Afflux at Arch Bridges

Report SR 182
December 1988

HR Wallingford

Registered Office: HR Wallingford Ltd. Howbery Park, Wallingford, Oxfordshire, OX10 8BA, UK
Telephone: 0491 835381 International + 44 491 835381 Telex: 848552 HRSWAL G.
Facsimile: 0491 832233 International + 44 491 832233 Registered in England No. 2562099
HR Wallingford Ltd. is a wholly owned subsidiary of HR Wallingford Group Limited.

ABSTRACT

Present methods of calculating afflux at bridge crossings have proved inappropriate to bridges with arched soffits. A new method of estimation of afflux at arched structures is presented in this report. The method was developed from laboratory tests on model bridges and verified with data from prototype bridges supplied by Water Authorities. The investigation was part of a programme of research into hydraulic structures sponsored by the Ministry of Agriculture, Fisheries and Food.

CONTENTS

CONTENTS (cont'd)

FIGURES

CONTENTS (cont'd)

PLATES

APPENDICES

1 INTRODUCTION

There are a large number of bridges in Britain today which, because of their structural design, cause substantial blockage to river flow during flood events, and effectively raise upstream river levels. Often in the design of a flood protection scheme engineers discover that an immediately effective method of reducing flood levels would be to remove obstructions to flow.

However, many bridge obstructions are of medieval arch design and are protected by preservation rulings. If the water level upstream of a bridge during flood events could be accurately predicted then flood protection schemes could be designed accordingly.

Present day formulae on bridge hydraulics are intended to apply to modern designs of bridges with regular shaped piers and horizontal soffits virtually spanning the river. Clearly these formulae are inappropriate to ancient arch structures.

In 1985 a programme of research was begun to investigate the hydraulic parameters associated with single and multiple arch bridges with the aim of producing an accurate method of predicting the water level upstream of a bridge from known downstream flow conditions. The term afflux is used to define the difference in river level either side of a bridge.

This is the final report of the investigation. It summarises early laboratory model testing of arch bridges, already previously reported in detail in interim report nos SR 60 and SR 115, and includes later tests and final analyses.

Results from these model tests are compared with actual field measurements from selected bridge sites, and a comprehensive method of afflux prediction is presented.

2 OBJECTIVES

The purpose of this study was to relate the increase in water level, or afflux, caused by arch bridges to determinable hydraulic parameters, so that afflux may be predicted from predominated flow conditions downstream of a bridge. Resultant relations would be validated with prototype data.

Hydraulics Research Ltd have developed a suite of computer programs named FLUCOMP that is designed to simulate and predict flow conditions within river channels and floodplains. Relationships derived from this study would be incorporated into the FLUCOMP mathematical model as a refinement.

3 MODEL TECHNIQUES

Model testing was carried out in two flumes, one with a fixed horizontal bed and the other with the facility to adjust the bed slope.

The fixed bed flume, 2.4m wide by 15m long by 0.5m deep, is shown in Plate 1. Flow was fed from a $0.17m^3/s$ pump and discharged over a B.S. half 90 degree V-notch at low to medium flows and over a B.S. rectangular notch at high flows. Downstream water levels were controlled with a horizontal hinged tailgate.

The adjustable bed flume, 0.9m wide by 24.5m long by 0.915m deep, is shown in Plate 2. Bed slope could be adjusted from horizontal to a maximum of 1:60. Flow was measured by a 90 degree V-notch and down-water level controlled with a vertical lift tailgate.

Static head water levels were measured from side tappings in the flume side wall at several locations and connected to stilling-pots outside the flume. Water level was read directly with micrometer point gauges accurate to 0.00003m. Figs 1 and 2 show the locations of the tapping points in both flumes.

Water levels along the channel centre line were measured with an electronic water sensitive point gauge. A miniature propeller meter was used to measure water velocities at 0.6 depth at positions either side of a bridge away from its immediate influence.

Flow conditions at each test were photographically recorded.

The model river bed was constructed of painted wood to be smooth and initially horizontal. Slope factors were introduced at a later stage. Channel banks, constructed of wood, were designed to be vertical and smooth. The side walls of the adjustable bed flume were glass panelled for viewing through the flow depth. The model bridges were constructed of either painted wood or plastic.

A practical range of parameters, relating bridge dimensions of length, width and height to pier width, was obtained from analysis of prototype arch bridge data. Model bridge dimensions were within this range. The results from the tests apply to any size of bridge since all analyses are based on relationships between dimensionless parameters.

4 TEST PROGRAMME

4.1 Single semi-circular arches

A single semi-circular arched bridge was the first to be tested. The springing point of the arch was set at the flume bed and the arch abutments were square and flush with the face of the arch i.e. did not protrude into the flow. Fig 3 and Plate 3 shows the basic model.

The model was fitted into the horizontal bed flume and the flume side walls adjusted so that the bridge was confined between vertical banks for a distance of more than 12 bridge widths both upstream and downstream. This ensured sufficient approach length to allow even flow distribution.

The test procedure for models in this flume was to introduce a low discharge into the channel and with no downstream level control, to measure centre and side channel longitudinal water level profiles. Whilst maintaining the discharge, tailwater control was imposed in increments and the measurement procedure repeated. A series of flow conditions were tested in this way. This procedure was used on all the model bridges.

Velocity profiles were measured at sections upstream and downstream of the bridge. Overtopping of the bridge was not permitted.

A further series of tests was performed on modifications to this basic semi-circular arched bridge.

The bridge length in the direction of flow was increased by 200 percent, and then the piers widened symmetrically in two stages which effectively increased the bridge structural area by 12 percent and 35 percent. Fig 3 and Plates 4 and 5 show the modified bridges.

4.2 Single elliptical arches

The effect of arch shape on the hydraulic performance was investigated on an elliptical arched model bridge.

The sectional area of the elliptical arch was made identical to the semi-circular arch. Fig 4 gives the dimensions of the model. This model was tested in the variable bed slope flume.

All models in this flume were tested under the same flow conditions. Normal depth conditions were reproduced in the flume in the absence of a model bridge for a set of corresponding discharges and bed slopes, with and without a tailgate control. The bridges were installed in the flume and measurements taken following the procedure of the earlier tests. Plates 6 and 7 show the elliptical arch model under various operating conditions.

4.3 Multiple semi-circular arches

Three single semi-circular arched bridges were connected widthways into a multiple arch structure with two full width central piers and two end half width piers.

This arrangement was used to determine whether relationships between hydraulic parameters defined for a single semi-circular arch bridge could be directly applied to a multiple arch structure.

Fig 3 and Plate 8 show the model arrangement and Plate 9 shows the model under test conditions in the horizontal bed flume.

4.4 Multiple semi-circular arches with different soffit levels

The hydraulic performance of multiple arches with different soffit levels was investigated on a three semicircular arched structure shown on Fig 5. This model was tested in the variable slope flume. As with earlier models, piers were square in section with no extension upstream of the bridge face. The three arches had equal radii and were separated by two full width central piers and two end half width piers. Plates 10 and 11 show this model in various modes of operation.

The model was also used to study eccentricity effects. Individual arches were blocked in sequence, thereby forcing flow through two arches only. This simulated the irregular flow through eccentric bridges, where the main flow stream is deflected from central. Plates 12 and 13 show the flow distribution under eccentric arch conditions.

5 PROTOTYPE DATA

Over 50 regional Water Authorities were contacted to enquire whether data was available for arch bridges in their area which could be included in the research programme to validate the laboratory results. A total of 192 bridges were reported as causing afflux problems.

This emphasised the need for a better method of afflux prediction. The full response from the Water Authorities is given in Table 1. Plate 14 shows flood conditions at two bridge sites.

Data required was in the form of corresponding upstream and downstream water levels measured at a bridge site during a flood event and some means of relating these levels to a discharge. Bridges were, of necessity, close to gauging stations. Plans and sectional drawings of each bridge were used to extract dimensions and aspect.

Although the Water Authorities reported a substantial number of arch structures with high afflux, they were able to supply only limited data for many of the bridge sites. Most commonly, related upstream and downstream water level records were absent or incomplete except where the bridge was being specifically monitored in connection with a flood problem. The Severn Trent, Wessex and Yorkshire Water Authorities had special interests in particular bridge sites and as part of their flood monitoring procedure offered to install maximum water level recorders at selected sites.

