLIOGRAPHY (contd)

20. HERR L.A and BOSSY H.G Capacity charts for the hydraulic design of highway culverts
U.S. Bureau of Public Roads. Hydraulic Engineering Circular No.10, March 1965

21. HERSCHY R.W and NEWMAN J.D The measurement of open channel flow by the electromagnetic gauge. Advances in Hydrometry. Proceedings of the Exeter Symposium International Association of Hydrological Sciences, July 1982 p.215-227

22. HOLLY E.R and WADDEL K.M Stratified flow in Great Salt Lake culvert
Proceedings American Society of Civil Engineers Vol.102 No.HY7, July 1976 p.969-985

23. HYDRAULICS RESEARCH STATION M64 and M42 Motorways. Hydraulic model tests on the proposed crossings of the River Trent at Stanton-by-Bridge
Hydraulics Research Station DE4, November 1972

24. HYDRAULICS RESEARCH STATION Hydraulic model of Diddington Reservoir
Hydraulics Research Station EX 184, August 1962

25. HYDRAULICS RESEARCH STATION Hydraulic design of culverts for Loch Long jetty access road
Hydraulics Research Station EX 1057, June 1982

26. HYDRAULICS RESEARCH STATION Hadlow culvert, Kent. Report on storm runoff calculations
Hydraulics Research Station EX 979, February 1981

27. HYDRAULICS RESEARCH STATION Inswork Point Power Station. Preliminary design of outfall channel
Hydraulics Research Station EX 534, January 1971

28. HYDRAULICS RESEARCH LTD. Performance of storm sewer system at Newton Mearns, Glasgow
Hydraulics Research Ltd. EX 1245

29. HYDRAULICS RESEARCH LTD. FLUCOMP-user defined control cells
Hydraulics Research Ltd. EX 1282, January 1985

BIBLIOGRAPHY (contd)

30. INTERNATIONAL INSTITUTE FOR LAND RECLAMATION AND IMPROVEMENT
Code of practice for the design of open watercourses and ancilliary structures, Wagenigen, The Netherlands. Bulletin 7, 1964

31. KRIMGOLD D.B Hydrology of culverts
Proceedings of the Highway Research Board, 1946

32. LINK J.R, TENNENT R.C. and HARRISON L.J. Electronic computer program for hydraulic analysis of box culverts
U.S. Department of Transportation. Bureau of Public Roads
No. PB191356, April 1969

33. MAVIS F.T Capacity of creosoted wood culverts
Report from Engineering News Record, October 18th 1934

34. MAYS L.W Optimal design of culverts under uncertainties
Proceedings American Society of Civil Engineers, Vol 105, No.HY5, May 1979 p.443-460

35. METZLER D.E and ROUSE H Hydraulics of box culverts
University of Iowa. Studies in Engineering, Bulletin 38, 1959

36. MILLER D.S Isle of Grain Power station. Model tests of the cooling water outfall structure
British Hydromechanics Research Association Fluid Engineering
RR 1119, November 1971

37. NEILL C.R Hydraulic investigations related to large corrugated metal culverts
A thesis submitted to the Faculty of Graduate Studies
Dept of Civil Engineering, University of Alberta,Canada, 1961

38. NEILL C.R Hydraulic tests on pipe culverts. Research Council of Alberta, Highway Research Report 62-1, 1962
A thesis submitted to the Faculty of Graduate Studies, Department of Civil Engineering, University of Alberta, Canada, 1961

39. NORMAN J.M, HOUGHTALEN R.J and JOHNSTON W.J Hydraulic design of highway culverts
Federal Highway Administration (United States of America)
Hydraulic Design Series No.5, September 1985

BIBLIOGRAPHY (contd)

40. NORMAN J.M Improved design of highway culverts
Civil Engineering (A.S.C.E.), March 1975 p.70-73.

41. PICKERING G.A Lock culvert valve coefficients; hydraulic laboratory investigation
United States Army Waterways Experiment Station Vicksburg
Technical Report HL-81-10, September 1981

42. POOTS A.D and COCHRANE S.R Design flood estimation for bridges, culverts and channel improvement works on small rural catchments.
Proceedings Institute of Civil Engineers Part 1: Design and Construction Vol.66, November 1979 p.663-666

43. PRICE B.E Digital computers in circular culvert design
Proceedings American Society of Civil Engineers, Vol.98 No.TE3, August 1972 p.547-562

44. ROSSMILLER R.L and DOUGAL M.D Tapered inlet design using specific energy curves
Proceedings American Society of Civil Engineers, Vol.108 No.HY1, January 1982 p.127-135.

45. ROZANOV N.P and ROZANOVA N.N Some problems of modelling water outlet structures with free-surface flow
Proceedings 19th Congress International Association for Hydraulic Research, New Delhi, 1-7th February 1981, Vol.V, p.81-91

46. SELVALINGHAM S An hydraulic design chart for free surface culverts
Civil Engineering and Public Works Review 66 No.777, April 1971 p.397-399

47. SHEN H.W (ed) River Mechanics Vol.2
Published by H.W. Shen Fort Collins Co, 1971

48. SMITH G.L Scour and scour control below cantilevered culvert outlets
Colorado State University Research Foundation Fort Collins Colorado CER No.61 GLS14, 1961

49. SMITH G.L Scour and energy dissipation below culvert outlets
Colorado Agricultural and Mechanical College, Fort Collins Colorado CER No.57 GLS10, April 1957

BIBLIOGRAPHY (contd)

50. STRAUB L.G, ANDERSON A.G and BOWERS C.E. Importance of inlet design on culvert capacity
University of Minnesota, St.Anthony Falls. Hydraulic Laboratory Technical Paper No.13 Series B, January 1953 p.1-21

51. STRAUB L.G and MORRIS H.M Hydraulic data comparison of concrete and corrugated metal culvert pipes
University of Minnesota, St.Anthony Falls. Hydraulic Laboratory Technical Paper No.3 Series B, July 1950 p.1-25.

52. STRAUB L.G and MORRIS H.M Hydraulic tests on concrete culvert pipes
University of Minnesota, St.Anthony Falls. Hydraulic Laboratory Technical Paper No.4 Series B, July 1950 p.1-22

53. STRAUB L.G and MORRIS H.M Hydraulic tests on corrugated metal culvert pipes
University of Minnesota, St.Anthony Falls. Hydraulic Laboratory Technical Paper No.5 Series B, July 1950 p.1-24

54. STRAUSS V Theoretical and experimental study of forces acting on a culvert tainter valve
Proceedings 20th Congress International Association for Hydraulic Research, Moscow, 5-9th September 1983 Vol.III p.436-442

55. TALBOT W Hydraulic elements of a partially silted round section.
Transactions of the American Society of Agricultural Engineers Vol.21, No.2, March-April 1978 p.288-292

56. TUNG Y.K and MAYS L.W Risk analysis for hydraulic design
Proceedings American Society of Civil Engineers Vol.106, No.HY5, May 1980 p.893-913

57. UNITED STATES DEPARTMENT OF TRANSPORTATION Hydraulic design of improved inlets for culverts
Federal Highway Administration. Hydraulic Engineering Circular No.13, August 1972

58. U.S. HIGHWAY RESEARCH BOARD Culvert hydraulics
Research Report 15-B, 1953

59. VALLENTINE H.R and CORNISH B.A Notes on the design of culverts with outlet scour control
University of New South Wales. Water Research Laboratory Report No.62, March 1962

BIBLIOGRAPHY (contd)

60. WRIGHT-MCLAUGHLIN ENGINEERS DENVER CO Urban storm drainage Criteria manual, March 1969

61. YEN B.C, CHENG S.T and TANG W.H Reliability of hydraulic design of culverts
Reprint from Proceedings of International Conference on Water Resources Development, Taipei, Taiwan, May 1980 p.991-1001

62. YEN B.C and TANG W.H Assessment of data worth in water resources projects
Proc IAHR 18th Congress, Cagliari Italy, September 1979, Vol.2 p.507-514

63. YIXING BAO, YEO-KOUNG TUNG and HASFURTHER V.R Evaluation of uncertainty in flood magnitude estimator on annual expected damage costs of hydraulic structures
Water Resources Research Vol.113 No.3, November 1987

64. YOUNG G.K, CHILDREY M.R and TRENT R.E Optimal design for highway drainage culverts
Proceedings American Society of Civil Engineers, Vol.100 No.HY7, July 1974 p.971-993

FIGURES.

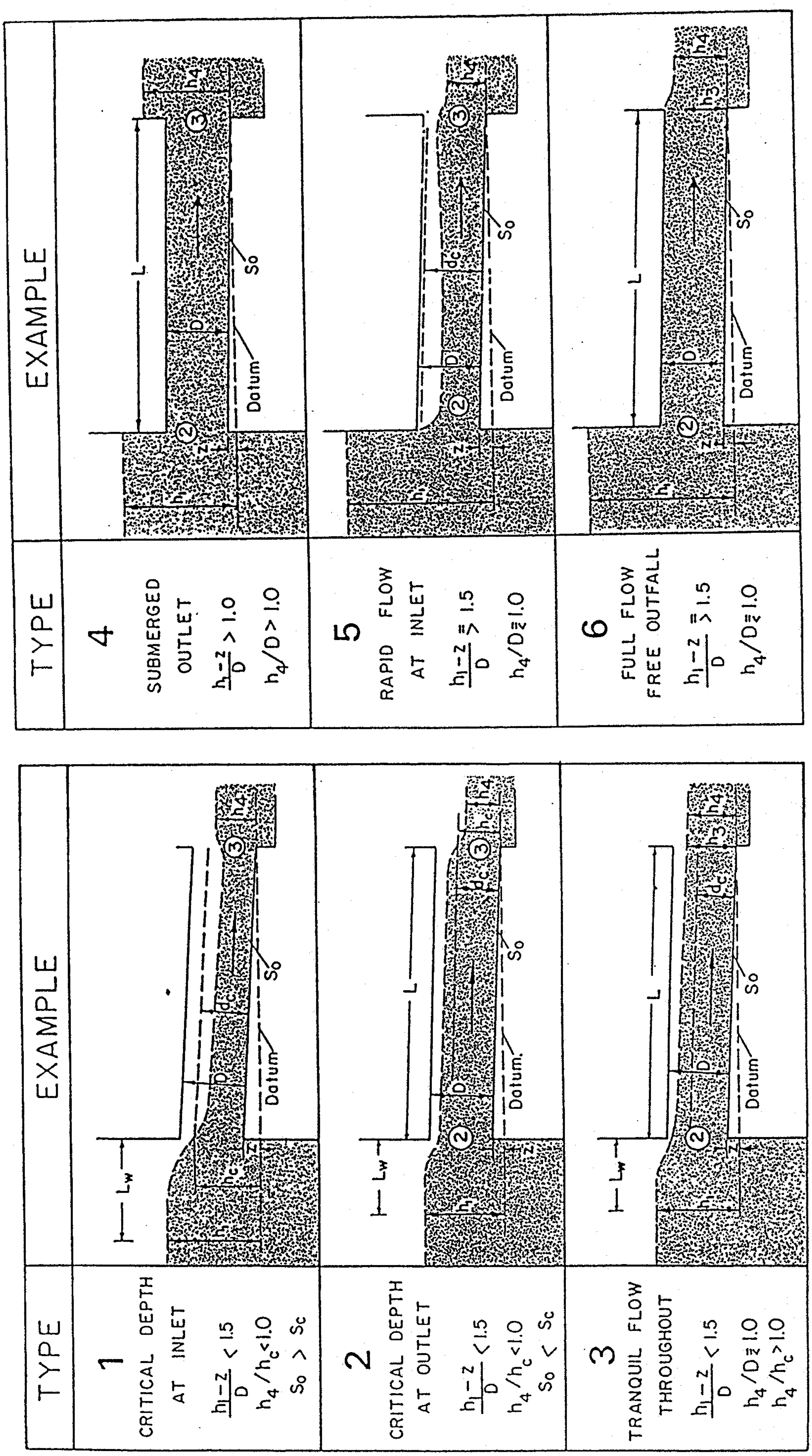


Fig 1 Types of culvert flow

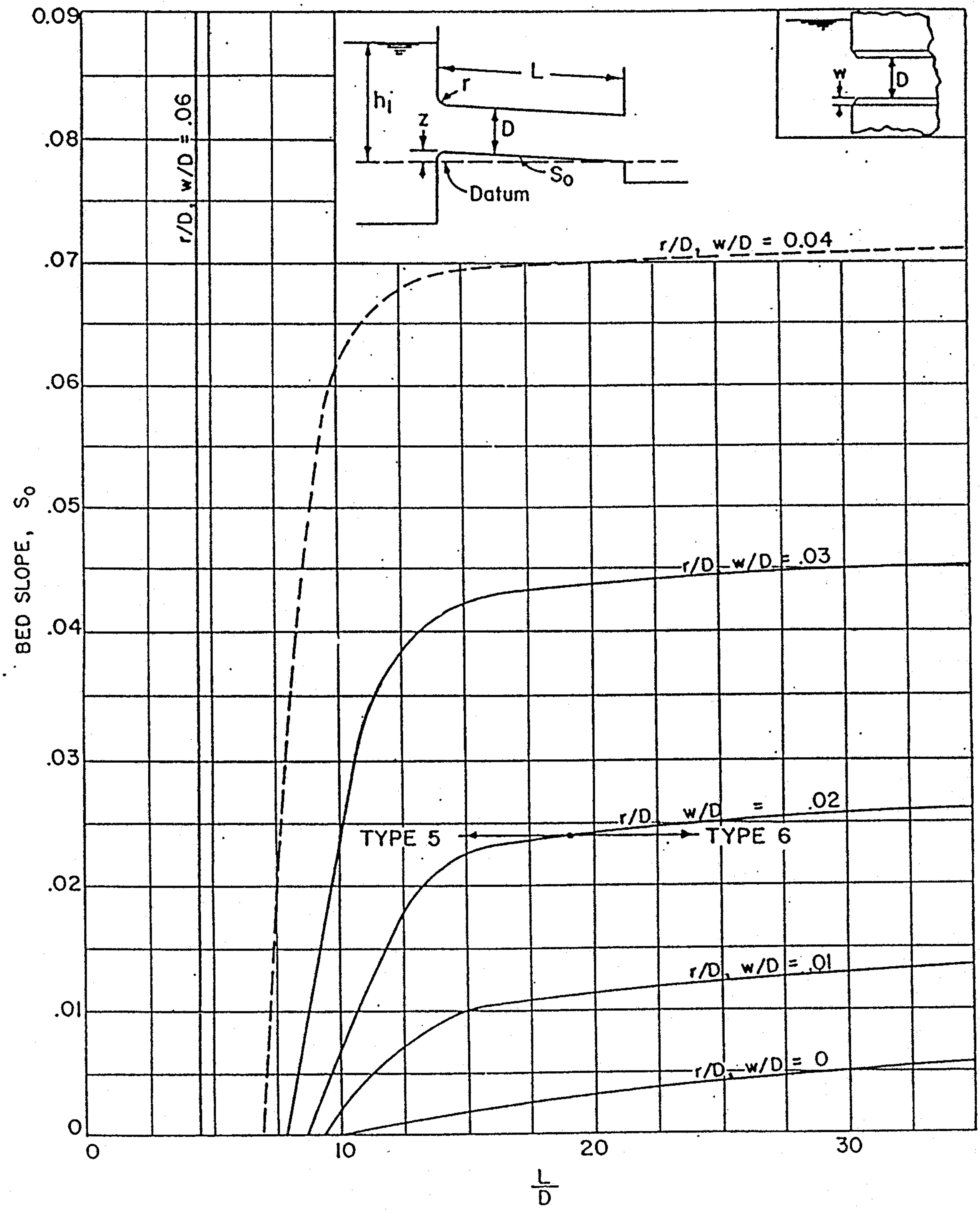


Fig 2 Criteria for types 5 and 6 flow in box or pipe culverts

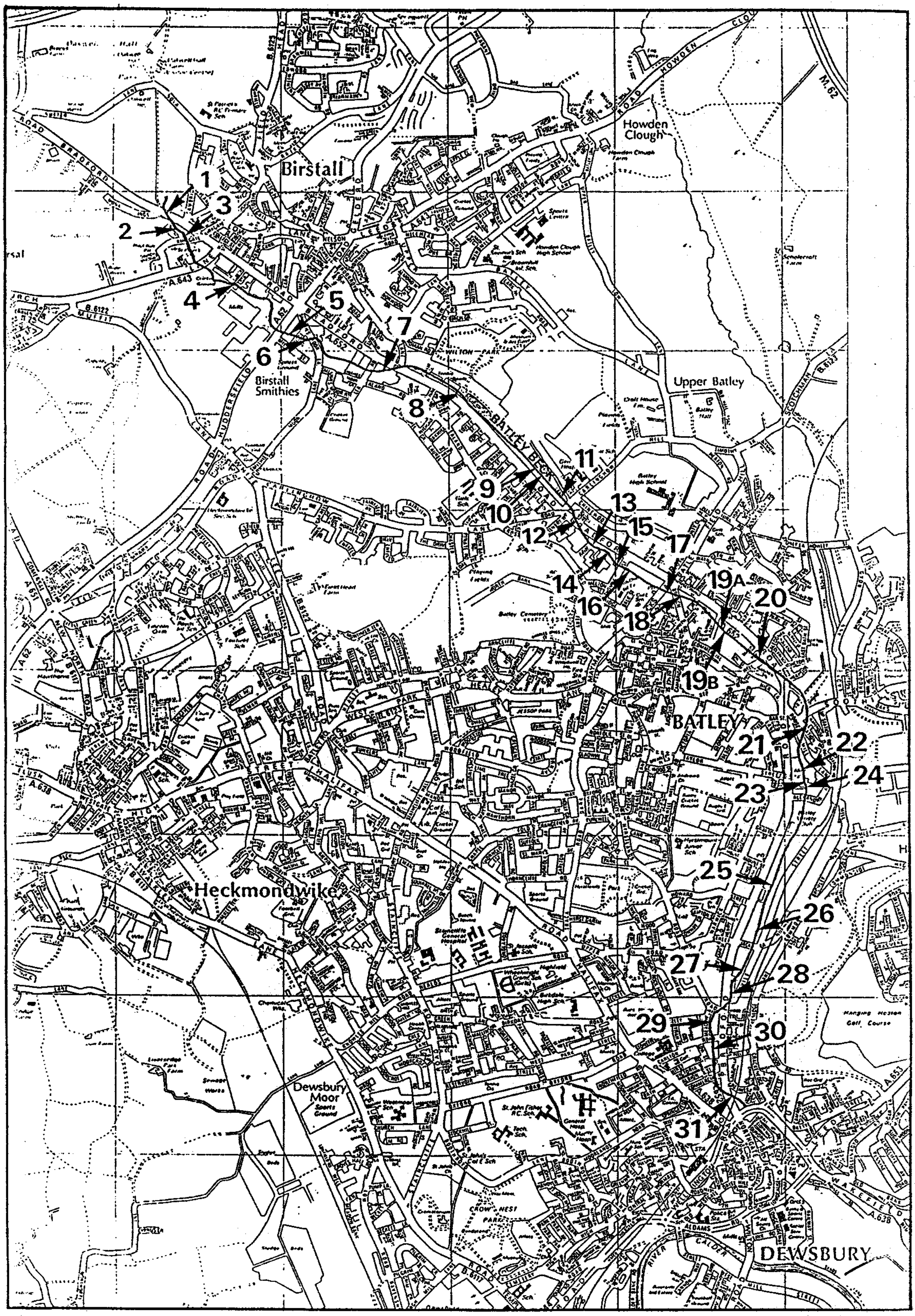


Fig 3 Location plan of culverts on Batley Beck

PLATES.