Elsewhere, numerous problems arose in gathering the data. Often, an Authority had undergone re-organisation and the whereabouts of data was unknown. Many bridge drawings were filed in Council Planning Offices and much effort was put into locating and sifting archive records. Often the only known drawings were on microfilm that frequently gave distorted images. Other drawings were without reference spot levels, dimensions or scale.

In many cases, the river bed section shown on the bridge drawing had not been updated and was not representative of present day conditions. High water levels were occasionally above river bank level and across the floodplain but drawings did not include floodplain details. Many recorded flow events were historic and suspect water level readings could not be checked as the recorders had long since been removed.

In many cases no indication of the location of the water level measurement relative to the bridge was given. The importance of this is shown in the two examples in Plate 15 where the gauge board is fixed on a pier and drawdown at the gauge is evident.

Discharge values supplied by the Water Authorities with the water level information was assumed to have been taken at the same time of day. Realistically this was a peak daily flow. In the instances where discharges were obtained separately from Water Resources Departments, peak daily flow values were extracted.

In some instances, there were tributaries between a gauging station and a bridge for which no discharge records were available.

In the light of the incomplete or suspect data from many of the sites, effort was concentrated into collecting full sets of information from the three large Water Authorities mentioned above. The selected bridge sites from these Authorities together with the raw data from various flood events are listed in Table 2. Plates 16 to 36 show each bridge and Figs 6 to 36 give cross-section and structural dimensions.

6 THEORETICAL ANALYSIS

The theoretical approach adopted during this research followed an analogical method suggested by Ranga Raju (Ref 3) for assessing the blockage to flow effect of smooth circular cylinders. This theory was based on the principle that afflux and related energy loss are dependent on the drag characteristics of the cylinders.

The method and its application to arch bridges is discussed in detail in Ref 1. New interpretation and development of the theory led to two basic applicable equations:-

$$(dh/D3)^3 + 3(dh/D3)^2 + 2dh/D3 - 2(F3)^2\, dh/D3 - CD*J1*(F3)^2 = 0 \qquad \text{.... (1)}$$

$$(dh/D3)^3 + 3(dh/D3)^2 + 2dh/D3 - 2(F3)^2\, dh/D3 - ((CD*J3*(F3)^2) \,/\, (dh/D3 + 1)) = 0 \qquad \text{.... (2)}$$

where

dh = afflux term (D1-D3), the difference between upstream and downstream water levels measured away from immediate influence of bridge

D1 = upstream depth of flow

D2 = downstream depth of flow

F3 = Froude number $V3/(g*D3)^{0.5}$ measured at depth D3 where mean velocity is V3

J1 = upstream blockage ratio, (area of blockage of bridge at depth D1)/ area of flow

J3 = downstream blockage ratio, (area of blockage of bridge at depth D3)/area of flow

CD = coefficient of drag
= $FD/(0.5*\rho*V1^2*J1*B*D1)$
where FD = drag force on bridge

$0.5*\rho*V1^2$ = kinetic energy of flow
J1*B*D1 = blockage area of bridge

Equations 1 and 2 show the dependence of dh/D3 on F3, CD and either J1 or J3.

7 DATA ANALYSIS

7.1 Laboratory data

Based on the theory described above the data from model tests was processed into dimensionless parameters of dh/D3, F3, J1 and J3.

The afflux term was calculated as the difference between the upstream and downstream gauged heads measured furthest from the bridge. Longitudinal water surface profiles were measured during all the laboratory tests to give a full picture of hydraulic performance. Velocity profiles measured during the semi-circular arch tests are presented in Ref 1.

Blockage terms were defined as the ratio between the area of structural blockage to flow and the total flow area at depths D1 and D3.

The hydraulic data is presented in Tables 3 to 6.

7.2 Prototype data

Prototype data was processed into the same form as the laboratory data. The afflux term was taken as the difference between upstream and downstream gauged heads regardless of the measurement position relative to the bridge.

Mean depth was obtained from the cross-section drawings, usually an upstream elevation, and the corresponding bed level applied to both sides of the bridge. Froude numbers were calculated from mean velocities based on mean depths, channel widths and recorded daily peak discharges.

Individual cross-sectional drawings were digitised below the water level to obtain the areas of blockage. The hydraulic data is tabulated on Table 7.

8 RESULTS

The results were initially considered as two separate groups, single arches and multiple arches. In each case, the ratio of afflux to downstream depth (dh/D3) was plotted against the downstream Froude Number (F3) for each of a range of blockage ratios. Two plots were obtained, one using upstream blockage ratio (J1) and the other using downstream blockage ratio (J3).

8.1 Single arch bridges

Fig 37 shows the plot of afflux ratio against Froude number related to upstream blockage ratio J1. Polynomial equations were calculated for each blockage ratio curve and are shown in Table 8. The data from both laboratory and prototype single arch bridges lie within a relatively narrow band. In order to quantify the data fit, standard deviations were calculated for each data set and for the total data population.

Table 9 gives the percentage standard deviation of the data from the computed curves of blockage ratio.

Standard deviation for the whole data set was approximately 10 percent. The laboratory data formed the bulk of the data set and the standard deviation for this part of the set therefore matched the overall deviation. There was no significant difference between the semicircular arch and the elliptical arch. As expected, the prototype data showed more scatter than the laboratory data; the standard deviation of this part of the data set was approximately 14 percent.

This plot can be used to determine the afflux at a single arch structure from pre-determined downstream conditions using an iterative procedure. A worked example of this method is given in Appendix 1.

The same afflux-ratio/Froude number plot is shown on Fig 38 related to downstream blockage ratio J3. Table 10 lists the polynomial equations for each curve of the family.

Table 9 which lists the percentage standard deviations of individual data sets from the computed curves, shows the prototype data and laboratory semi-circular arch data more closely fit these curves. However, there is more scatter of the elliptical arch bridge data. Overall the contours of J3 fit the data to within 12 percent. Although the J1 curves fit the data rather more closely than the J3 curves the advantage in using the latter plot is that estimates of afflux can be determined directly from predetermined downstream conditions. Appendix 2 gives a worked example of this method.

8.2 Multiple arch bridges

Consideration was given to means of calculating afflux at a multiple arch bridge by application of single arch results to each element of the bridge. However, an attempt to define downstream conditions for each arch from the starting point of mean values for the river as a whole leads to iterations of extreme complexity. This approach was soon abandoned when it became clear that overall blockage was as dominant a factor as for single arch afflux and complicated refinements were of doubtful reliability.

The results were therefore plotted in the same form as for single arch bridges, treating the multiple arches as a single unit. Fig 39 shows the plot of afflux ratio (dh/D3) against downstream Froude Number (F3) related to upstream blockage ratio (J1).

While the blockage ratio was relatively low, 40 percent or less, the curves were identical to those for a single arch bridge. At higher blockage ratios, the plots gave rather higher afflux ratios for a given Froude Number than for a single arch bridge. The polynomial equations for the family of curves are given in Table 8. Standard deviation of the laboratory results from the curves was 10.0 percent.

The variation between single and multiple arch results in terms of upstream blockage ratio was not apparent when the plot of afflux ratio against downstream Froude Number was related to downstream blockage ratio (J3). In this case, the curves for a multiple arch bridge were identical to those for a single arch (Fig 38 and Table 10). Standard deviation of the laboratory results from the curves was 8.8 percent.

The reason why single arch and multiple arch results agreed when related to downstream blockage ratio but varied when related to upstream blockage ratio was not immediately apparent. An explanation was not pursued since the downstream blockage ratio curves are preferred as they require no iteration.

The difficulties encountered in analysing the prototype data for multiple arch bridges were reflected in the results. There was such a high degree of scatter that, while not opposing the laboratory results, they did not give the support that had been hoped for. Standard deviation of the prototype data from the curves of Fig 39 was 37 percent and from the curves of Fig 38, 45 percent.

8.3 Eccentricity

When the centre of area of a bridge is offset from the centreline of the approach channel it is said to be eccentric to the flow. This condition was tested but the results showed no variations that could be attributed to the eccentricity. This was not unexpected; previous tests have shown that the effect of eccentricity is less than the overall tolerance of the results of the present tests unless the bridge width to channel width ratio is small and the offset is extreme. Such conditions were not reached within the limits of the experimental facilities that were used.