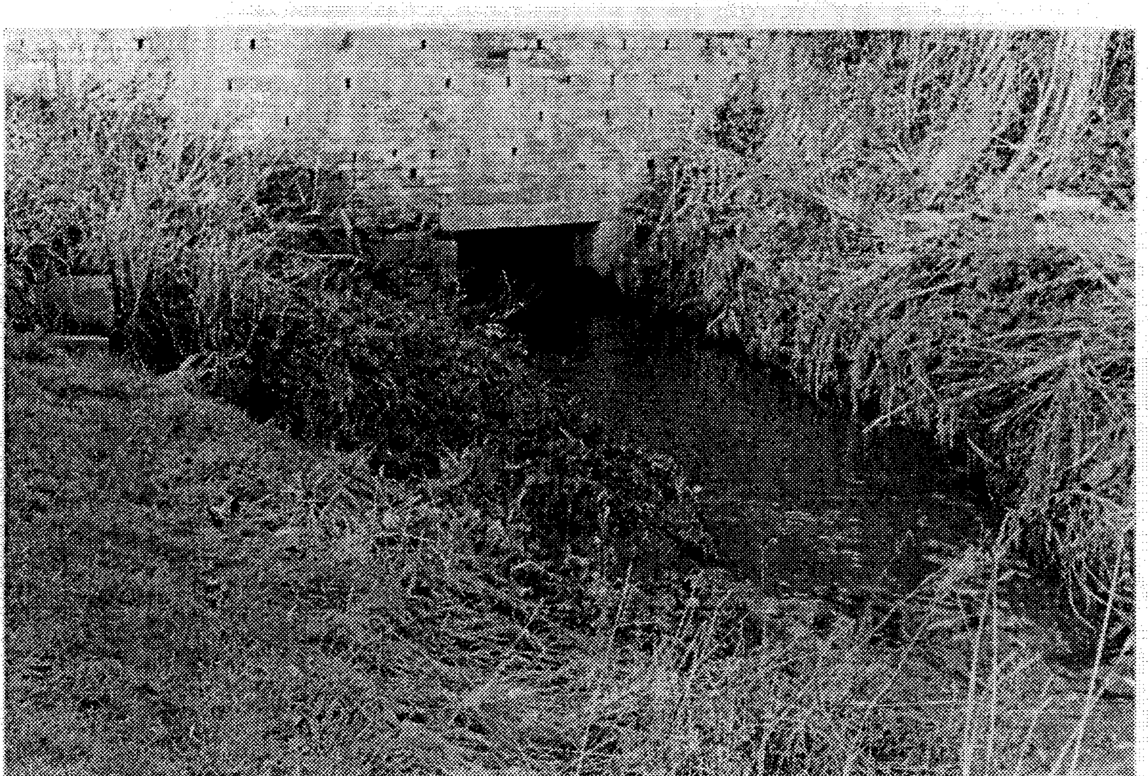
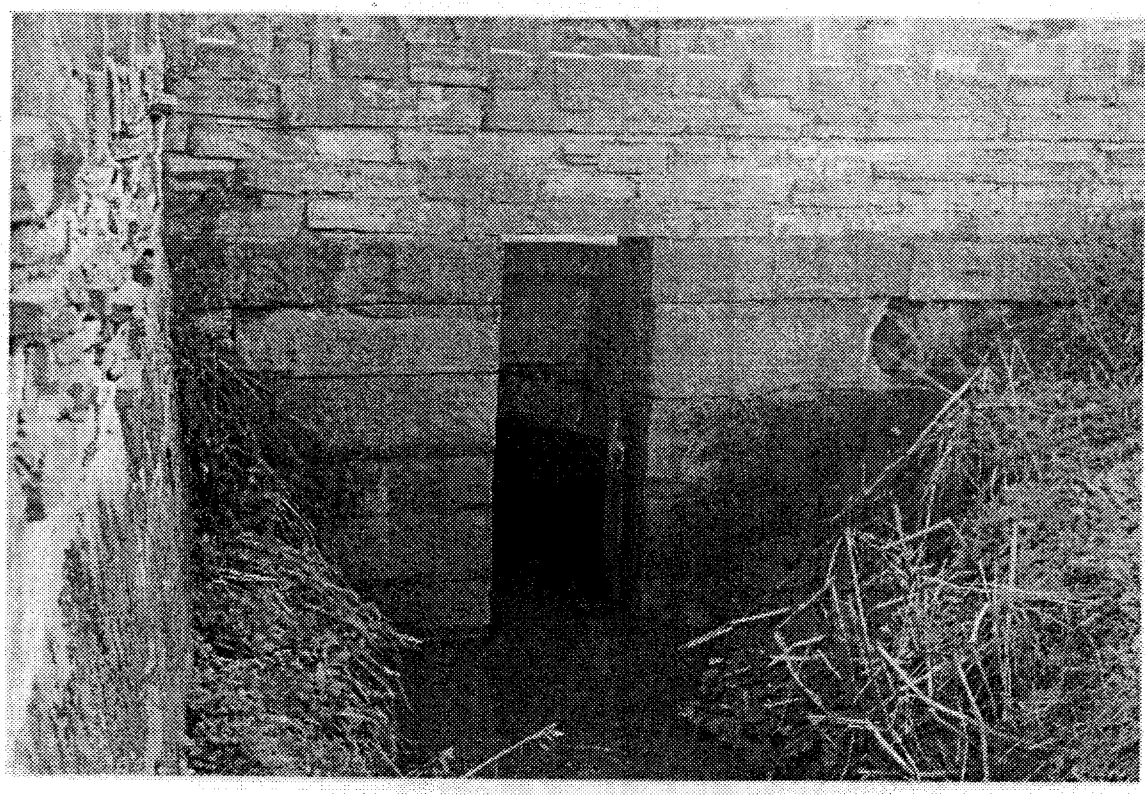


PLATE 1 CULVERT No.1 (Inlet above - Outlet below)



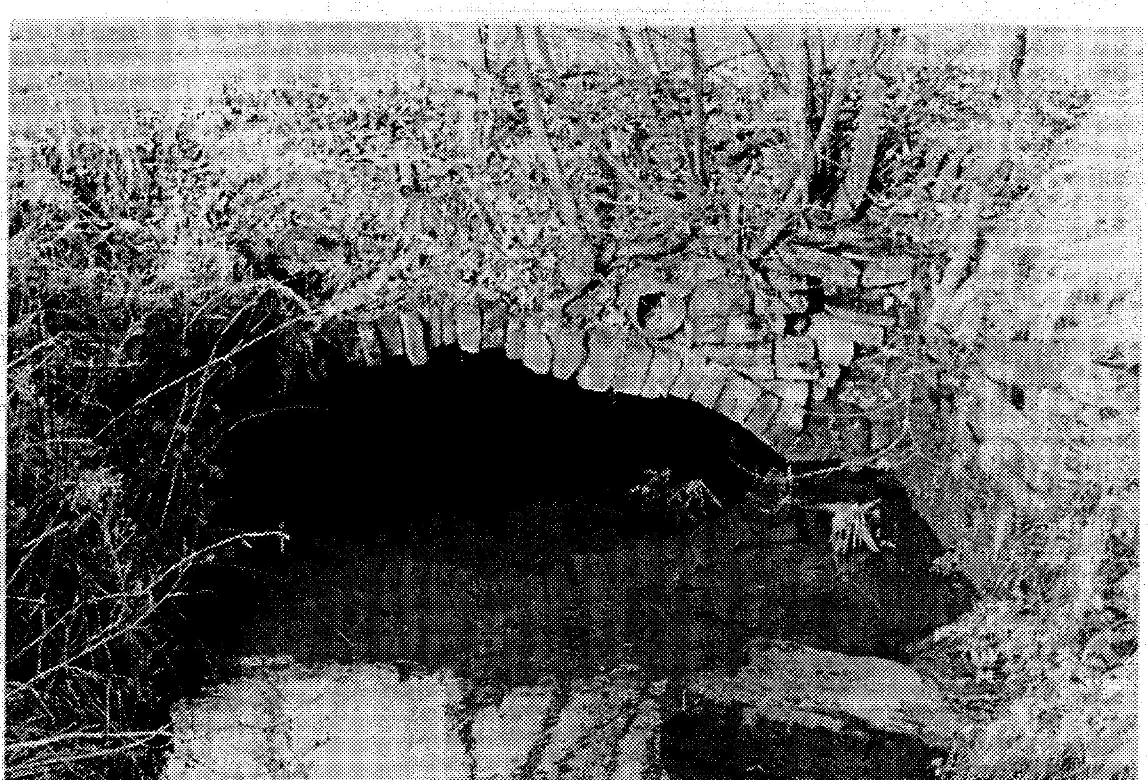


PLATE 2 CULVERT No.2 (Inlet above - Outlet below)

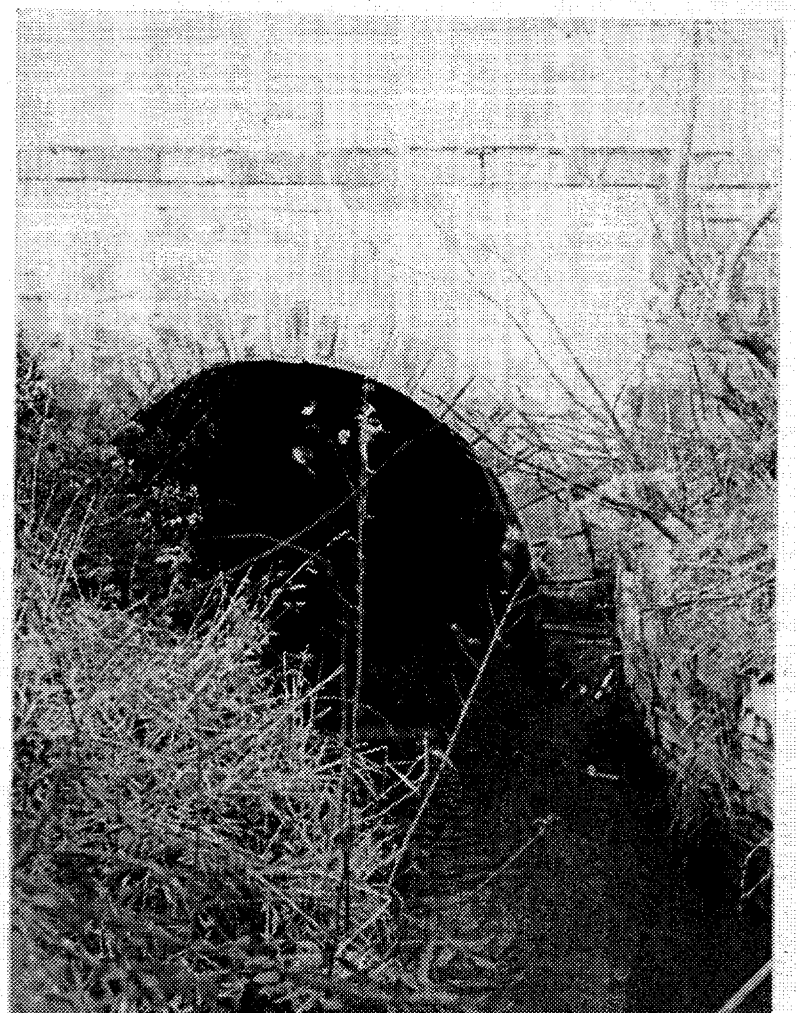
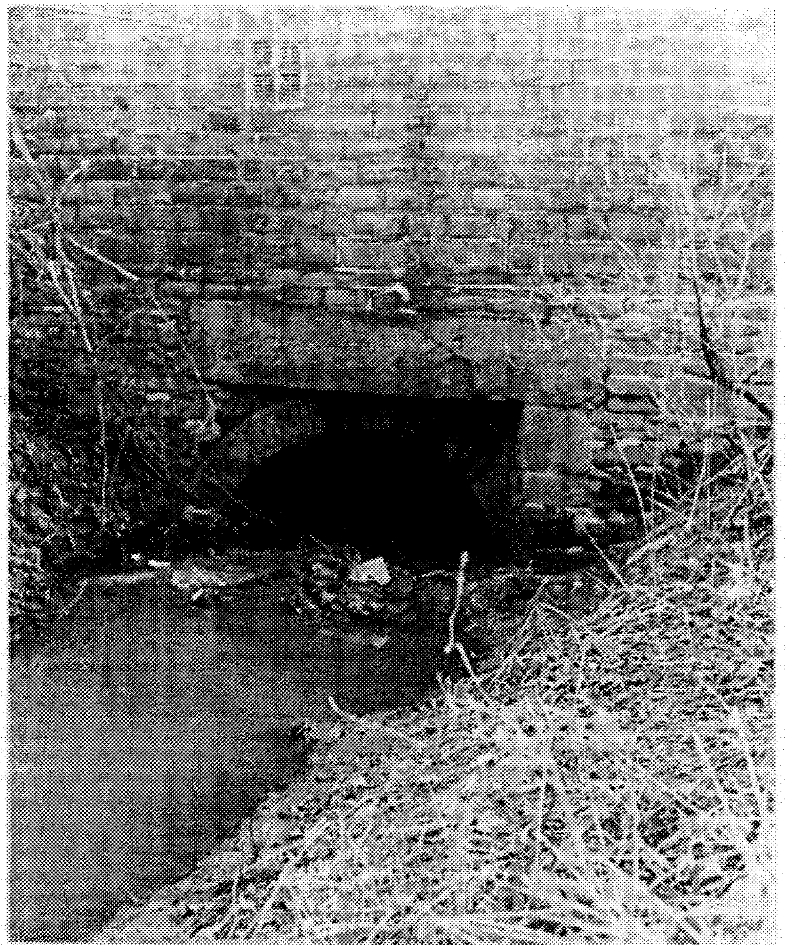


PLATE 3 CULVERT No.3 (Inlet above - Outlet below)



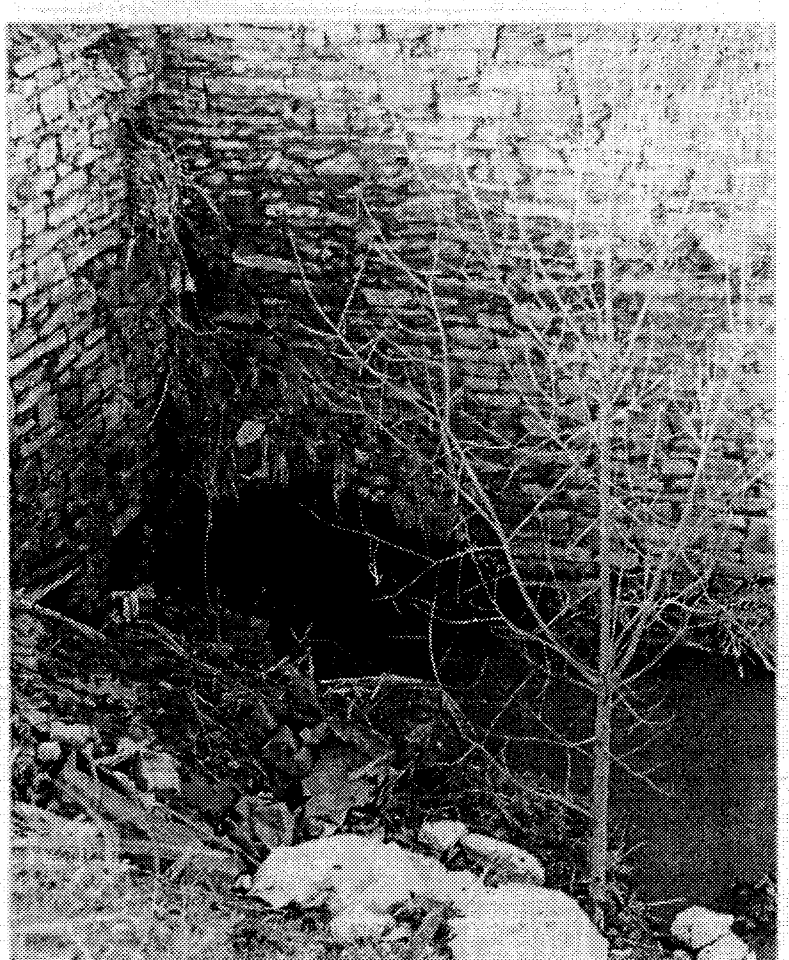
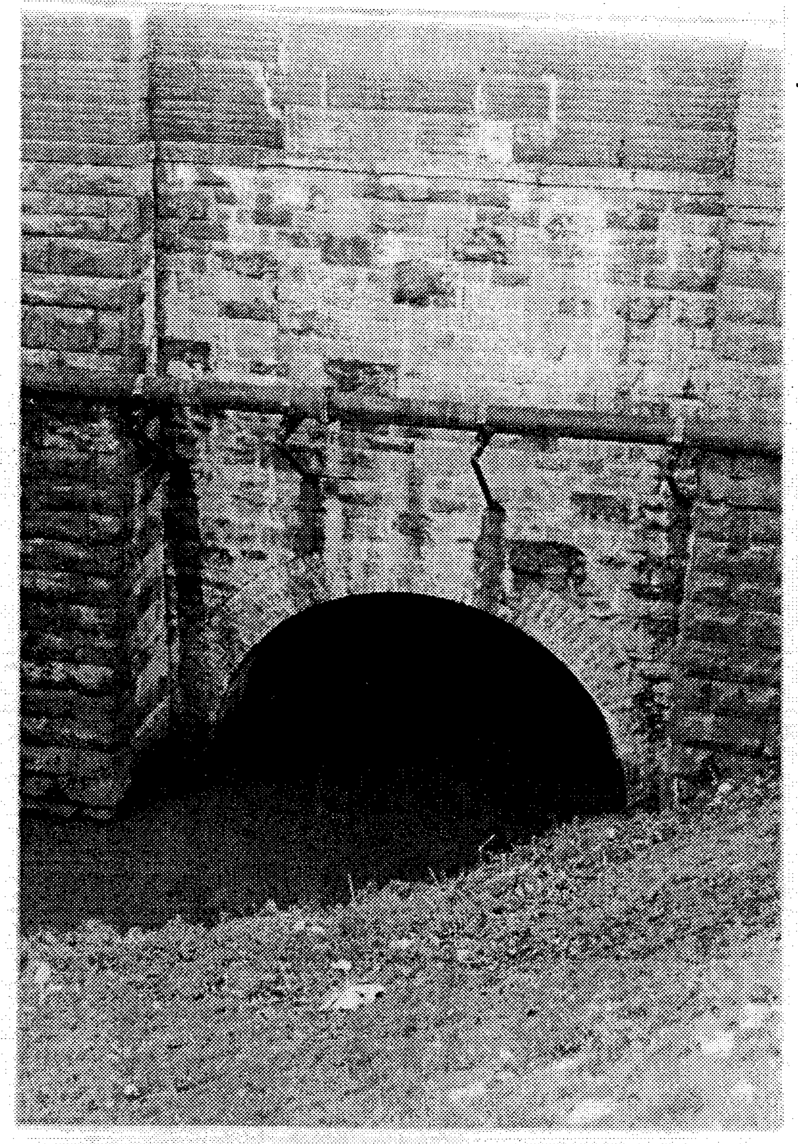