9 CONCLUSIONS

1. The laboratory results give an empirical method of determining the afflux at single arch or multiple arched bridges. Data required are the bridge geometry and the water depth and Froude Number at the downstream side of the bridge. The accuracy of the result is +10 percent.

2. The results are presented in terms of the upstream blockage ratio or the downstream blockage ratio. In terms of accuracy, there is no clear cut advantage in the use of one rather than the other. However, use of upstream blockage ratio requires an iterative procedure whereas use of downstream blockage ratio enables afflux to be obtained in a single step. The latter method is therefore preferred.

3. The same method applies to single or multiple arch bridges provided that the multiple arches are essentially a single unit separated only by typical pier widths. Other configurations of multiple arches were not tested.

4. The influence of eccentricity of the bridge to the river channel is insignificant relative to the overall tolerance on the calculation of afflux.

5. Prototype data supports the method in the case of single arch bridges. Equally close confirmation for multiple arch bridges was not possible due to lack of data.

10 ACKNOWLEDGEMENTS

Grateful thanks are extended to all those Water Authorities who supplied information on arch bridges. Particular thanks are expressed to Severn-Trent Authority, Yorkshire Water and Wessex Water.

11 REFERENCES

1. Brown P M, Afflux at British bridges. Hydraulics Research Ltd, Report No SR 60, August 1985

2. Brown P M, Afflux at arch bridges. Second interim report. Hydraulics Research Ltd, Report No SR 115, March 1987

3. Ranga Raju K G, Asawa G L, Rana O P S, Pillai A S N, Rational assessment of blockage effect in channel flow past smooth circular cylinders. J. Hyd. Res. V21, 1983 No.4

4. Hydraulics of bridge waterways. U.S. Dept. of Transport, Bureau of Public Roads, Washington, 1970

5. Biery P F, Delleur J W, Hydraulics of single span arch bridge constrictions. J. Hyd. Res. V88, No HY2, Pt 1, March 1962

TABLES.

TABLE 1: Summary of available data on bridges with high afflux from Water Authorities

Authority	River	Bridge	Data information
Yorkshire Water	Aire	Kildwick	a
		Carleton	c
		Inghey	a
		Silsden	c
	Spen	Station Rd	a
		Union St	a
		Rawfolds	a
		St Pegs	a
		Balme Rd	a
	Wharfe	Pool	a
		Ilkley	a
		Ilkley Old	e
		Bolton	a
		Grassington	a
		Otley	b
		Linton	b
		Thorpe Arch	b
		Wetherby	b
		Tadcaster	e
	Nidd	Summer	b
		Hampsthwaite	b
		Skip	e
		Killinghall	c
		Conyham	c
		Knaresborough High	c
		Knaresborough Low	c
		Cattall	a
	Swale	Skipton	c
		Thornton	c
	Ure	Borough Bridge	e
		Tanfield	e
		Rippon North	b
		Bridge Hewick	c
		Kilgram	c
		Cover	c
		Middleham	c
		Wensley	c
	Ouse	Clifton	e
		Scarborough	e
		Ouse at York	e
	Derwent	Howsham	e
	Batley Beck	several sites	d

Key: a = data used in analysis
b = insufficient structural information
c = insufficient discharge data
d = insufficient water level data
e = incomplete data

TABLE 1 (cont'd)

Authority	River	Bridge	Data information
Welsh Water	Rhymney	Draethan	b,c,d
		Forge Rd	c,d
		Iron Bridge	b,c,d
		Bedwas	c
		Corbets	b,c
		Ystrad Mynach	c
		Twyn Sion Ifan	e
	Taff	Ynys	b,c,d
		Leiners	b,d
		Tin Plate	b,d
		Castle Inn	b,d
		Machine	b,d
		Ynysangharad Park	b,c,d
		Quakers Yard	b,d
	Rhondda	Gelli Rail	c,d
		Ton Petre	c,d
		Treherbert	c,d
	Cynon	Mountain Ash	b,d
		Peace Park	b,d
		Cwmbach	b,d
		Aberdare	b,d
		Robertstown	b,d
	Ely	Ely Rd	b,d
		Ely Foot	b,d
		St Georges	b,d
		Peterson-s-Ely	b,d
		Pontyclun Rail	d
		U-Pant	b,d
		Pont Lyddan	b,d
		Rail Viaduct	b,d
	Cadoxton	Dinas Powys	b,c,d
	Dee	Farndon	b,d
		Bangor-on-Dee	b,d
	Elwy	Pont-y-Gwyddel	b,d
	Alyn	Pont-y-Capel	b,d
	Clywedog	Bowling Bank	b,d
Severn Trent	Avon	Dow	a
		Boughton	a
		Avon Mill	a
		Lea Crescent	a
		Bretford	a
		Wolston	a

Key: a = data used in analysis
b = insufficient structural information
c = insufficient discharge data
d = insufficient water level data
e = incomplete data

TABLE 1 (cont'd)

Authority	River	Bridge	Data information
Severn Trent	Avon	Ryton	a
		Bubbenhall	a
		Cloud	a
		Stare	a
		Chesford	b
		Blackdown	b
		Binton	c
	Arrow	Washford	c
		Gunnings	a
		Statford Rd	b
		Oversley	a
		Castle Rd	c
		Spernall	c
		Wixford	a
		Broom	a
		Salford	a
	Leam	Victoria	c
		Mill	c
		Willes	c
		Hunningham	c
		Offchurch	c
		Adelaide	c
	Piddle	Grafton Flyford	c
		Tilesford Farm	c
		Wyre Rail	c
		Wyre Rd	c
	Erewash	Stanton Gate	a
Anglian Water	Stour	Kedington	b,d
		Baythorne End	b,c,d
		Pentlow	b,d
	Stour Brook	Sturmer	b,d
	Colne	Earls Colne	b,d
	Brett	Chelsworth	b,c,d
		Hadleigh	b,d
	Black Water	Wickham	b,c,d
	Wid	Whites Bridge	b,c,d
	Welland	Duddington	b,d
	Nene	Wansford	b,d
		Milton Ferry	b,c,d
		Fotheringhay	b,c,d
		Oundle	b,c,d
		Thrapston	b,c,d

Key: a = data used in analysis
b = insufficient structural information
c = insufficient discharge data
d = insufficient water level data
e = incomplete data

TABLE 1 (cont'd)

Authority	River	Bridge	Data information
Wessex Water	Stour	Iford	e
		Longham	b
		Canford	a
		Julians	a
		Sturminster Marshall	e
		Crawford	a
		Blandford	a
	Avon	Crane	c,d
		Bicton	c,d
		Bradford-on-Avon	b,d
	Frome	Wool	d
		Damsons	b,d
		Holme	d
		Greys	d
	Brit	Bridport West	d
		North Mills	d
		Bridport	e
	Biss Congresbury	Cradle	c,d
	Yeo	Perry A38	b,d
		A370	d
	Banwell	Ebdon	b,d
	Brue	Leggs	c,d
		Church	c,d
		Bridgefoot	b,d
	Cam	Frog Lane	c,d
	Yeo	Load	c,d
		Ilchester	c,d
	Hartlake	Hartlake	b,c,d
	Kings Sedgemoor Drain	Rail	c,d
		Dunball	c,d
	Isle	Midelney	b,c,d
		Ilford	b,d
	Five Hd	Pot	b,c,d
	Tone	Creech Rd	b,d
		Athelney	b,c,d
	Haleswater	Bishops Hill	b,d
Forth River Purification Bd	Tyne	A1 Rd	d
		Abbey	b,d
		Nungate	b,d
	Allan	Cromlix	b,d

Key: a = data used in analysis
b = insufficient structural information
c = insufficient discharge data
d = insufficient water level data
e = incomplete data

TABLE 1 (cont'd)