PLATE 4   CULVERT No.4   (Inlet above - Outlet below)



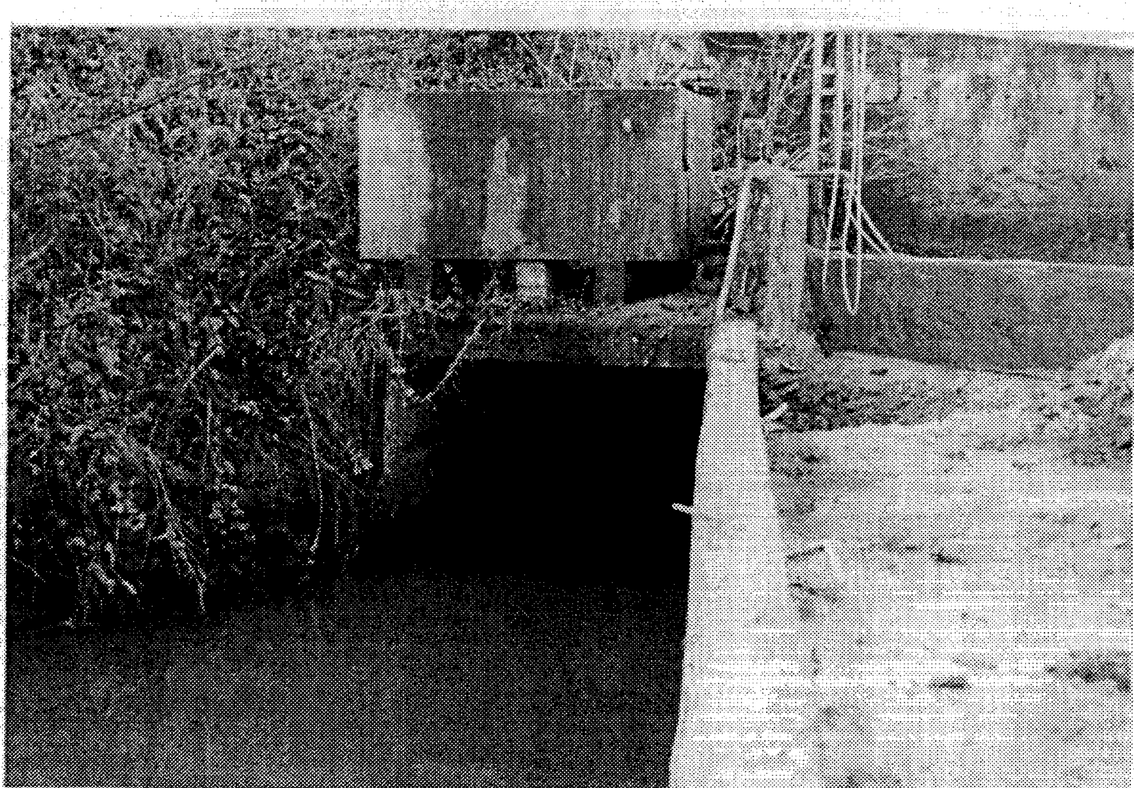
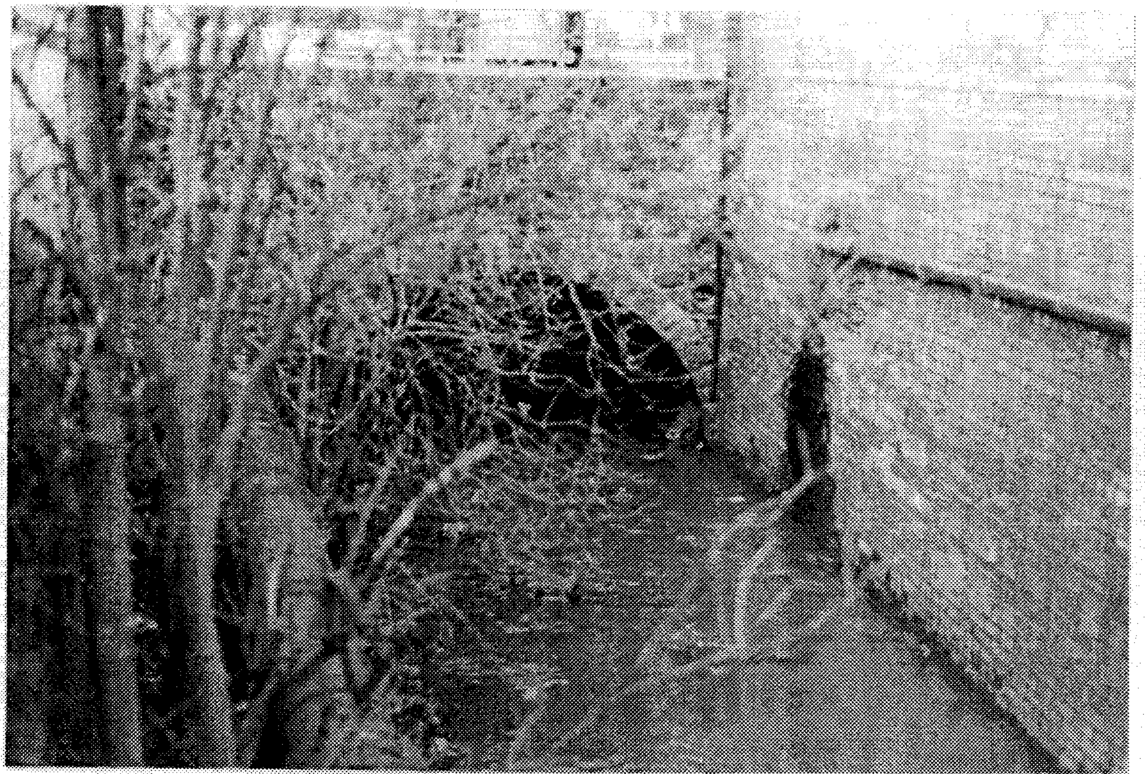


PLATE 5 CULVERT No.5 (Inlet above - Outlet below)

PLATE 6 CULVERT No.6 (Inlet above - Outlet below)



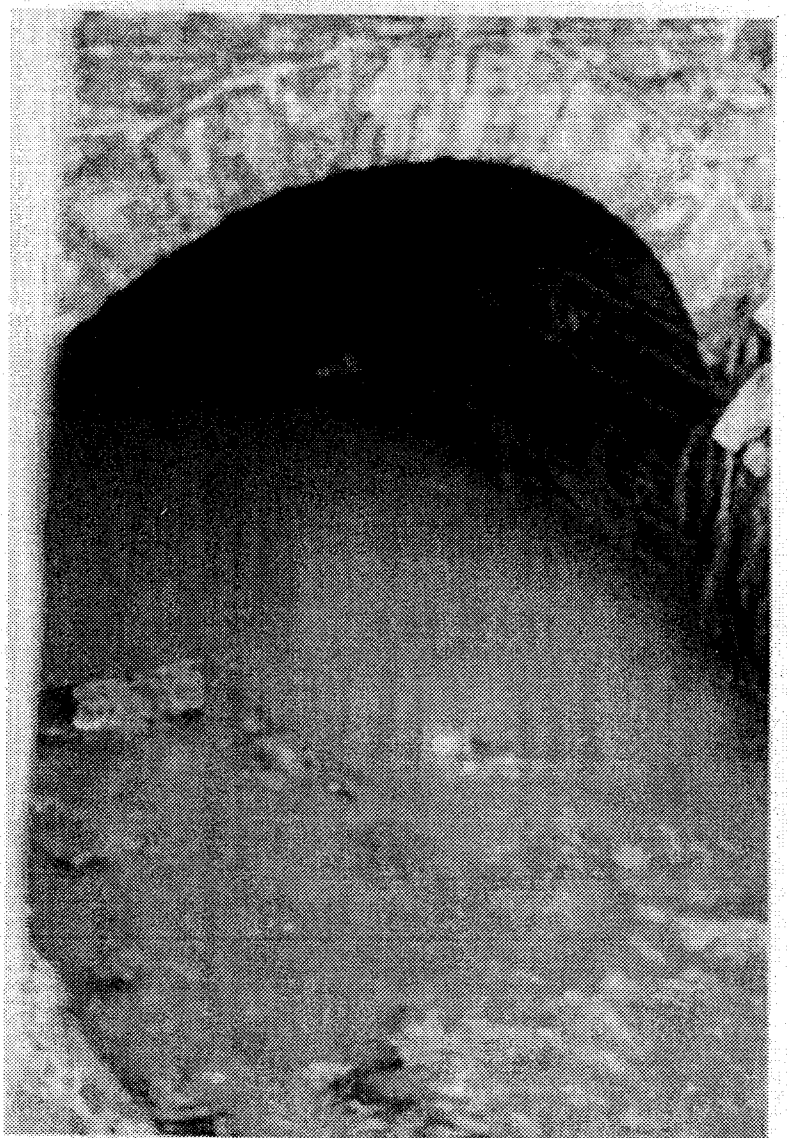


PLATE 7 CULVERT No.7 (Inlet above - Outlet below)

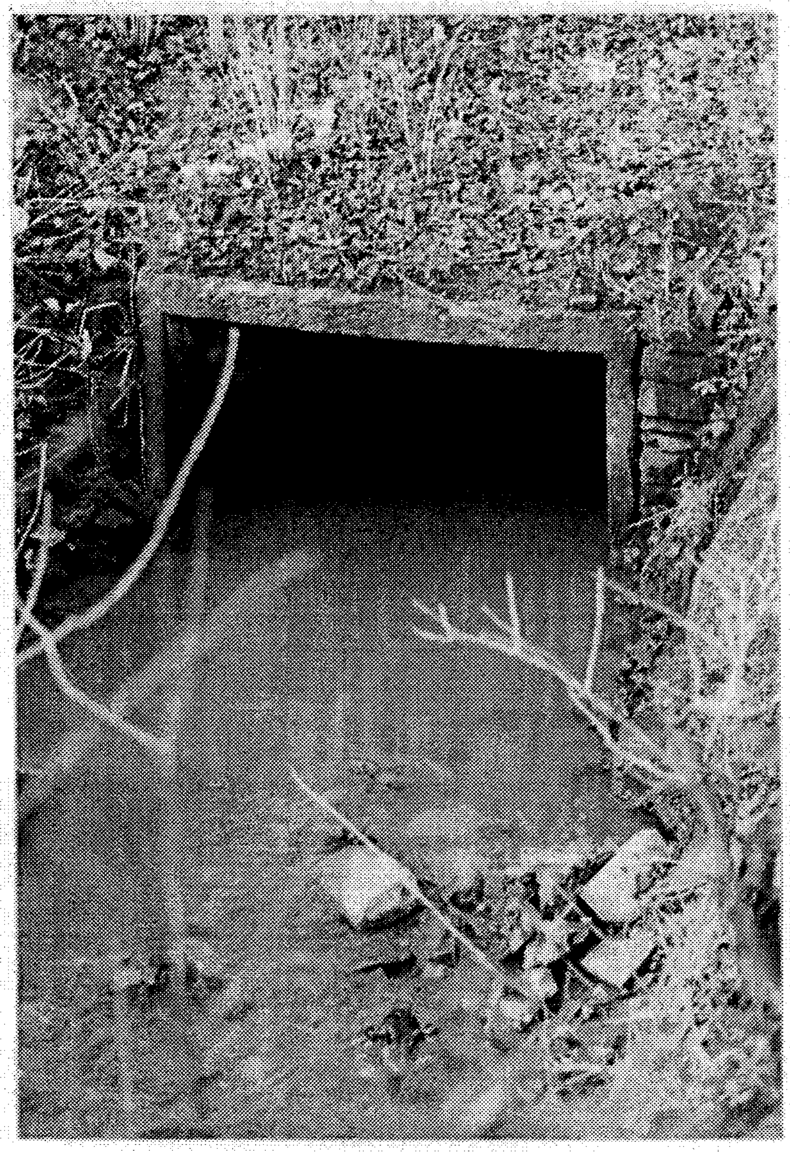


PLATE 8 CULVERT No.8 (Inlet above - Outlet below)

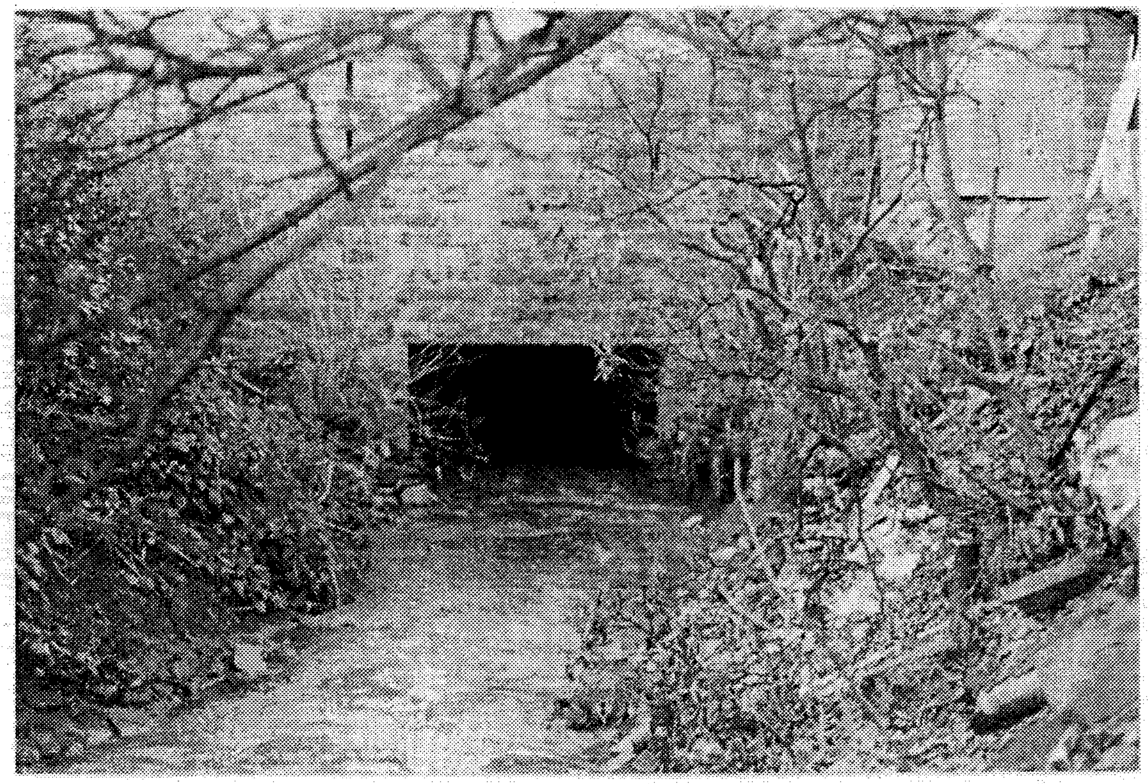
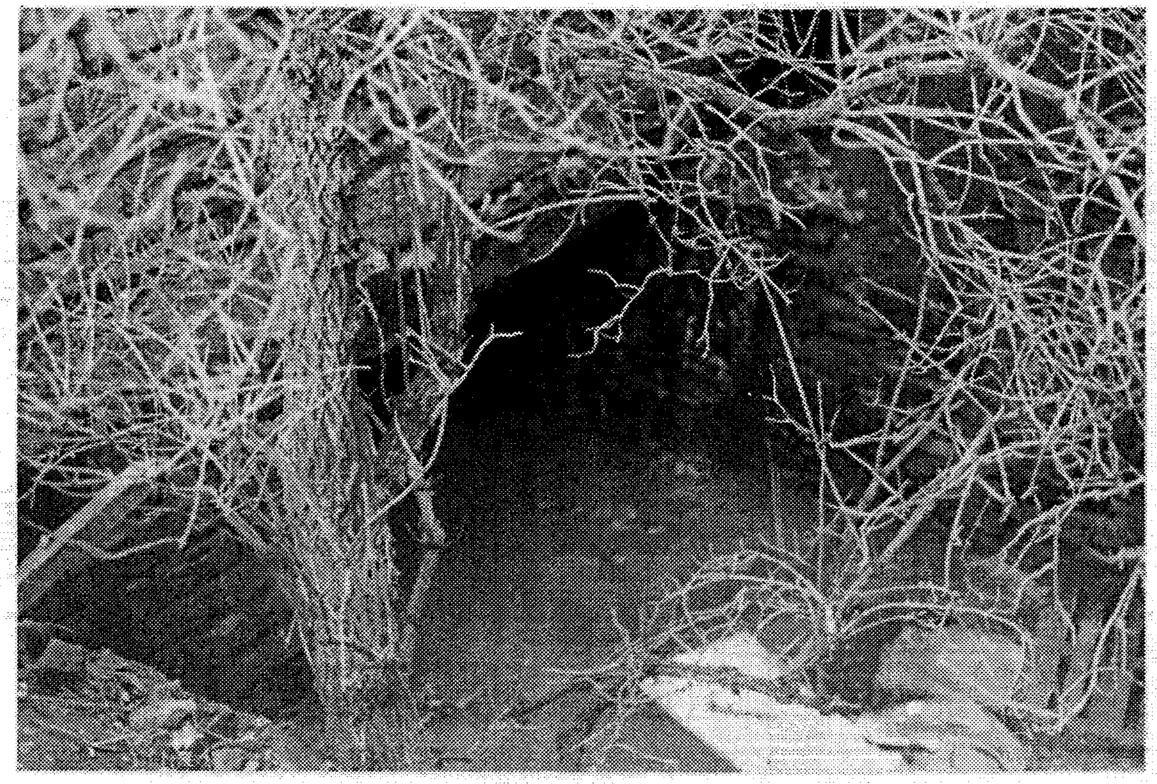


PLATE 9 CULVERT No.9 (Inlet above - Outlet below)



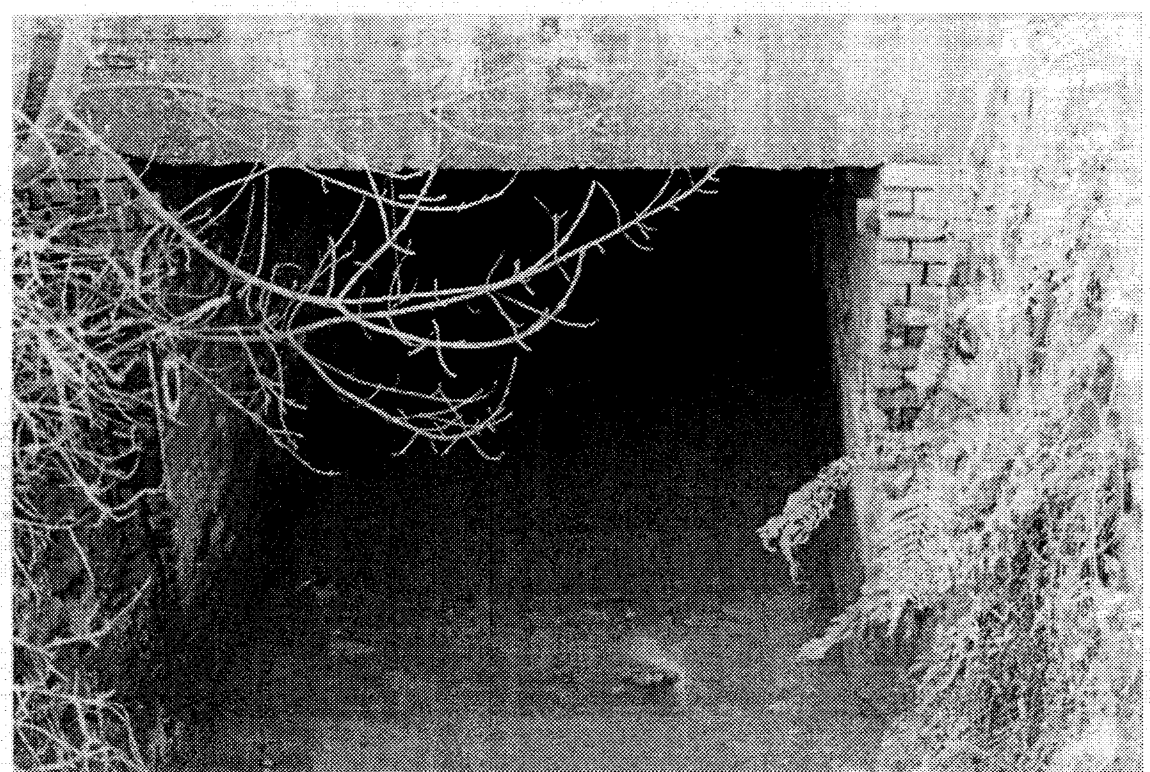


PLATE 10 CULVERT No.10 (Inlet above - Outlet below)

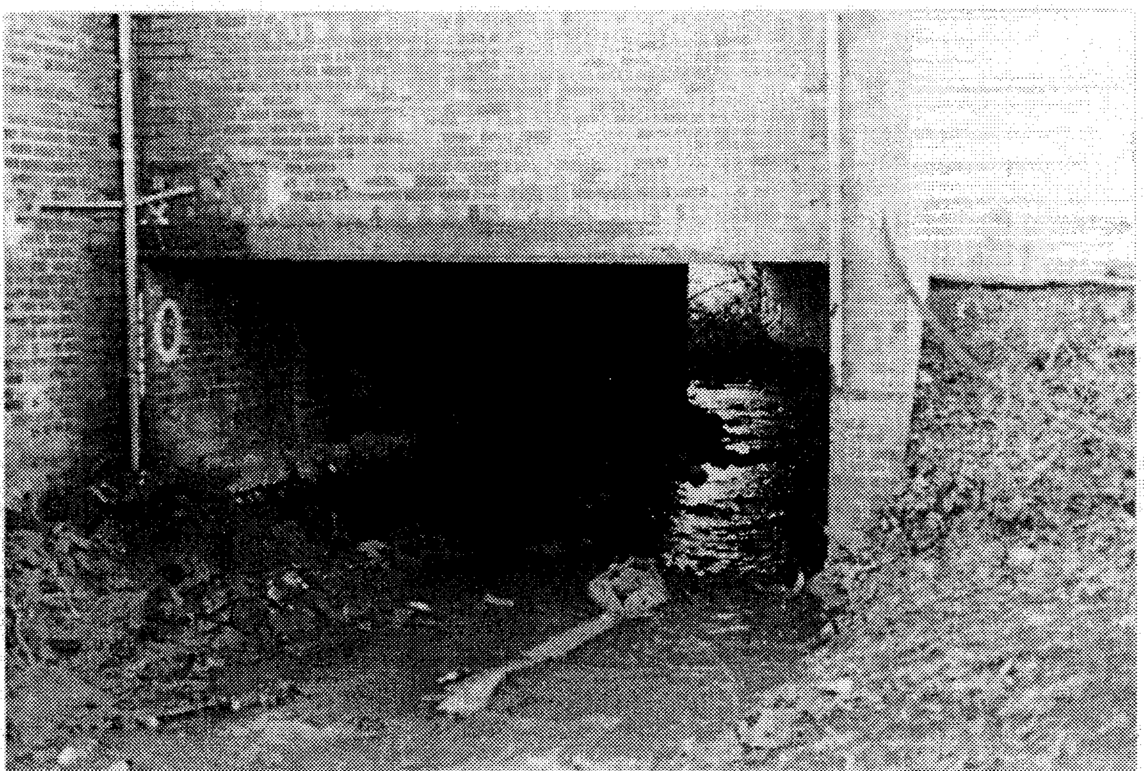


PLATE 11 CULVERT No.11 (Inlet above - Outlet below)

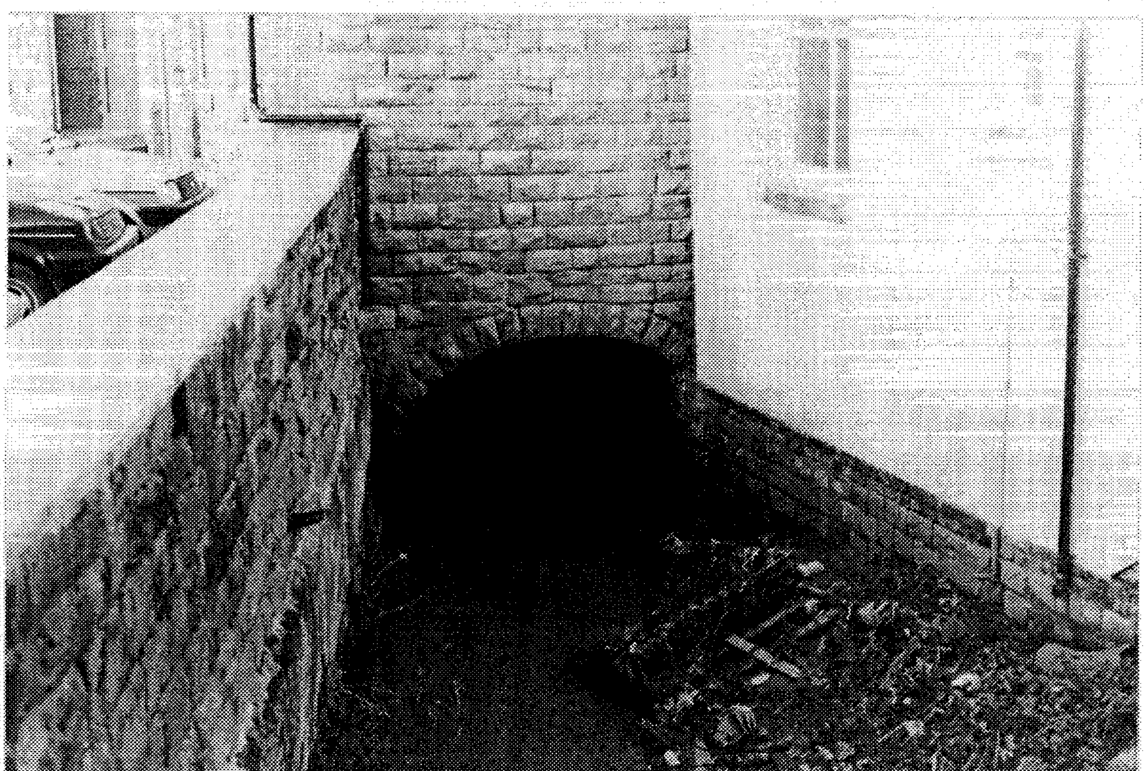


PLATE 12 CULVERT No.12 (Inlet above - Outlet below)

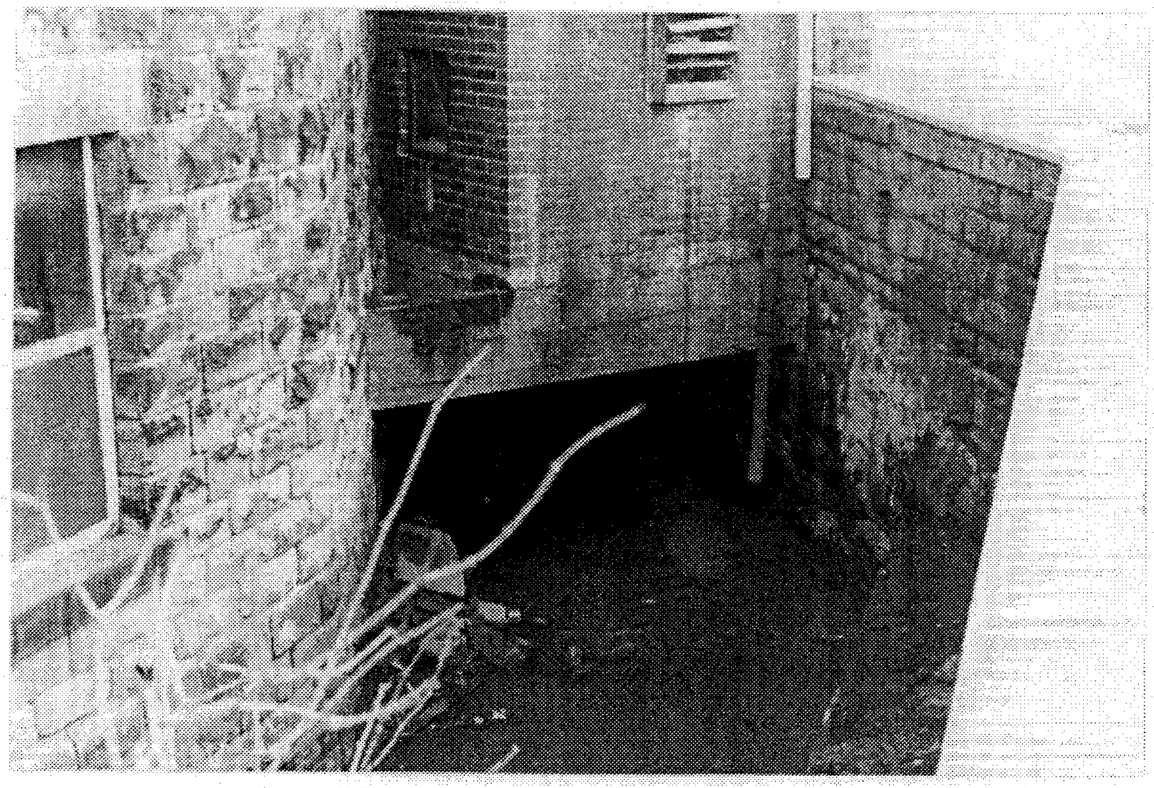
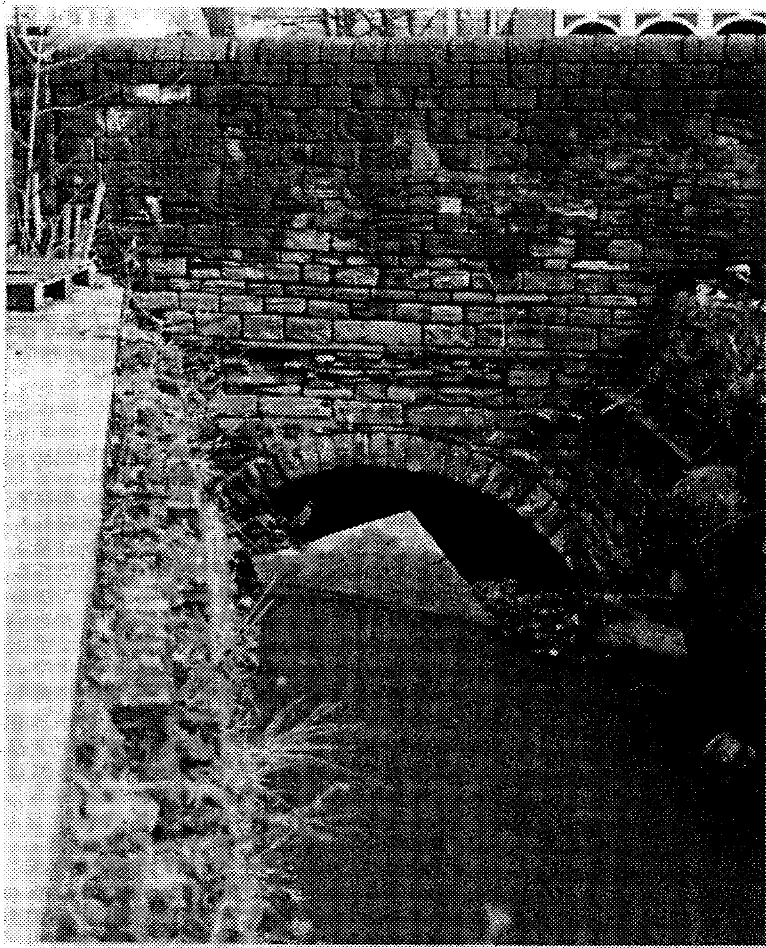


PLATE 13 CULVERT No.13 (Inlet above - Outlet below)



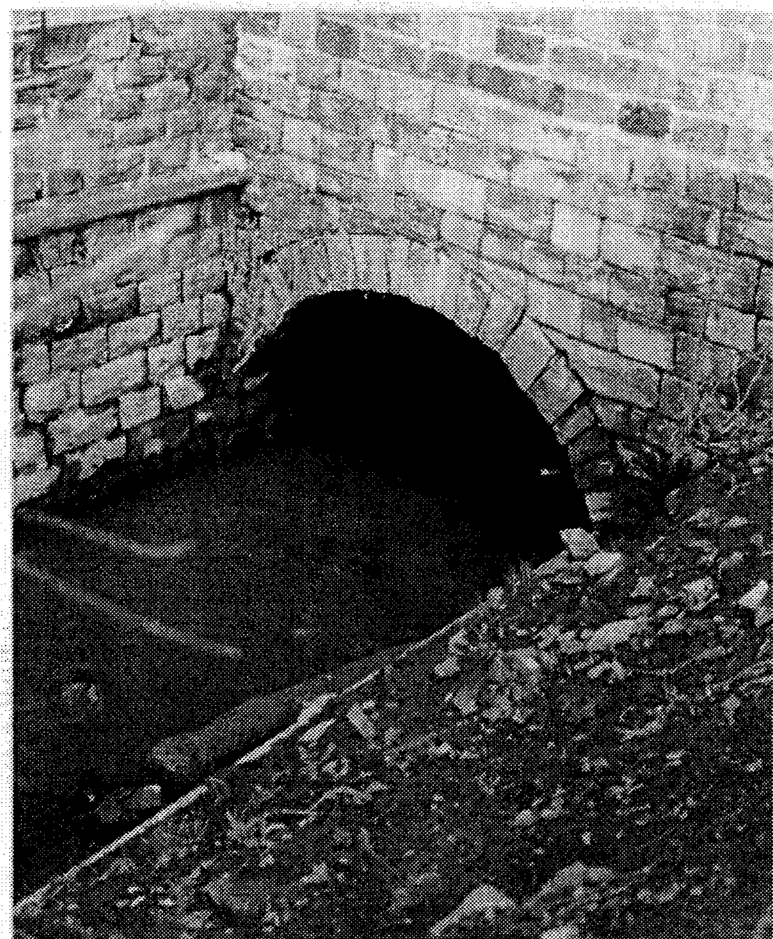
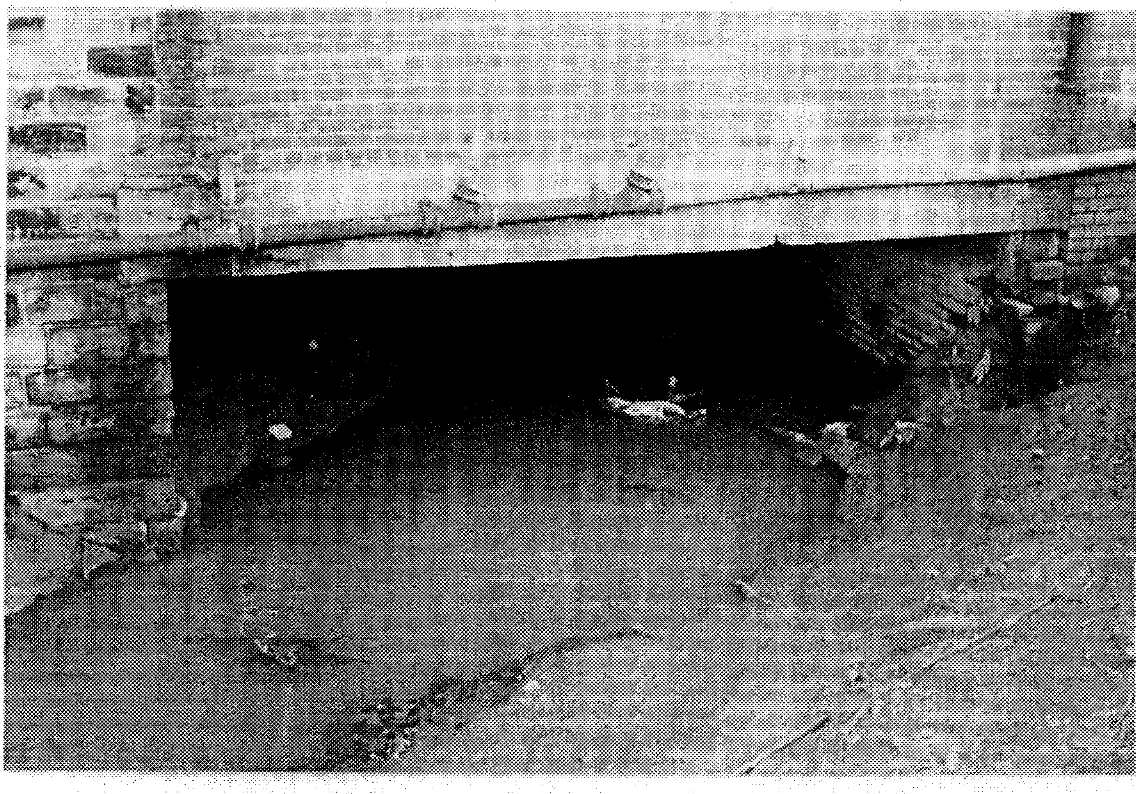