Authority	River	Bridge	Data information
Tay River Purification Bd	Eden	Cupar	d
	Earn	Forteviot	d
	Almond	Newton	d
		Almond Bank	d
	Tay	Aberfeldy	d
		Logierait	d
		Perth	d
	Isla	Crathies	d
	Dighty	Mill of Mains	d
	Lunan	Inverkeilor	d
	S Esk	Brechin	d
	N Esk	North Water	d
Northumbrian Water	Coquet	Rothbury	b,d
	Wansbeck	Telford	e
		Elliot	b
	Tyne	Corbridge	b,d
	Wear	Eastgate	b
		Sunderland	b,d
	Leven	Hutton Rudby	b,c,d
	Tees	Yarm	b,c,d
		Croft	b,c,d
North West Water	Irk	Blackley Rd	b
		Boothroyden	b
	Mersey	Barfoot	e
	Tame	Broomstairs	b
	Sankey Bk	Sankey Mill	e
	Kent	Nether	d
	Leven	Newby	d
	Greta	Keswick	b,c,d
Thames Water	Salmons Bk	Enfield Rd	b,c,d
		Clarendon Arch	b,c,d
	Hounsden Gutter	Houndsden Rd	b,c,d
	Rib	Bengeo	b,c,d
	Nimney	Wareside	b,c,d
	Roding	Abridge	e
		Shonks Mill	b
		Roding Lane	b,c,d

Key: a = data used in analysis
b = insufficient structural information
c = insufficient discharge data
d = insufficient water level data
e = incomplete data

TABLE 1 (contd)

Authority	River	Bridge	Data information
Thames Water	Ingrebourne	A13 Rd	c,d
	Ching Brook	Beech Hall Rd	b,c,d
	Nazing Brook	Nazing	b,c,d
Southern Water	E Yar	Alverstone	b,c,d
		Longwood	b,c,d
		Langbridge	b,c,d
		Horringford	b,c,d
		Morton	b,c,d
		High St Whitwell	b,c,d
	Eden	Town Bridge	b,d
		Vexour	b,d
	Medway	Colliers Land	b,d
		Eusfield	b,c,d
		E Farleigh	b,d
	Dudwell	Budwash	b,d
	Rother	Withereaden	b,c
		Etchingham	b,d
		Udiam	b,d
		Blackwall	b,c
	Teise	Stonebridge	b,d
	Beult	Stile Bridge	b,d
	Gt Stour	Wye	b,d
		A28 Rd	b,c
	Hexden Channel	Hope Mill	b,c,d

Key: a = data used in analysis
b = insufficient structural information
c = insufficient discharge data
d = insufficient water level data
e = incomplete data

TABLE 2: Selected prototype bridge data

No	River	Bridge	Date	u/s mAD	d/s mAD	Q cumecs	B m	Arch
1	Avon	Dow	14. 3.47	92.660	92.560	19.0	48.05	M
2		Boughton	11. 7.68	87.020	86.500	25.0	30.20	M
3			11. 7.68	87.020	86.500	25.0	27.60	M
4			9. 3.75	86.080	85.970	19.0	28.20	M
5		Lea Crsnt	9. 3.75	80.910	80.450	56.6	29.10	M
6			30.12.81	80.100	79.990	53.0	25.30	M
7		Bretford	9. 3.75	72.530	72.420	55.9	46.40	M
8			9. 3.75	72.530	72.420	55.9	41.90	M
9			30.12.81	72.330	72.200	56.3	44.60	M
10			30.12.81	72.330	72.200	56.3	41.90	M
11		Wolston	11. 7.68	70.662	70.568	71.4	30.15	M
12			30.12.81	70.330	70.230	56.3	28.00	M
13		Avon Mill	30.12.81	83.630	83.500	53.0	18.70	M
14		Ryton	30.12.81	64.230	64.170	56.3	44.50	M
15		Bubbenhall	9. 3.75	59.100	58.780	55.9	27.50	M
16			30.12.81	59.140	59.030	56.3	27.25	M
17		Cloud	9. 3.75	58.490	58.190	55.9	46.00	M
18			30.12.81	58.190	58.150	56.3	44.40	M
19		Stare	30.12.81	56.490	56.420	56.3	66.60	M
20	Erewash	Stanton Gt	26. 2.77	38.730	38.180	41.0	17.60	M
21	Arrow	Wixford	25. 1.60	33.205	32.991	69.0	38.72	S
22		Broom	25. 1.60	31.288	31.187	69.0	49.21	M
23		Salford	25. 1.60	28.971	28.502	69.0	14.85	S
24		Gunnings	25. 1.60	40.718	40.444	69.0	28.81	M
25		Oversley	25. 1.60	39.368	39.097	69.0	87.90	M
26	Stour	Blandford	28.12.79	34.150	33.840	204.0	81.88	M
27			11. 3.81	32.398	32.320	95.0	81.38	M
28			15.12.81	32.460	32.380	98.0	81.38	M
29			16. 3.82	32.690	32.600	114.0	81.38	M
30		Julians	11. 3.81	17.590	17.550	95.0	90.40	M
31			15.12.81	17.720	17.680	98.0	90.15	M
32			16. 3.82	17.800	17.770	114.0	90.45	M
33		Canford	11. 3.81	16.110	16.050	95.0	80.90	M
34			15.12.81	16.090	16.050	98.0	90.90	M
35			16. 3.82	16.330	16.300	114.0	82.85	M
36		Crawford	16. 3.82	26.940	26.860	114.0	80.00	M
37	Aire	Kildwick	22. 1.75	89.820	89.670	65.0	48.20	M
38			28.10.80	90.790	90.610	99.0	69.50	M
39			3. 1.82	89.900	89.740	67.0	56.50	M
40		Inghey	.46	96.410	95.970	118.0	165.30	M
41			22. 1.75	96.230	95.890	99.0	164.70	M
42			2. 1.76	96.120	95.740	87.0	164.40	M
43			15. 1.74	95.850	95.700	57.0	21.80	M
44	Spen	Station Rd	26. 4.83	53.430	53.190	17.4	6.50	S
45			1. 6.83	53.460	53.200	17.7	6.50	S

Key: M = multiple arched bridge
S = single arched bridge

TABLE 2 (cont'd)

No	River	Bridge	Date	u/s mAD	d/s mAD	Q cumecs	B m	Arch
46	Spen		9.12.83	53.530	53.230	18.2	6.50	S
47		Union St	26. 4.83	55.380	55.220	17.1	6.00	S
48			9.12.83	55.310	55.230	17.5	6.00	S
49		Rawfolds	26. 4.83	68.500	67.850	14.7	7.50	S
50			1. 6.83	68.270	67.750	13.1	7.50	S
51			9.12.83	68.310	67.850	12.9	7.50	S
52		St Pegs	26. 4.83	70.870	70.650	13.4	8.80	S
53			1. 6.83	70.590	70.430	10.8	8.03	S
54			9.12.83	70.530	70.430	10.4	7.90	S
55		Balme Rd	26. 4.83	77.890	77.410	10.7	8.80	M
56			1. 6.83	77.520	77.180	8.2	8.80	M
57			9.12.83	77.530	77.140	7.8	8.80	M
58	Wharfe	Pool	20. 9.46	45.310	44.900	416.4	90.75	M
59			16. 2.50	45.610	45.300	437.4	93.00	M
60			9.12.65	45.660	45.460	405.0	93.00	M
61		Ilkley	20. 9.46	73.880	73.630	436.4	36.59	S
62			16. 2.50	74.130	73.820	457.4	36.59	S
63	Nidd	Cattal	9.12.65	18.510	18.030	242.5	58.02	M
64	Wharfe	Bolton	16. 2.50	95.690	95.190	462.4	44.20	M
65			9.12.65	95.480	94.930	427.1	43.75	M
66		Grassington	9.12.65	166.520	165.810	437.1	66.00	M