PLATE 14 CULVERT No.14 (Inlet above - Outlet below)



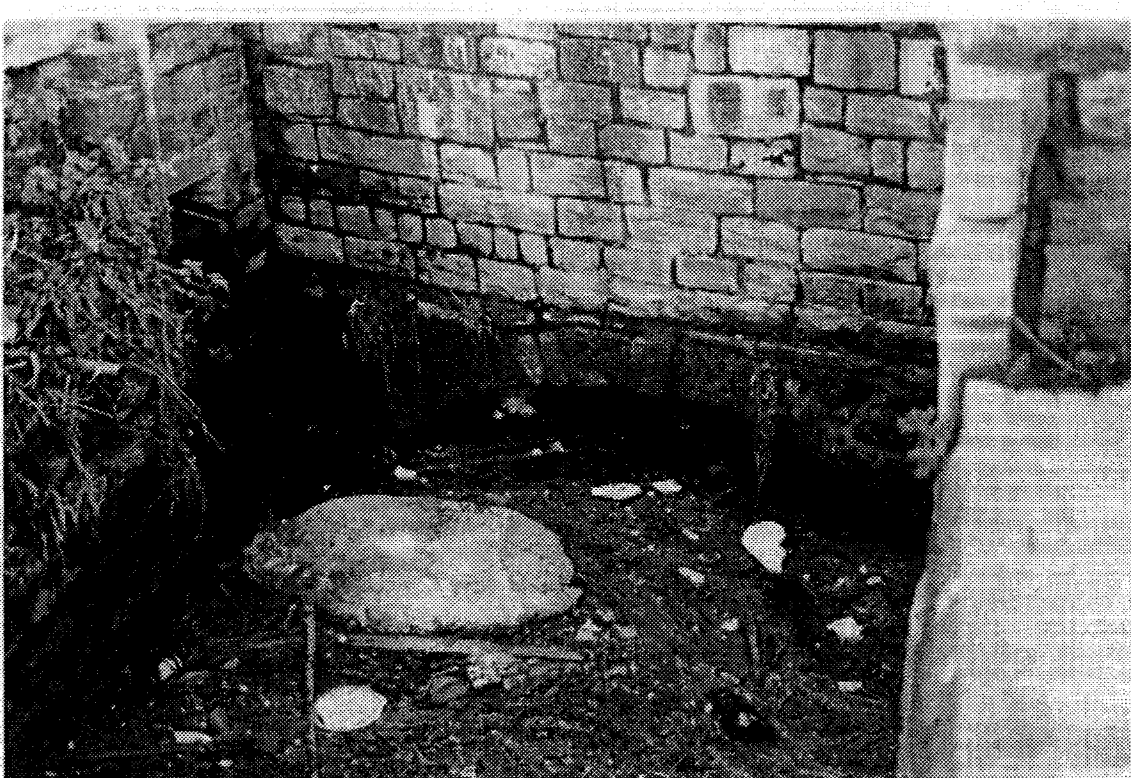
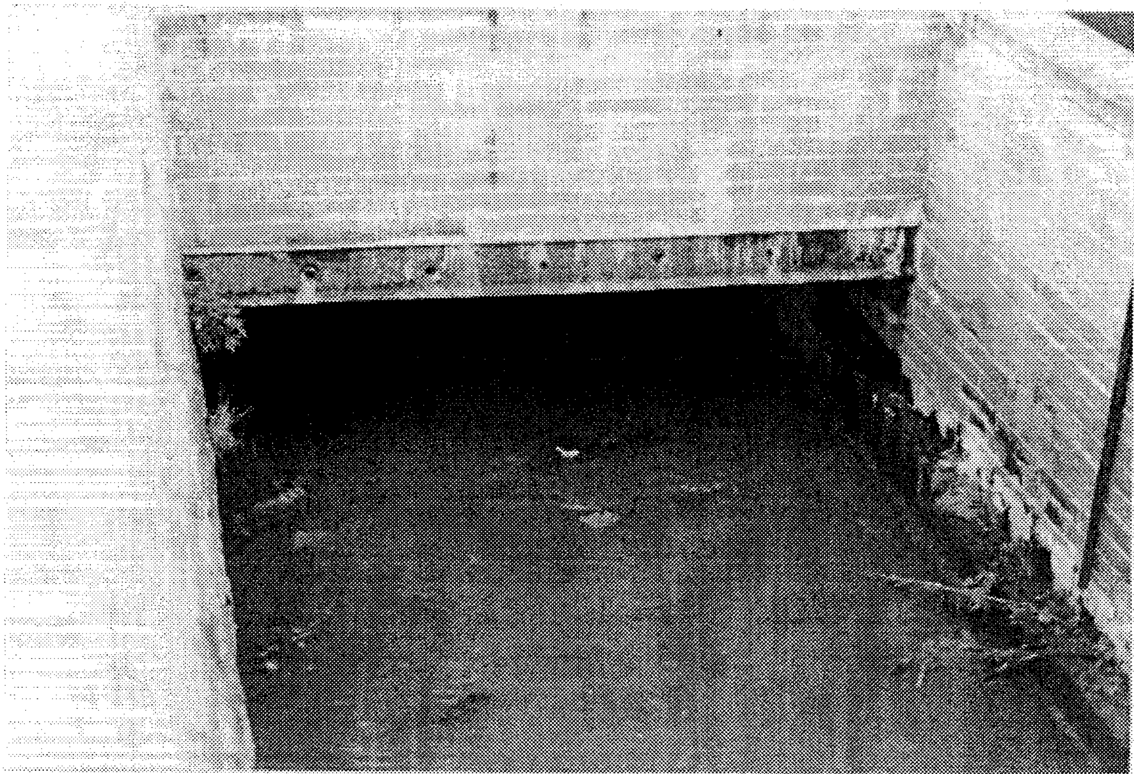


PLATE 15 CULVERT No.15 (Inlet above - Outlet below)



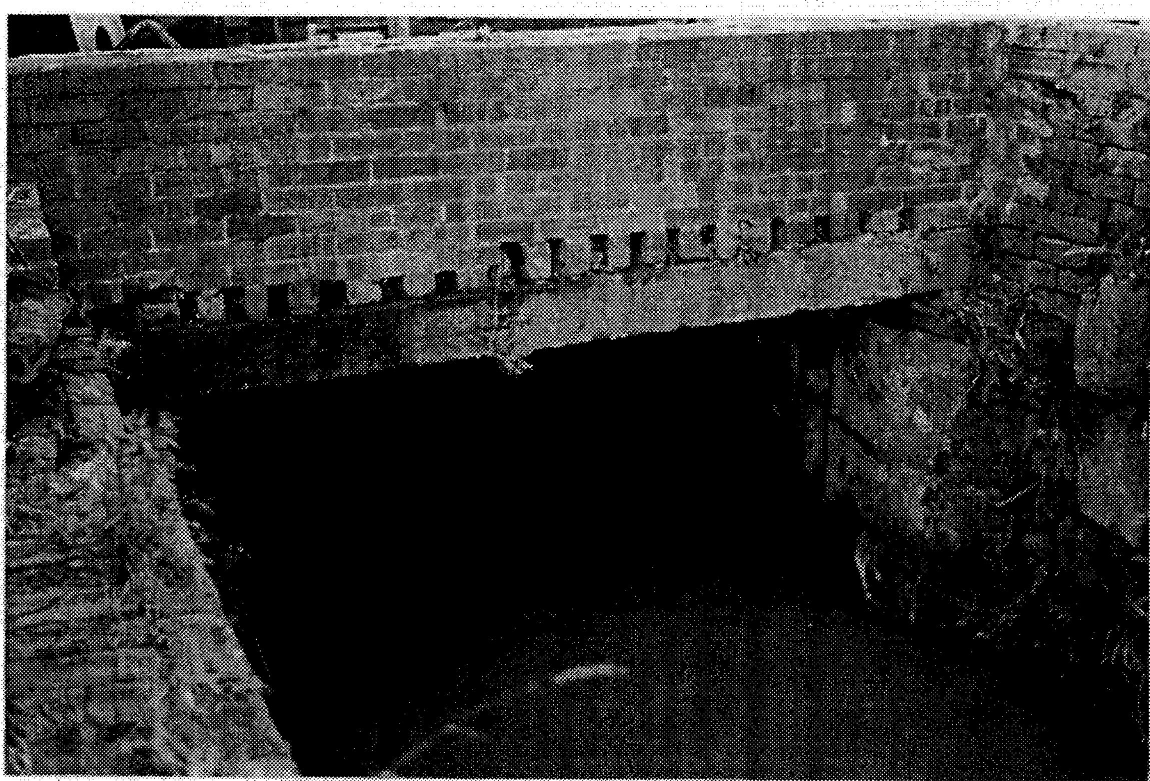
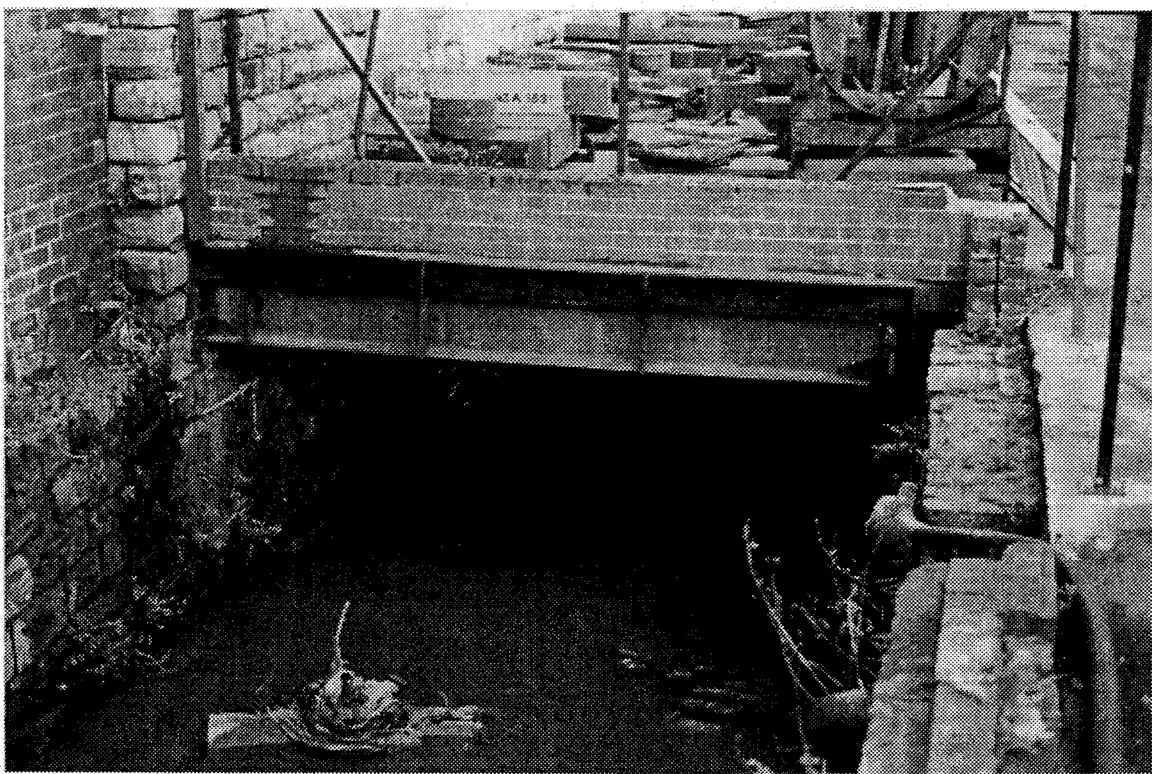


PLATE 16 CULVERT No.16 (Inlet above - Outlet below)



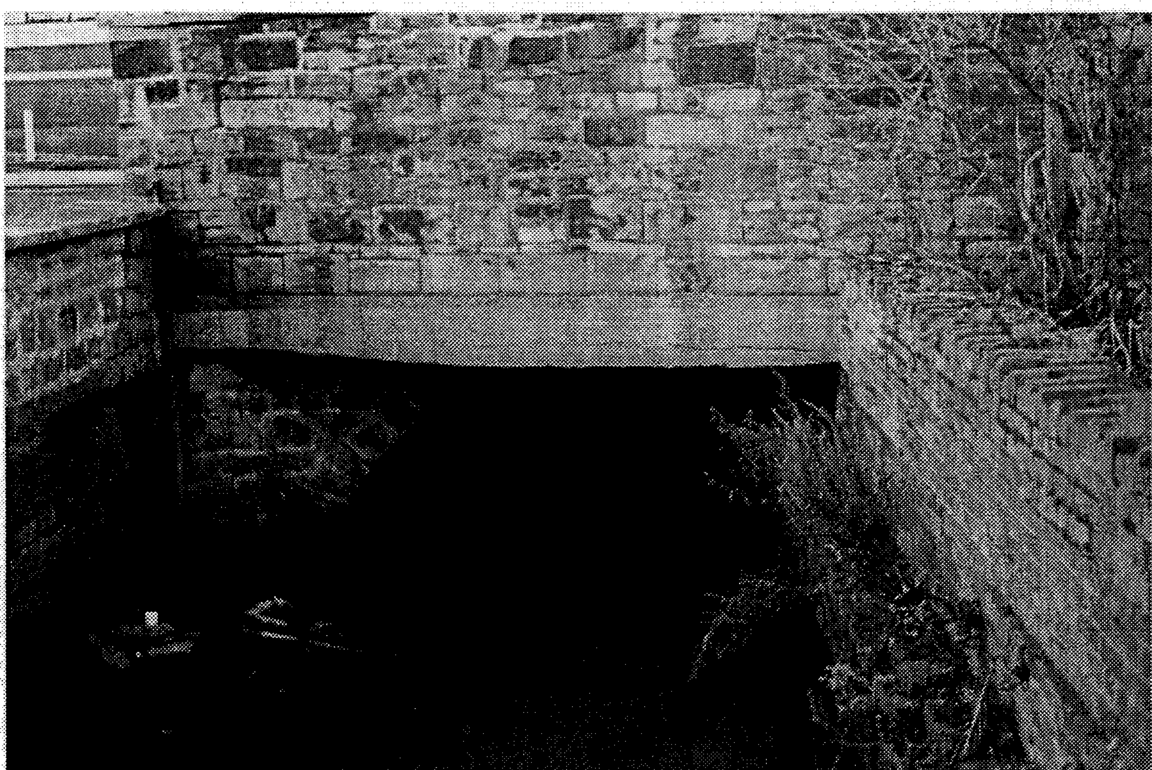
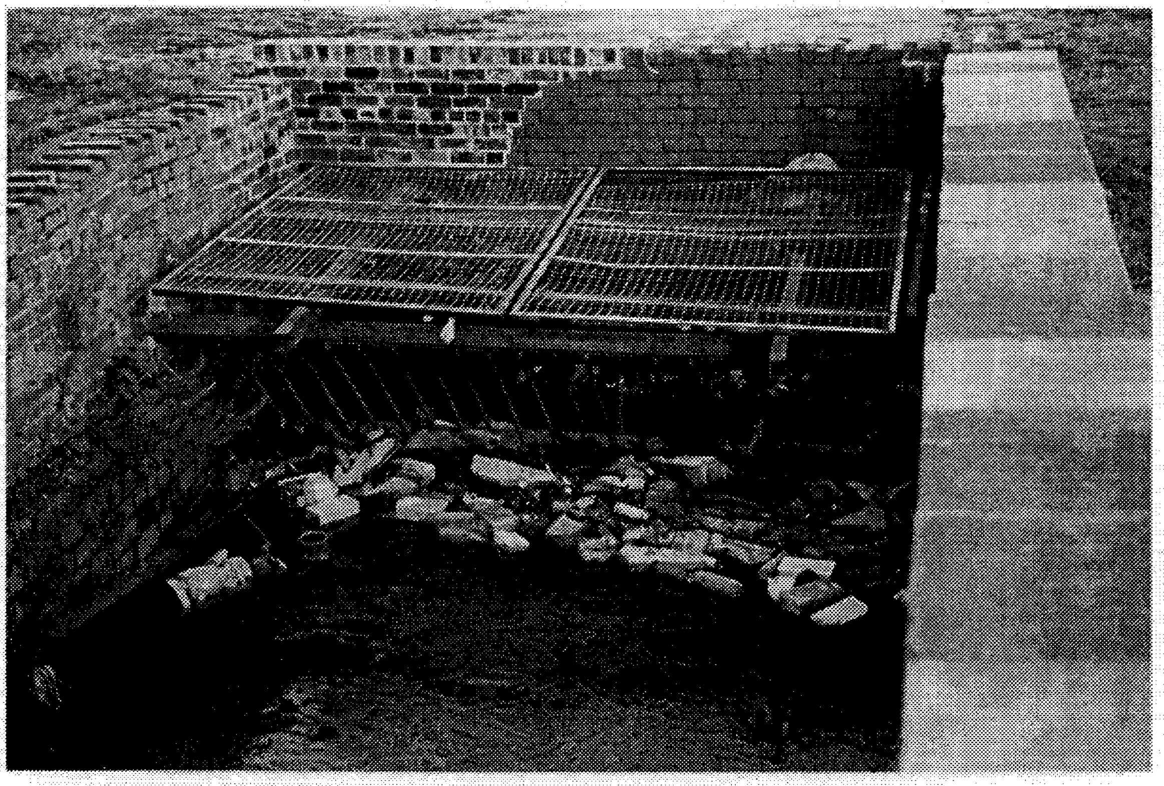


PLATE 17 CULVERT No.17 (Inlet above - Outlet below)



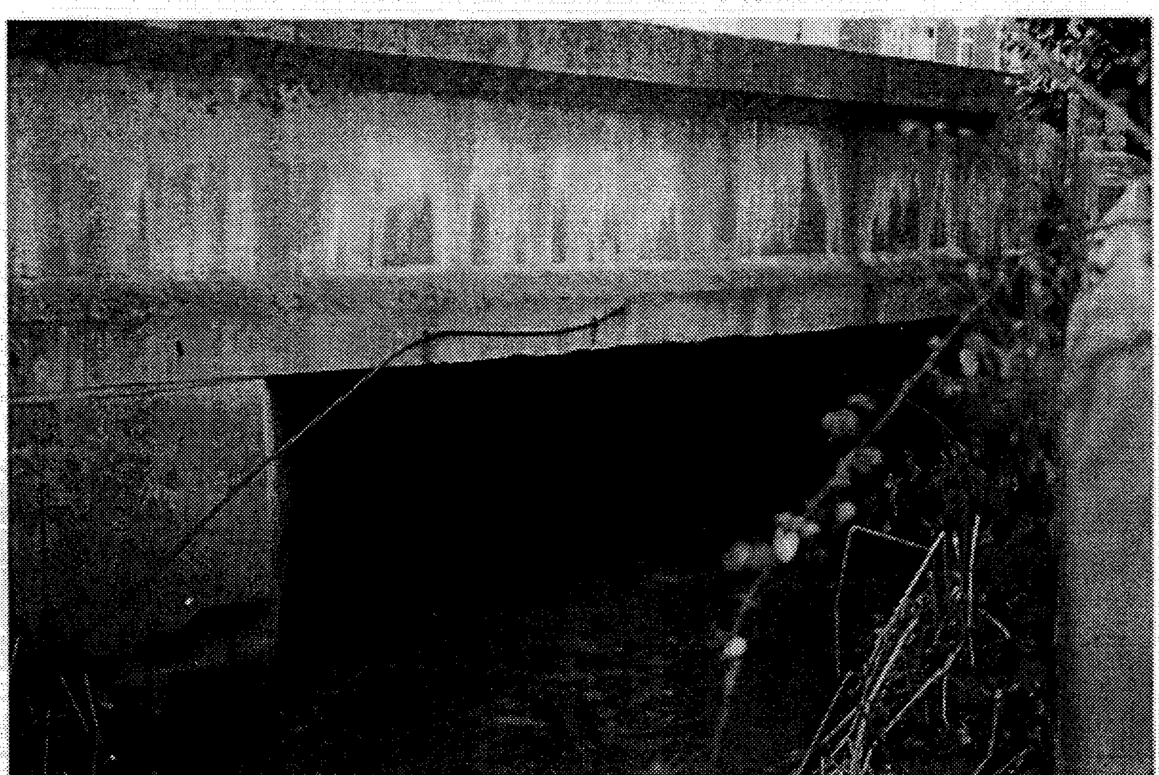
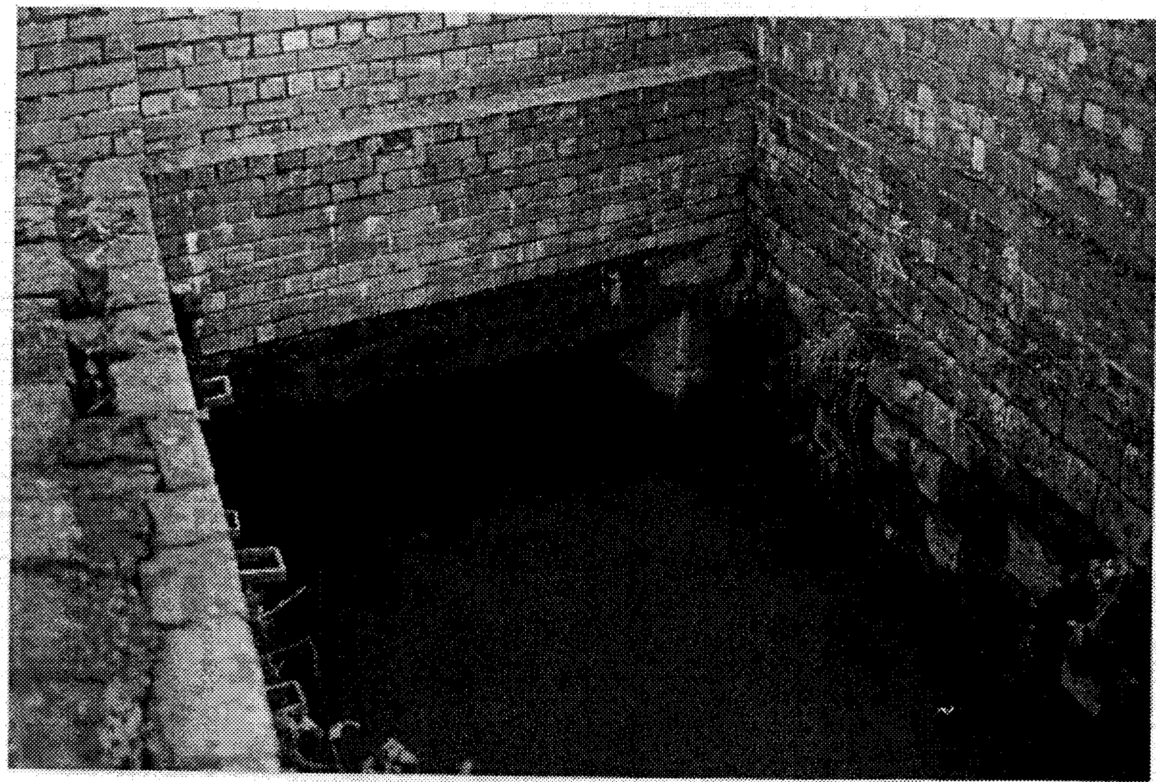


PLATE 18 CULVERT No.18 (Inlet above - Outlet below)



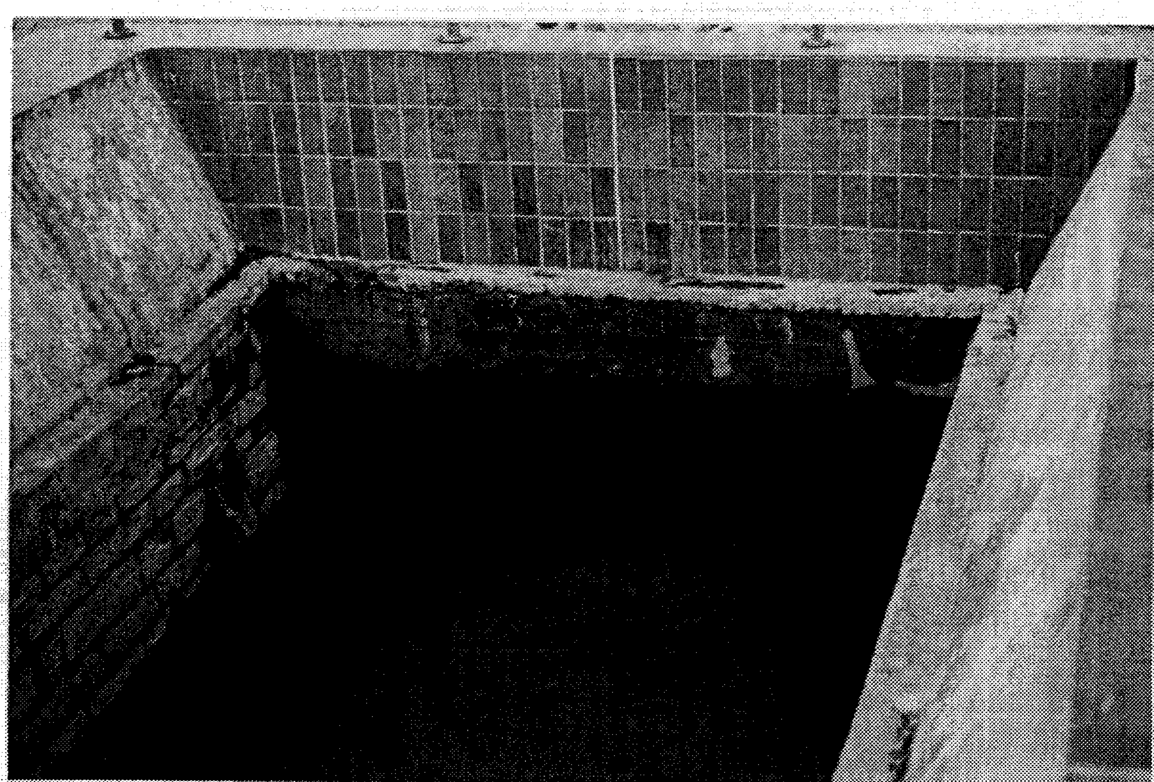
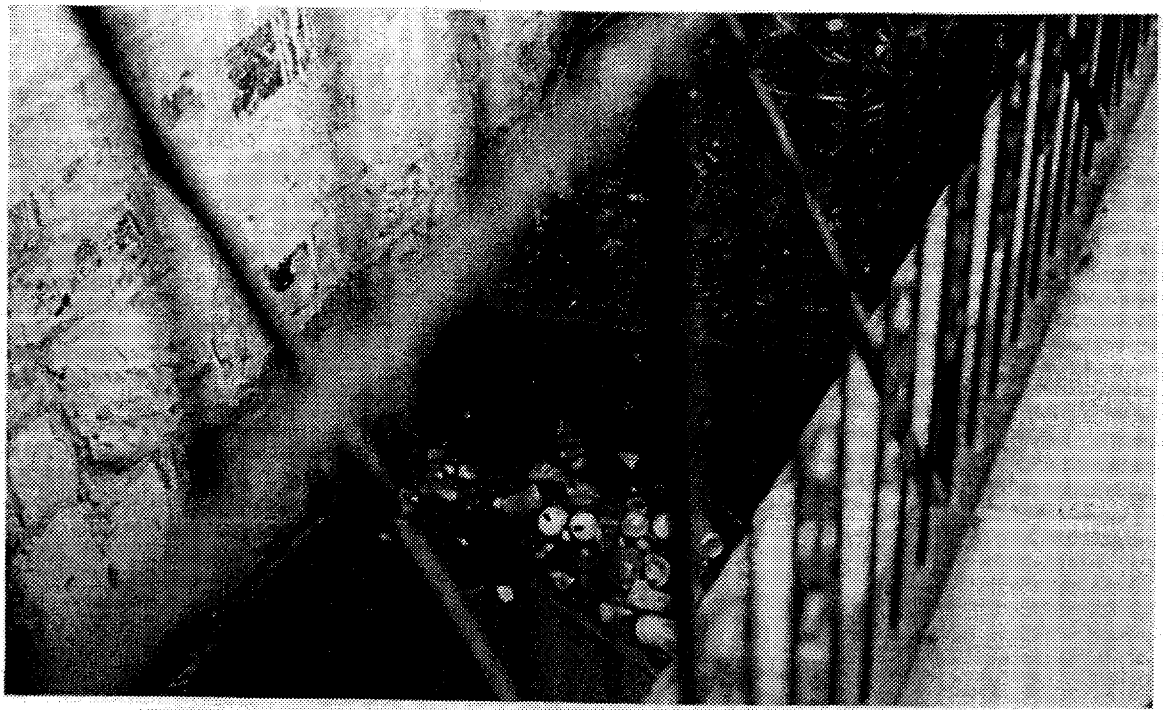


PLATE 19A CULVERT No.19A (Inlet above - Outlet below)

PLATE 19B CULVERT No.19B (Inlet above - Outlet below)



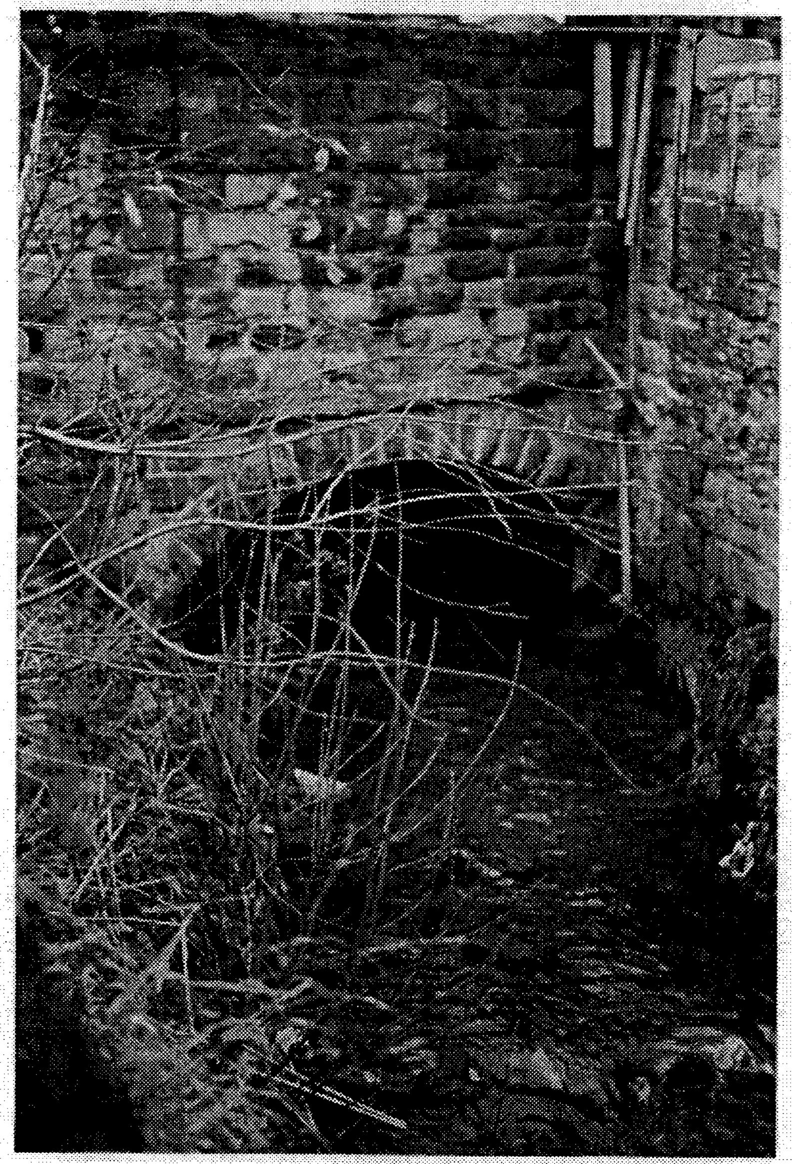


PLATE 20 CULVERT No.20 (Inlet above - Outlet below)

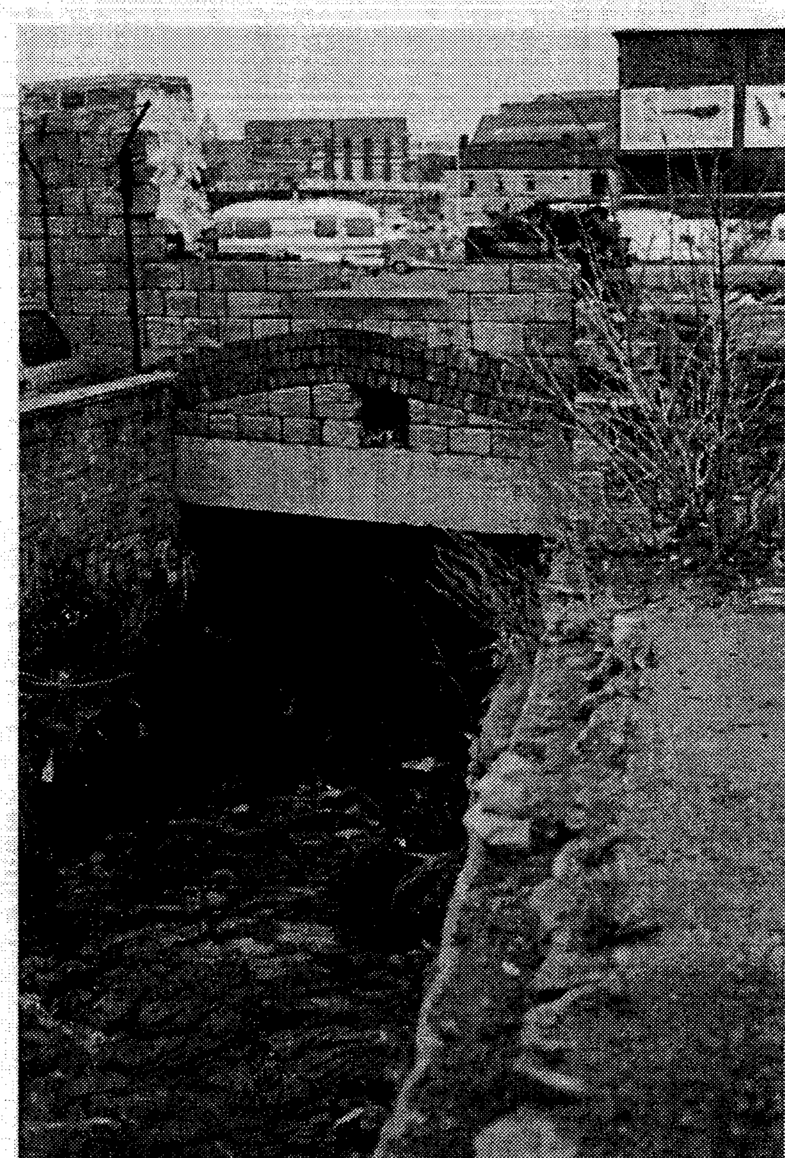


PLATE 21 CULVERT No.21 (Inlet above - Outlet below)