Key: M = multiple arched bridge
S single arched bridge

TABLE 3: Hydraulic data; single semi-circular arched bridges

Test	Q cumecs	D1 m	D3 m	J1	J3	F3	dh/D3
2A	0.01	0.0747	0.0698	0.1556	0.1506	0.5092	0.0702
2B	0.01	0.0907	0.0876	0.1748	0.1707	0.3622	0.0354
2C	0.01	0.1227	0.1207	0.2295	0.2254	0.2239	0.0166
2D	0.01	0.1487	0.1468	0.3016	0.3000	0.1669	0.0129
2E	0.01	0.1875	0.1849	0.4456	0.4378	0.1181	0.0141
2F	0.01	0.2136	0.2105	0.5133	0.5062	0.0972	0.0147
3A	0.025	0.1189	0.0845	0.2217	0.1668	0.9557	0.4071
3B	0.025	0.1354	0.1182	0.2598	0.2203	0.5777	0.1455
3C	0.025	0.1571	0.1427	0.3383	0.2809	0.4355	0.1009
3D	0.025	0.1989	0.1807	0.4774	0.4247	0.3056	0.1007
3E	0.025	0.2379	0.2175	0.5630	0.5221	0.2314	0.0938
4A	0.035	0.1625	0.1012	0.3603	0.1901	1.0209	0.6057
4B	0.035	0.1713	0.1360	0.3932	0.2614	0.6553	0.2596
4C	0.035	0.2043	0.1698	0.4912	0.3878	0.4697	0.2032
4D	0.035	0.2363	0.1957	0.5601	0.4688	0.3796	0.2075
5A	0.044	0.2311	0.0919	0.5502	0.1765	1.4831	1.5147
5B	0.044	0.2348	0.1556	0.5573	0.3319	0.6732	0.5090
6A	0.0098	0.0767	0.0713	0.1578	0.1521	0.4834	0.0757
6B	0.0098	0.1134	0.1107	0.2110	0.2060	0.2498	0.0244
6C	0.0098	0.1446	0.1424	0.2869	0.2799	0.1712	0.0155
6D	0.0102	0.1679	0.1656	0.3809	0.3723	0.1421	0.0139
6E	0.0102	0.1993	0.1961	0.4784	0.4699	0.1103	0.0163
6F	0.0102	0.2365	0.2328	0.5605	0.5535	0.0853	0.0159
7A	0.0248	0.1196	0.0867	0.2231	0.1696	0.9122	0.3795
7B	0.0245	0.1429	0.1311	0.2815	0.2488	0.4847	0.0900
7C	0.0245	0.1728	0.1613	0.3984	0.3555	0.3551	0.0713
7D	0.0248	0.2037	0.1884	0.4897	0.4482	0.2847	0.0812
7E	0.025	0.2417	0.2201	0.5699	0.5277	0.2273	0.0981
8A	0.035	0.1643	0.1003	0.3673	0.1887	1.0347	0.6381
8B	0.035	0.1683	0.1300	0.3823	0.2462	0.7012	0.2946
8C	0.035	0.1878	0.1586	0.4465	0.3446	0.5203	0.1841
8D	0.035	0.2359	0.1993	0.5593	0.4784	0.3694	0.1836
9A	0.044	0.2288	0.0888	0.5457	0.1723	1.5614	1.5766
9B	0.044	0.2352	0.1734	0.5580	0.4005	0.5722	0.3564
10A	0.0105	0.0795	0.0715	0.2492	0.2415	0.4614	0.1119
10B	0.0104	0.1123	0.1080	0.2922	0.2858	0.2452	0.0369
10C	0.0106	0.1416	0.1380	0.3535	0.3441	0.1737	0.0261
10D	0.0103	0.1692	0.1655	0.4503	0.4380	0.1285	0.0224
10E	0.01	0.1996	0.1954	0.5340	0.5240	0.0973	0.0215
10F	0.01	0.2318	0.2273	0.5987	0.5906	0.0775	0.0202
11A	0.0249	0.1282	0.0844	0.3217	0.2542	0.8547	0.5208
11B	0.0248	0.1375	0.1128	0.3429	0.2924	0.5529	0.2233
11C	0.025	0.1589	0.1398	0.4147	0.3487	0.4018	0.1366
11D	0.0248	0.1901	0.1685	0.5107	0.4490	0.3004	0.1262
11E	0.0247	0.2388	0.2112	0.6105	0.5602	0.2134	0.1291
12A	0.035	0.1787	0.0897	0.4795	0.2599	1.1038	1.0034
12B	0.035	0.1868	0.1405	0.5021	0.3511	0.5572	0.3276
12C	0.035	0.2165	0.1724	0.5704	0.4608	0.4104	0.2551
12D	0.0349	0.2481	0.1985	0.6251	0.5312	0.3318	0.2505
13A	0.0429	0.2376	0.0737	0.6085	0.2434	1.8089	0.2233
14A	0.011	0.0838	0.0717	0.3835	0.3736	0.3977	0.1688

TABLE 3 (cont'd)

Test	Q cumecs	D1 m	D3 m	J1	J3	F3	dh/D3
14B	0.0105	0.1039	0.0972	0.4046	0.3969	0.2405	0.0689
14C	0.0104	0.1304	0.1254	0.4435	0.4349	0.1625	0.0399
14D	0.0102	0.1576	0.1529	0.5125	0.4975	0.1184	0.0307
14E	0.0104	0.1847	0.1796	0.5840	0.5722	0.0948	0.0284
14F	0.0104	0.2192	0.2134	0.6495	0.6399	0.0732	0.0272
14G	0.0103	0.2447	0.2386	0.6860	0.6780	0.0613	0.0256
15A	0.0258	0.1402	0.0832	0.4628	0.3830	0.7462	0.6851
15B	0.0262	0.1439	0.1033	0.4713	0.4039	0.5477	0.3930
15C	0.026	0.1621	0.1300	0.5260	0.4428	0.3850	0.2469
15D	0.0261	0.1889	0.1586	0.5933	0.5155	0.2868	0.1910
15E	0.0265	0.2115	0.1773	0.6367	0.5666	0.2464	0.1929
15F	0.0264	0.2362	0.1988	0.6747	0.6135	0.2067	0.1881
15G	0.0262	0.2483	0.2105	0.6906	0.6350	0.1883	0.1796
16A	0.029	0.1529	0.0803	0.4975	0.3805	0.8845	0.9041
16B	0.0285	0.1537	0.1086	0.5001	0.4104	0.5527	0.4153
16C	0.0288	0.1713	0.1319	0.5515	0.4463	0.4173	0.2987
16D	0.0285	0.1936	0.1558	0.6031	0.5068	0.3217	0.2426
16E	0.0290	0.2203	0.1794	0.6512	0.5717	0.2649	0.2280
16F	0.0285	0.2482	0.2050	0.6904	0.6252	0.2131	0.2107
17A	0.036	0.1936	0.0844	0.6031	0.3841	1.0190	1.2938
17B	0.0355	0.1943	0.1308	0.6046	0.4445	0.5209	0.4855
17C	0.0352	0.2120	0.1505	0.6376	0.4895	0.4184	0.4086
17D	0.0350	0.2276	0.1674	0.6624	0.5335	0.3547	0.3596
17E	0.0347	0.2465	0.1876	0.6883	0.5904	0.2964	0.3140
18A	0.0385	0.2141	0.0865	0.6411	0.3860	1.0504	1.4751
18C	0.0378	0.2101	0.1334	0.6343	0.4491	0.5385	0.5750
18D	0.0373	0.2275	0.1550	0.6623	0.5043	0.4242	0.4677
18E	0.0380	0.2385	0.1656	0.6778	0.5360	0.3914	0.4402
19A	0.0398	0.2236	0.0903	0.6563	0.3897	1.0180	1.4762
19B	0.0394	0.2229	0.1395	0.6550	0.4613	0.5248	0.5978
19C	0.04	0.2467	0.1611	0.6885	0.5231	0.4294	0.5313
20A	0.0412	0.2392	0.0934	0.6788	0.3928	1.0018	1.5610