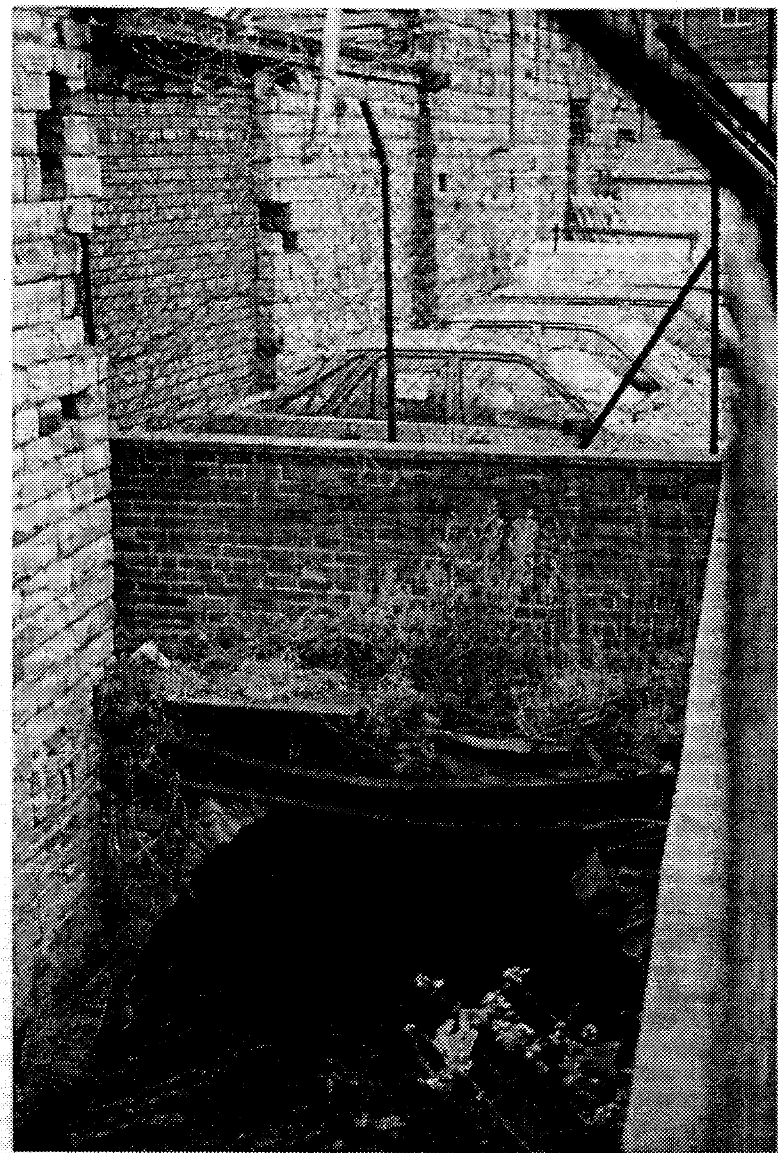
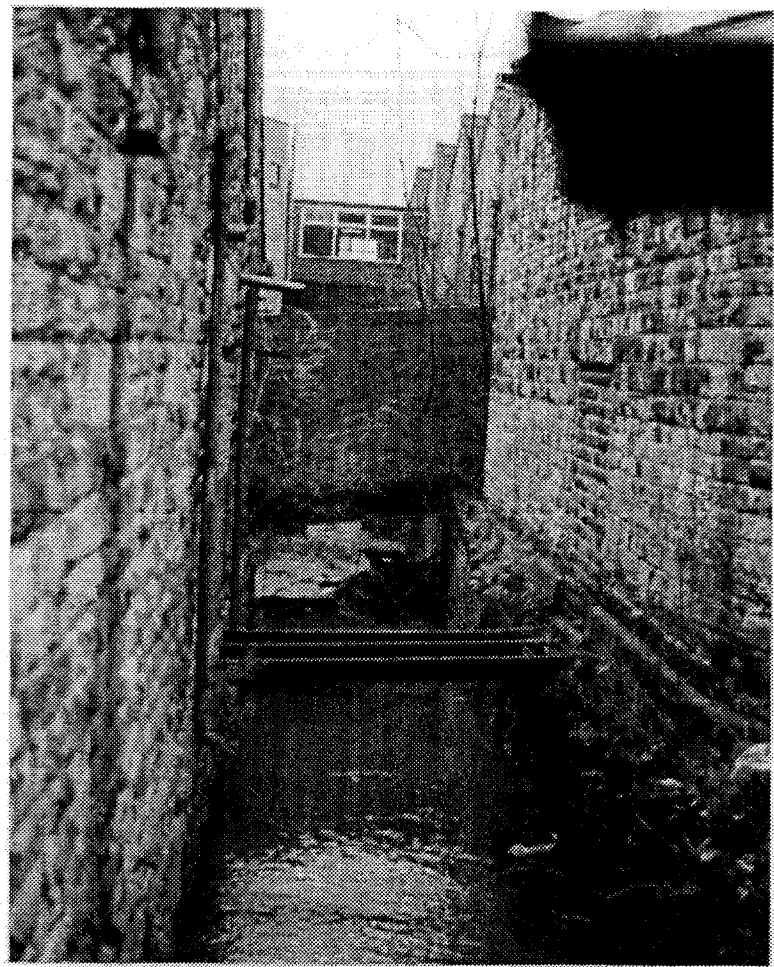


PLATE 22 CULVERT No.22 (Inlet above - Outlet below)



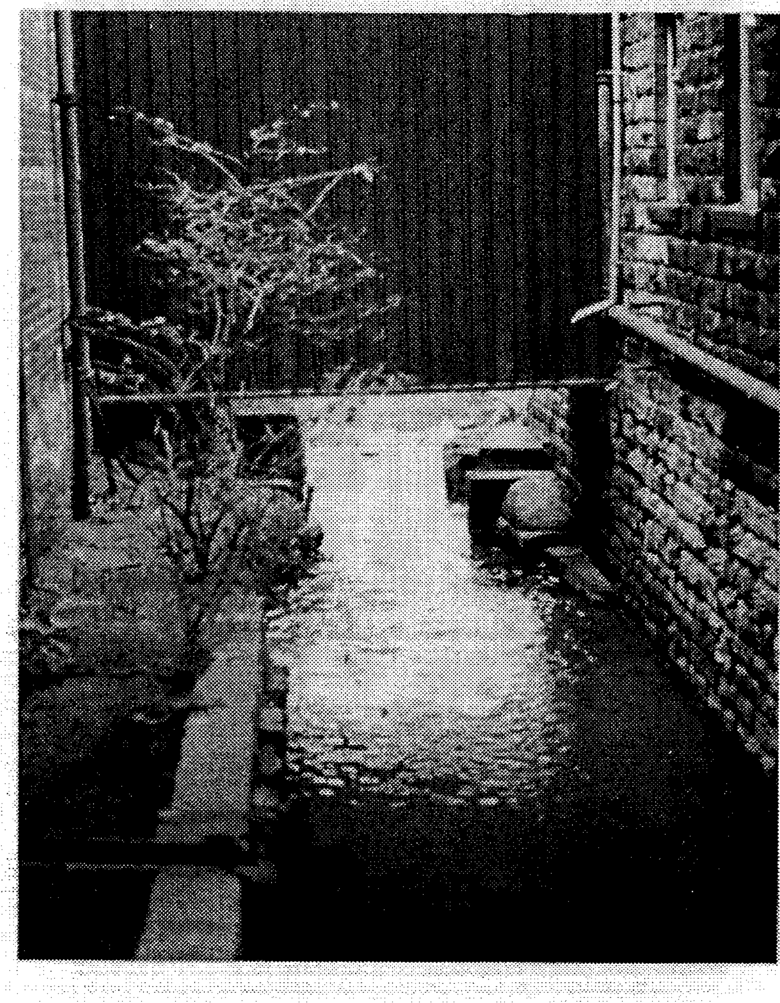
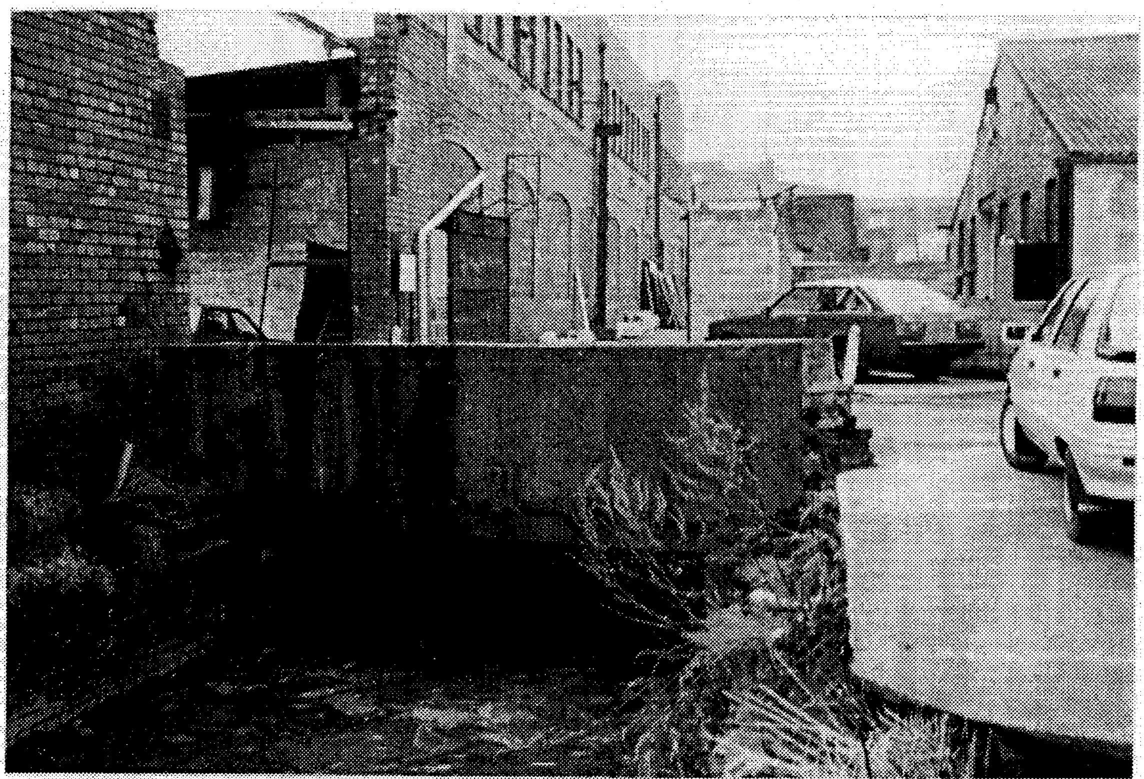


PLATE 23 CULVERT No.23 (above) and CULVERT No.24 (below)



11566

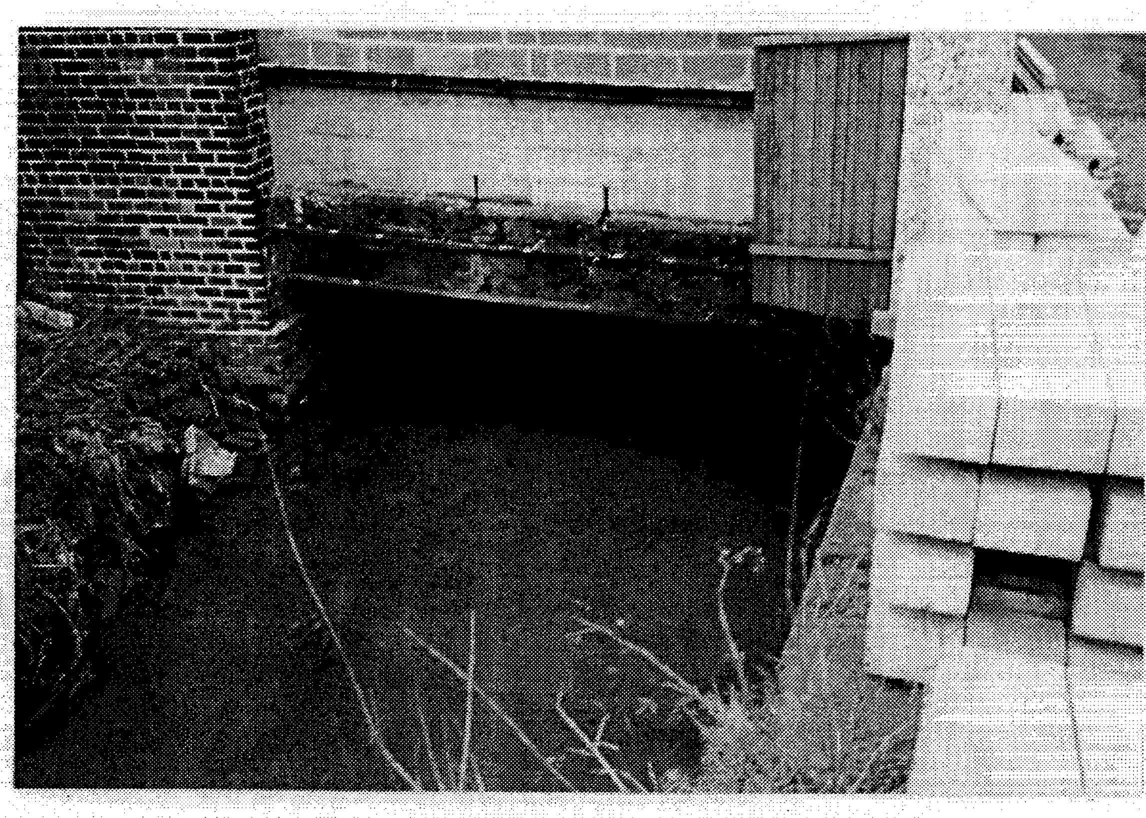


PLATE 24 CULVERT No.25 (Inlet above - Outlet below)

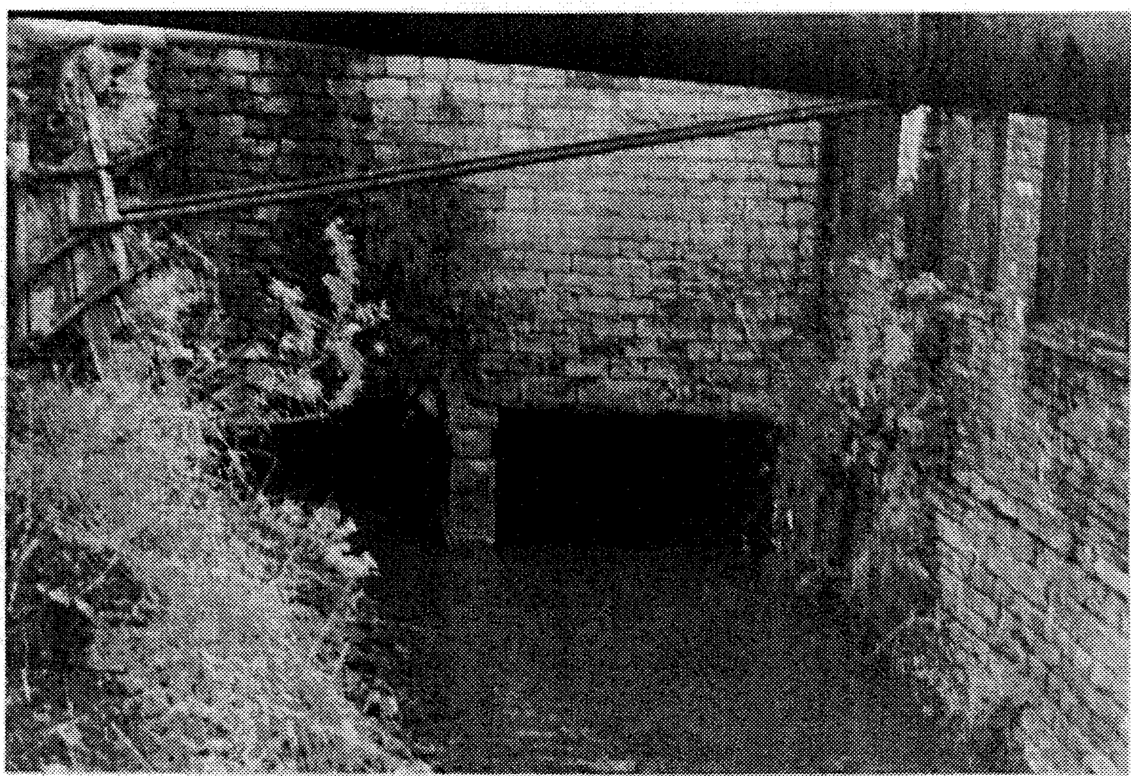


PLATE 25 CULVERT No.26 (Inlet above - Outlet below)