TABLE 4: Hydraulic data; single elliptical arched bridges

Test	Q cumecs	D1 m	D3 m	dH/D3	dh/D3	J1	J3	F3
1	0.015	0.06435	0.0553	0.1414	0.1624	0.1459	0.1385	0.4018
2	0.0213	0.08323	0.0630	0.2729	0.3198	0.1657	0.1448	0.4693
3	0.03	0.09316	0.0754	0.1913	0.2353	0.1786	0.1568	0.5054
4	0.0405	0.11376	0.1059	0.0622	0.0733	0.2120	0.1982	0.4095
5	0.05	0.12798	0.1175	0.0739	0.0885	0.2417	0.2194	0.4327
6	0.061	0.14083	0.1306	0.0635	0.0776	0.2755	0.2482	0.4505
7	0.07	0.17149	0.1473	0.1395	0.1639	0.3941	0.2968	0.4318
8	0.0795	0.19733	0.1586	0.2095	0.2435	0.4734	0.3452	0.4388
9	0.09	0.24257	0.1669	0.3975	0.4534	0.5717	0.3774	0.4606
10	0.025	0.08454	0.0801	0.0469	0.0544	0.1673	0.1620	0.3843
11	0.03	0.09228	0.0873	0.0481	0.0567	0.1774	0.1707	0.4056
12	0.035	0.10071	0.0949	0.0509	0.0605	0.1897	0.1811	0.4174
13	0.04	0.10947	0.1027	0.0544	0.0649	0.2042	0.1930	0.4235
14	0.025	0.10201	0.1001	0.0168	0.0182	0.1918	0.1889	0.2751
15	0.03	0.14232	0.1406	0.0117	0.0121	0.2800	0.2748	0.1985
16	0.035	0.19932	0.0936	0.0287	0.0293	0.4787	0.1792	0.1433
17	0.045	0.11855	0.1106	0.0599	0.0716	0.2213	0.2063	0.4267
18	0.05	0.12752	0.1183	0.0649	0.0777	0.2406	0.2209	0.4287
19	0.055	0.13814	0.1261	0.0799	0.0951	0.2677	0.2375	0.4284
20	0.045	0.13569	0.1291	0.0452	0.0505	0.2609	0.2445	0.3382
21	0.05	0.16107	0.1521	0.0538	0.0584	0.3549	0.3172	0.2939
22	0.055	0.20422	0.1878	0.0828	0.0871	0.4912	0.4469	0.2357
23	0.065	0.15838	0.1401	0.1099	0.1301	0.3440	0.2735	0.4323
24	0.07	0.17263	0.1477	0.1434	0.1681	0.3981	0.2985	0.4299
25	0.075	0.18906	0.1545	0.1926	0.2234	0.4504	0.3277	0.4308
26	0.08	0.20772	0.1614	0.2502	0.2868	0.4998	0.3563	0.4304
27	0.065	0.17065	0.1514	0.1110	0.1268	0.3911	0.3139	0.3848
28	0.07	0.19629	0.1695	0.1422	0.1577	0.4707	0.3872	0.3499
29	0.075	0.23896	0.1978	0.1939	0.2078	0.5652	0.4749	0.2973
31	0.082	0.21172	0.1489	0.3591	0.4217	0.5092	0.3028	0.4979
32	0.085	0.22255	0.1490	0.4203	0.4936	0.5331	0.3031	0.5157
33	0.09	0.23131	0.1642	0.3532	0.4084	0.5508	0.3674	0.4718

TABLE 5: Multiple semi-circular arched bridges

Test	Q cumecs	D1 m	D3 m	J1	J3	F3	dh/D3
21A	0.0038	0.0636	0.0619	0.1448	0.1434	0.0768	0.0275
21B	0.0029	0.1073	0.1062	0.2001	0.1982	0.0262	0.0104
21C	0.0028	0.1572	0.1561	0.3387	0.3341	0.0145	0.0070
21D	0.0029	0.2022	0.2011	0.4859	0.4831	0.0101	0.0055
21E	0.0029	0.2449	0.2444	0.5755	0.5747	0.0075	0.0020
22A	0.0099	0.0743	0.0726	0.1552	0.1534	0.1584	0.0234
22B	0.0099	0.1138	0.1129	0.2117	0.2101	0.0817	0.0080
22C	0.01	0.1527	0.1513	0.3192	0.3129	0.0532	0.0093
22D	0.0102	0.1995	0.1977	0.4789	0.4742	0.0365	0.0091
22E	0.01	0.2403	0.2387	0.5674	0.5645	0.0268	0.0067
23A	0.0254	0.0935	0.0892	0.1787	0.1728	0.2984	0.0482
23B	0.0256	0.1402	0.1373	0.2733	0.2650	0.1575	0.0211
23C	0.0253	0.1942	0.1906	0.4647	0.4546	0.0952	0.0189
23D	0.0257	0.2333	0.2289	0.5544	0.5459	0.0734	0.0192
24A	0.0347	0.1021	0.0966	0.1915	0.1831	0.3618	0.0569
24B	0.0343	0.1484	0.1445	0.3004	0.2866	0.1954	0.0270
24C	0.0350	0.1863	0.1813	0.4420	0.4266	0.1419	0.0276
24D	0.0340	0.2218	0.2152	0.5313	0.5170	0.1066	0.0307
24E	0.0358	0.2494	0.2417	0.5832	0.5699	0.0943	0.0319
25A	0.0445	0.1117	0.1036	0.2079	0.1939	0.4177	0.0782
25B	0.0442	0.1439	0.1378	0.2847	0.2664	0.2705	0.0443
25C	0.0443	0.1768	0.1695	0.4120	0.3867	0.1987	0.0431
25D	0.0441	0.2143	0.2048	0.5149	0.4924	0.1489	0.0464
25A	0.0441	0.2453	0.2344	0.5762	0.5565	0.1216	0.0465
26B	0.0611	0.1308	0.1167	0.2481	0.2173	0.4797	0.1208
26C	0.0612	0.1719	0.1586	0.3953	0.3446	0.3033	0.0839
26D	0.0617	0.2115	0.1933	0.5085	0.4622	0.2272	0.0942
26E	0.0608	0.2413	0.2211	0.5692	0.5298	0.1830	0.0914
27A	0.0800	0.1558	0.1288	0.3328	0.2435	0.5417	0.2097
27B	0.0795	0.1976	0.1704	0.4739	0.3904	0.3538	0.1596
27C	0.0792	0.2391	0.2053	0.5652	0.4937	0.2665	0.1646
28A	0.0930	0.1741	0.1360	0.4029	0.2614	0.5804	0.2801
28B	0.0900	0.2325	0.1932	0.5529	0.4619	0.3317	0.2034
29A	0.11	0.2199	0.1407	0.5273	0.2747	0.6524	0.5629
29B	0.11	0.2270	0.1721	0.5421	0.3960	0.4823	0.3190

TABLE 6: Hydraulic data; multiple semi-circular arches bridge with different soffit levels

Test	Q cumecs	D1 m	D3 m	F3	dh/D3	dH/D3	J1	J3
1	0.015	0.0677	0.0602	0.3542	0.1257	0.1126	0.359	0.355
2	0.021	0.0835	0.0729	0.3667	0.1454	0.1289	0.369	0.362
3	0.03	0.1037	0.0886	0.3968	0.1710	0.1497	0.391	0.373
4	0.0405	0.1252	0.1038	0.4225	0.2067	0.1788	0.428	0.391
5	0.05	0.1469	0.1185	0.4277	0.2396	0.2077	0.463	0.417
6	0.061	0.1719	0.1323	0.4420	0.2987	0.2590	0.512	0.440
7	0.07	0.1962	0.1441	0.4463	0.3613	0.3155	0.556	0.459
8	0.0795	0.2221	0.1552	0.4536	0.4311	0.3785	0.606	0.479
9	0.025	0.1054	0.0968	0.2893	0.0886	0.0821	0.394	0.382
10	0.03	0.1524	0.1345	0.2121	0.1330	0.1280	0.473	0.443
11	0.035	0.1999	0.1882	0.1495	0.0620	0.0608	0.563	0.542
12	0.045	0.1443	0.1233	0.3624	0.1701	0.1524	0.459	0.425
13	0.05	0.1720	0.1469	0.3097	0.1706	0.1576	0.512	0.464
14	0.055	0.2150	0.1854	0.2404	0.0716	0.1526	0.593	0.537
15	0.065	0.1925	0.1490	0.3942	0.2918	0.2607	0.550	0.467
16	0.07	0.2239	0.1702	0.3477	0.3156	0.2901	0.609	0.509
17	0.075	0.2548	0.1945	0.3049	0.3098	0.2904	0.656	0.553
18	0.015	0.0584	0.0464	0.5227	0.2577	0.2075	0.354	0.350
19	0.03	0.0900	0.0739	0.5201	0.2169	0.1730	0.375	0.362
20	0.05	0.1485	0.1192	0.4237	0.2461	0.2141	0.466	0.418
21	0.015	0.0748	0.0504	0.4626	0.4856	0.4270	0.381	0.570
22	0.0213	0.1066	0.0630	0.4690	0.6901	0.6186	0.615	0.575
23	0.03	0.1396	0.0730	0.5300	0.9111	0.8091	0.669	0.580
24	0.0405	0.1874	0.0805	0.6183	1.3269	1.1711	0.747	0.585
25	0.05	0.2428	0.0866	0.6845	1.8046	1.6002	0.803	0.590
26	0.025	0.1337	0.1024	0.2659	0.3049	0.2903	0.664	0.608
27	0.03	0.1814	0.1360	0.2086	0.3340	0.3244	0.738	0.663
28	0.035	0.2412	0.1841	0.1546	0.3103	0.3053	0.803	0.742
29	0.045	0.2102	0.1057	0.4565	0.9883	0.9105	0.774	0.613
30	0.025	0.1196	0.0797	0.3874	0.5008	0.4590	0.572	0.564
31	0.03	0.1565	0.1329	0.2158	0.1773	0.1708	0.598	0.578
32	0.035	0.2055	0.1811	0.1584	0.1349	0.1321	0.663	0.630
33	0.045	0.1711	0.1101	0.4296	0.5537	0.4997	0.617	0.569
34	0.05	0.1954	0.1315	0.3656	0.4858	0.4492	0.649	0.577
35	0.055	0.2314	0.1612	0.2963	0.4352	0.4126	0.701	0.605
36	0.025	0.1135	0.0706	0.4642	0.6060	0.5400	0.570	0.563
37	0.03	0.1242	0.0760	0.4987	0.6326	0.5550	0.574	0.563
38	0.035	0.1358	0.0828	0.5118	0.6395	0.5573	0.580	0.564
39	0.045	0.1614	0.0901	0.5801	0.7910	0.6752	0.605	0.565
40	0.05	0.1810	0.0893	0.6535	1.0268	0.8653	0.630	0.565
41	0.055	0.1954	0.0845	0.7800	1.3099	1.0627	0.648	0.564
42	0.025	0.1300	0.1012	0.2709	0.2847	0.2703	0.641	0.602
43	0.03	0.1677	0.1358	0.2089	0.2343	0.2268	0.678	0.648
44	0.035	0.2191	0.1828	0.1562	0.1984	0.1947	0.734	0.692
45	0.045	0.1974	0.1286	0.3403	0.5346	0.5013	0.706	0.640
46	0.05	0.2295	0.1493	0.3024	0.5373	0.5110	0.746	0.661
47	0.025	0.1231	0.0827	0.3665	0.4878	0.4510	0.633	0.586
48	0.03	0.1346	0.0885	0.3975	0.5206	0.4758	0.646	0.590

TABLE 6 (cont'd)

Test	Q cumecs	D1 m	D3 m	F3	dh/D3	dH/D3	J1	J3
49	0.035	0.1538	0.0959	0.4108	0.6031	0.5516	0.666	0.597
50	0.045	0.1852	0.1106	0.4264	0.6733	0.6148	0.694	0.616
51	0.05	0.2186	0.1222	0.4080	0.7885	0.7312	0.733	0.632
52	0.055	0.2337	0.1284	0.4168	0.8195	0.7588	0.750	0.640

TABLE 7: Hydraulic data prototype bridges

No	u/s mAD	d/s mAD	dh m	Q cumecs	J1	B m	F3	dh/D3	J3
1	92.660	92.560	0.100	19	0.440	48.05	0.080	0.074	0.424
2	87.020	86.500	0.520	25	0.547	30.20	0.073	0.221	0.416
3	87.020	86.500	0.520	25	0.532	27.60	0.072	0.206	0.416
4	86.080	85.970	0.110	19	0.309	28.20	0.082	0.058	0.238
5	80.910	80.450	0.460	56.6	0.291	29.10	0.290	0.277	0.219
6	80.100	79.990	0.110	53	0.190	25.30	0.379	0.075	0.189
7	72.530	72.420	0.110	55.9	0.563	46.40	0.156	0.060	0.538
8	72.530	72.420	0.110	55.9	0.550	41.90	0.153	0.056	0.538
9	72.330	72.200	0.013	56.3	0.504	44.60	0.194	0.008	0.506
10	72.330	72.200	0.013	56.3	0.496	41.90	0.192	0.007	0.506
11	70.662	70.586	0.076	71.4	0.391	30.15	0.240	0.035	0.376
12	70.330	70.230	0.100	56.3	0.345	28.00	0.237	0.052	0.338
13	83.630	83.500	0.130	53	0.367	18.70	0.294	0.061	0.317
14	64.230	64.170	0.060	56.3	0.326	44.50	0.109	0.025	0.303
15	59.110	58.780	0.330	55.9	0.247	27.50	0.276	0.187	0.198
16	59.140	59.030	0.110	56.3	0.243	27.25	0.240	0.056	0.217
17	58.490	58.190	0.300	55.9	0.435	46.00	0.097	0.119	0.357
18	58.190	58.150	0.040	56.3	0.360	44.40	0.098	0.015	0.356
19	56.490	56.420	0.070	56.3	0.539	66.60	0.116	0.040	0.532
20	38.730	38.180	0.550	41	0.524	17.60	0.460	0.399	0.348
21	33.205	32.991	0.214	69	0.288	38.72	0.129	0.079	0.260
22	31.288	31.187	0.101	69	0.064	49.21	0.210	0.061	0.061
23	28.971	28.502	0.469	69	0.082	14.85	0.274	0.152	0.047
24	40.718	40.444	0.274	69	0.471	28.81	0.209	0.115	0.371
25	39.368	39.097	0.271	69	0.645	87.90	0.072	0.118	0.606
26	34.150	33.840	0.310	204	0.670	81.88	0.067	0.060	0.619
27	32.398	32.320	0.098	95	0.528	81.38	0.120	0.046	0.498
28	32.460	32.380	0.080	98	0.514	81.38	0.110	0.035	0.500
29	32.690	32.600	0.090	114	0.532	81.38	0.106	0.034	0.527
30	17.590	17.550	0.040	95	0.355	90.40	0.250	0.033	0.353
31	17.720	17.680	0.040	98	0.371	90.15	0.212	0.029	0.368
32	17.800	17.770	0.030	114	0.381	90.45	0.220	0.020	0.376
33	16.110	16.050	0.060	95	0.264	80.90	0.145	0.032	0.260
34	16.090	16.050	0.040	98	0.264	90.90	0.157	0.024	0.260
35	16.330	16.300	0.030	114	0.283	82.85	0.131	0.013	0.283
36	26.940	26.860	0.080	114	0.372	80.00	0.317	0.063	0.348
37	89.820	89.670	0.150	65	0.326	48.20	0.239	0.101	0.299
38	90.790	90.610	0.180	99	0.488	69.50	0.188	0.100	0.452
39	89.900	89.740	0.160	67	0.337	56.50	0.252	0.122	0.309
40	96.410	95.970	0.440	118	0.552	165.30	0.317	0.548	0.427
41	96.230	95.890	0.340	99	0.522	164.70	0.288	0.446	0.382
42	96.120	95.740	0.380	87	0.490	164.40	0.358	0.627	0.350
43	95.850	95.700	0.150	57	0.485	21.80	0.345	0.083	0.325
44	53.430	53.190	0.240	17.4	0.426	6.50	0.492	0.166	0.325
45	53.460	53.200	0.260	17.7	0.448	6.50	0.477	0.174	0.352
46	53.530	53.230	0.300	18.2	0.474	6.50	0.468	0.195	0.383
47	55.380	55.220	0.160	17.1	0.099	6.00	0.536	0.112	0.097
48	55.310	55.230	0.080	17.5	0.067	6.00	0.534	0.055	0.064
49	68.500	67.850	0.650	14.7	0.355	7.50	0.467	0.534	0.218
50	68.270	67.750	0.520	13.1	0.242	7.50	0.505	0.487	0.126
51	68.310	67.850	0.460	12.9	0.277	7.50	0.415	0.382	0.138

TABLE 7 (cont'd)