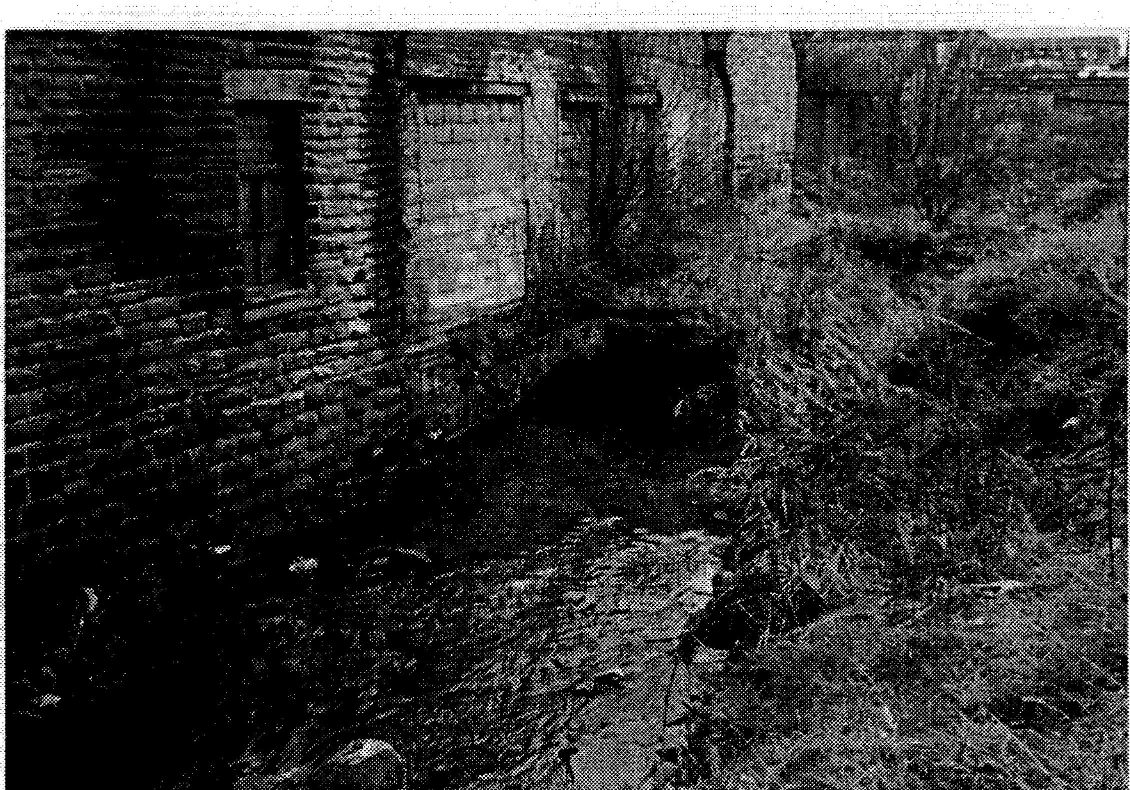
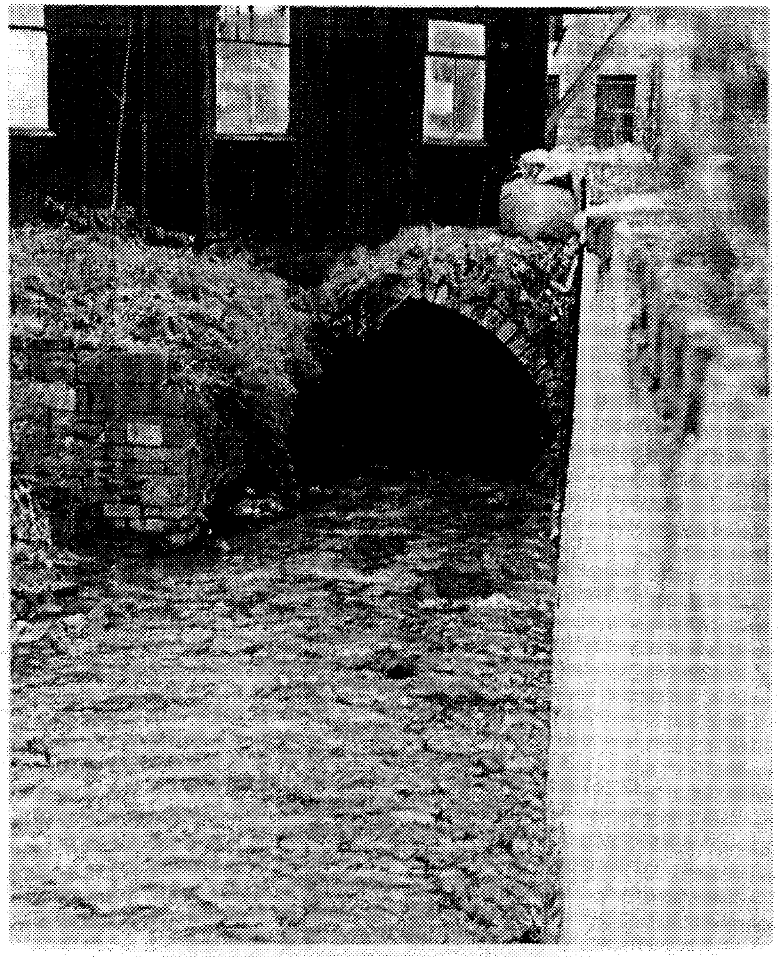


PLATE 26 CULVERT No.27 (Inlet above - Outlet below)



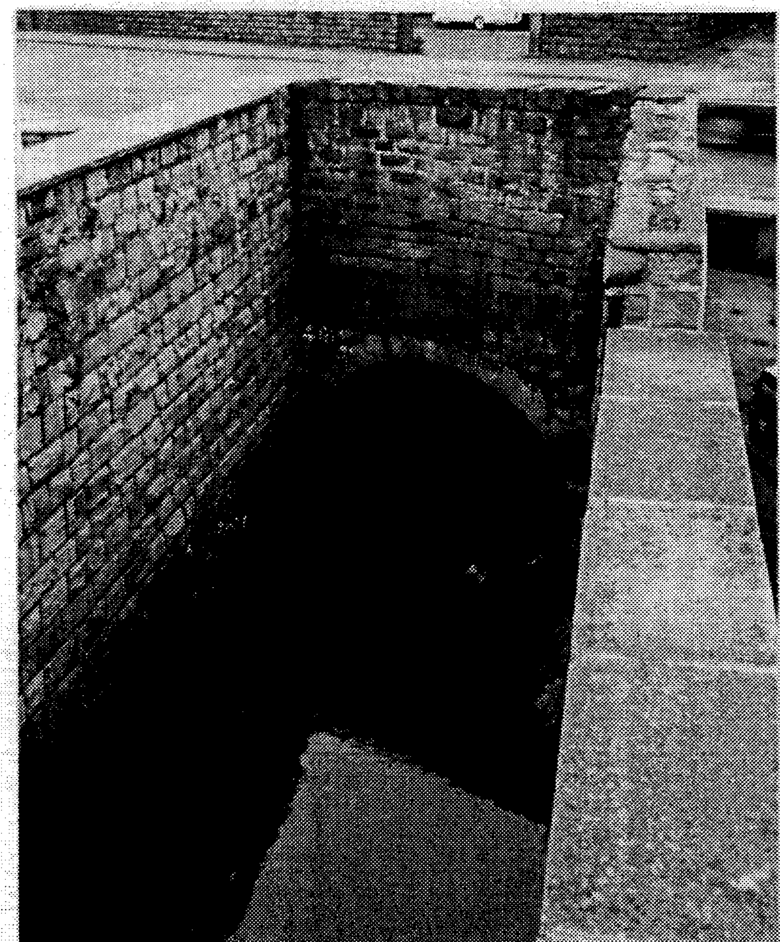
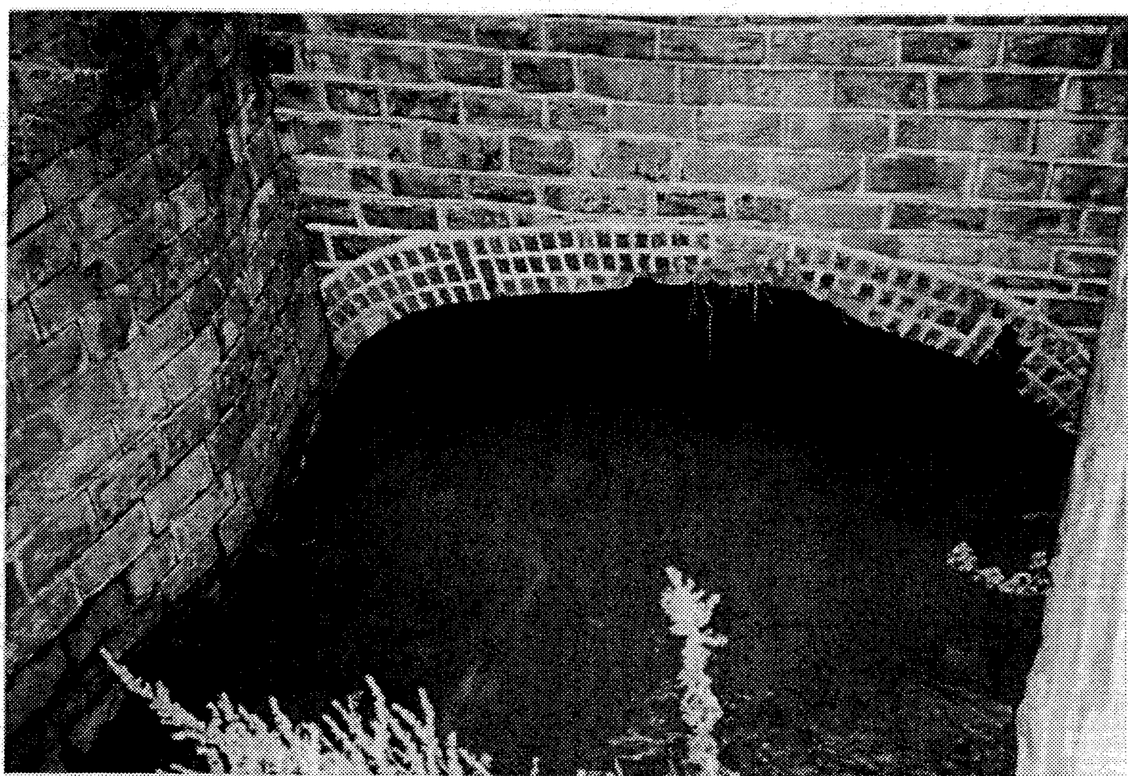


PLATE 27 CULVERT No.28 (Inlet above - Outlet below)



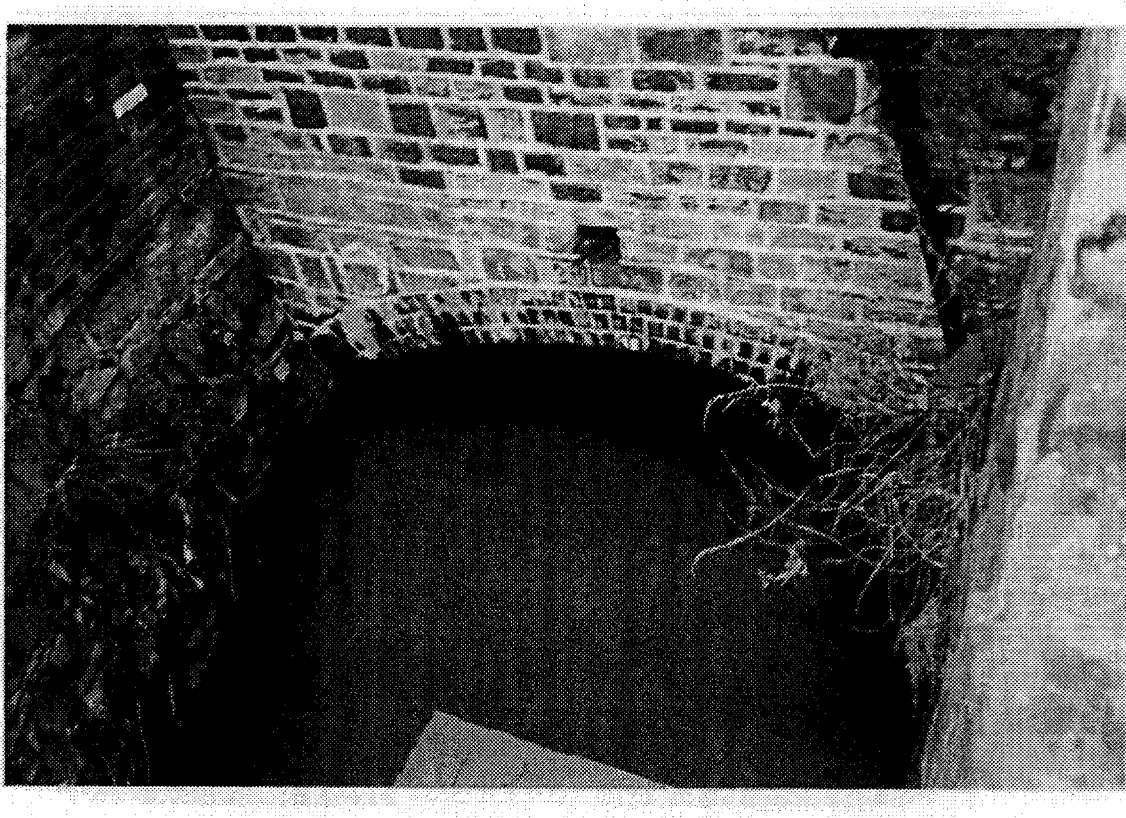


PLATE 28 CULVERT No.29 (Inlet above - Outlet below)

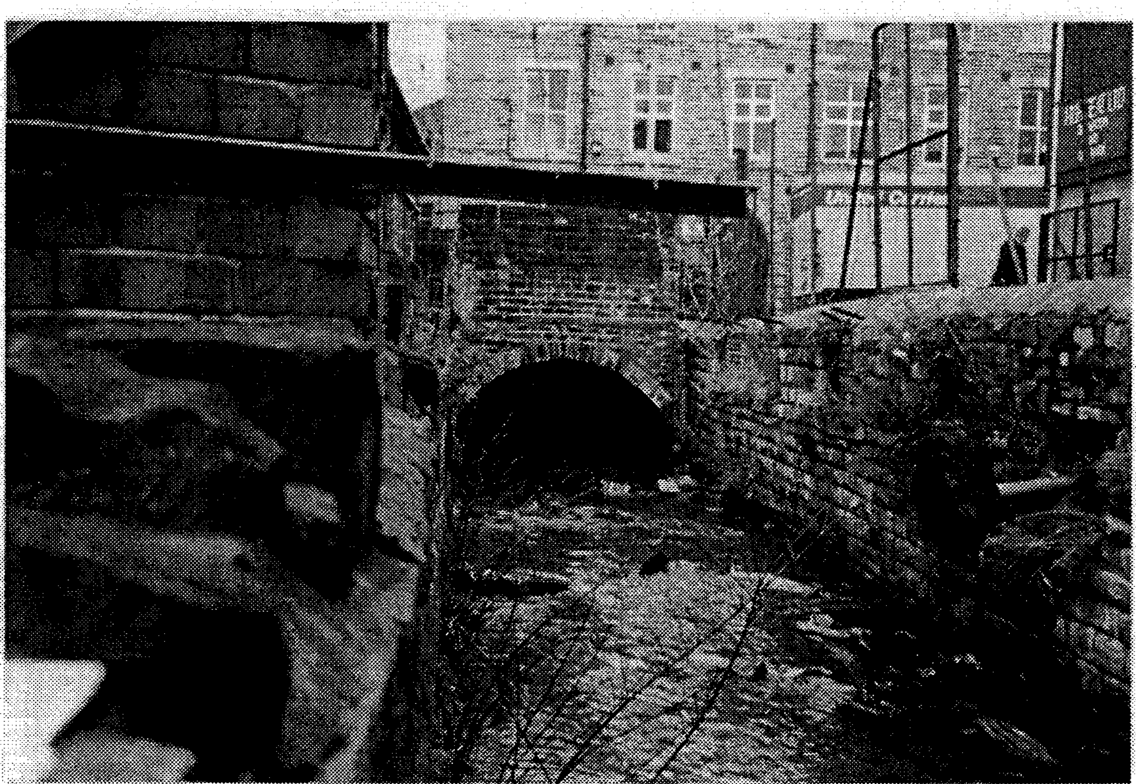


PLATE 29 CULVERT No.30 (Inlet above - Outlet below)

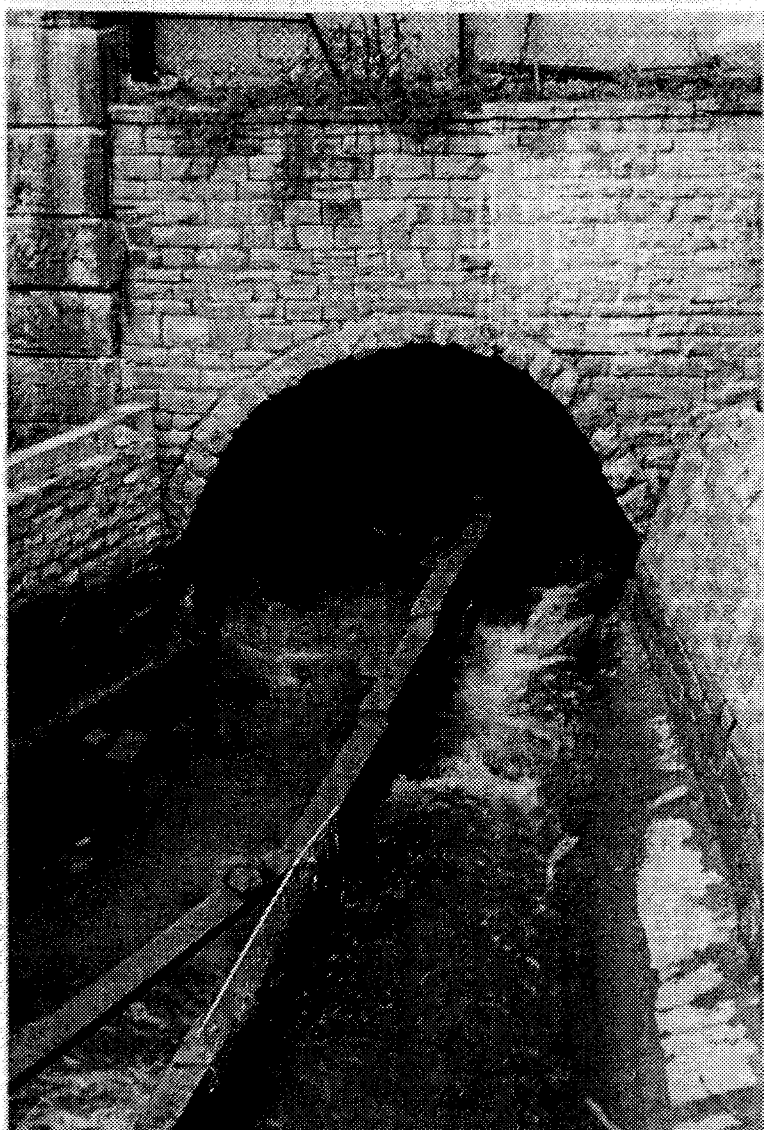


PLATE 30 CULVERT No.31 (Inlet above - Outlet below)