No	u/s mAD	d/s mAD	dh m	Q cumecs	J1	B m	F3	dh/D3	J3
52	70.870	70.650	0.220	13.4	0.384	8.80	0.293	0.157	0.330
53	70.590	70.430	0.160	10.8	0.320	8.03	0.279	0.120	0.281
54	70.530	70.430	0.100	10.4	0.311	7.90	0.263	0.073	0.281
55	77.890	77.410	0.480	10.7	0.515	8.80	0.258	0.365	0.336
56	77.520	77.180	0.340	8.2	0.406	8.80	0.249	0.302	0.196
57	77.530	77.140	0.390	7.8	0.406	8.80	0.254	0.362	0.158
58	45.310	44.900	0.410	416.4	0.268	90.75	0.327	0.151	0.225
59	45.610	45.300	0.310	437.4	0.294	93.00	0.284	0.102	0.262
60	45.660	45.460	0.200	405.0	0.294	93.00	0.249	0.064	0.279
61	73.880	73.630	0.250	436.4	0.240	36.59	0.306	0.047	0.226
62	74.130	73.820	0.310	457.4	0.260	36.59	0.319	0.058	0.239
63	18.510	18.030	0.480	242.5	0.389	58.02	0.240	0.153	0.321
64	95.690	95.190	0.500	462.4	0.157	44.20	0.832	0.198	0.136
65	95.480	94.930	0.550	427.1	0.141	43.75	0.925	0.245	0.120
66	166.520	165.810	0.710	437.1	0.350	66.00	1.241	0.498	0.314

TABLE 8: Equations of contours of J1 for single and multiple arched bridges

Single arch bridges

J1	Equation of contour
0.2	$Y = (0.0083074\ X)+(0.100316\ X^2)+(0.716605\ X^3)-(0.399426\ X^4)$
0.3	$Y = (0.00337637\ X)+(0.627119\ X^2)-(0.124796\ X^3)$
0.4	$Y = (0.0382022\ X)+(0.852195\ X^2)-(0.214903\ X^3)$
0.5	$Y = (0.195424\ X)+(0.724589\ X^2)-(0.00226744\ X^3)$
0.6	$Y = (0.320591\ X)+(1.45138\ X^2)-(0.534293\ X^3)$
0.7	$Y = (0.737665\ X)+(1.32557\ X^2)-(0.414776\ X^3)$

Multiple arch bridges

J1	Equation of contour
0.2	$Y = (0.0083074\ X)+(0.100316\ X^2)+(0.716605\ X^3)-(0.399426\ X^4)$
0.3	$Y = (0.00337637\ X)+(0.627119\ X^2)-(0.124796\ X^3)$
0.4	$Y = (0.0382022\ X)+(0.852195\ X^2)-(0.214903\ X^3)$
0.5	$Y = (0.0456109\ X)+(1.62435\ X^2)-(0.65887\ X^3)$
0.6	$Y = (0.268273\ X)+(2.40478\ X^2)-(0.982461\ X^3)$
0.7	$Y = (0.875772\ X)+(2.48884\ X^2)-(1.3122\ X^3)$
0.8	$Y = (1.40736\ X)+(4.50426\ X^2)-(4.37891\ X^3)$

TABLE 9: Summary of percentage standard deviation from calculated curves

	J1	J3
Prototype single arched bridges	13.60	12.48
Model elliptical arched bridges	10.45	12.00
Model semi-circular arched bridges	9.56	8.43
All model single arched bridges	9.96	9.78
All model and prototype single arched bridges	10.15	9.97
Prototype multiple arched bridges	36.75	45.42
All model multiple arched bridges	10.0	8.80

TABLE 10: Equations of contours of J3 for single and multiple arched bridges

J3	Equation of contour
0.2	$Y = (0.065289\ X) - (0.407001\ X^2) + (1.72763\ X^3) - (0.784489\ X^4)$
0.3	$Y = (0.0146852\ X) + (0.385273\ X^2) + (0.720249\ X^3) - (0.223369\ X^4)$
0.4	$Y = (0.0251314\ X) + (0.583369\ X^2) + (1.73559\ X^3) - (0.942262\ X^4)$
0.5	$Y = (0.171767\ X) + (0.266569\ X^2) + (5.34647\ X^3) - (4.34132\ X^4)$
0.6	$Y = (0.13921\ X) + (2.28321\ X^2) + (4.96646\ X^3) - (6.02973\ X^4)$
0.7	$Y = (0.490648\ X) + (2.88447\ X^2) + (26.2231\ X^3) - (37.0117\ X^4)$

FIGURES.

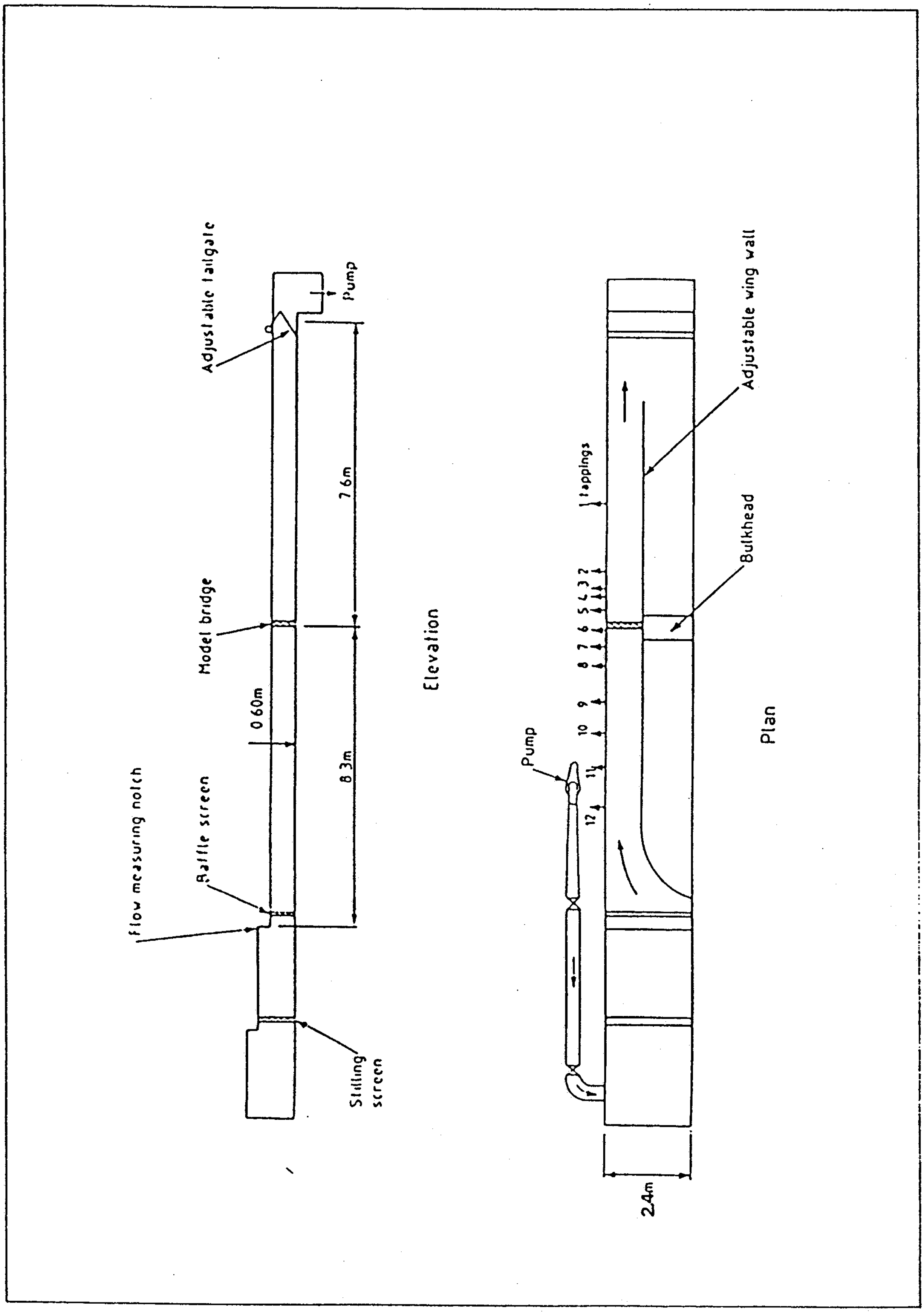


FIG 1   Layout of fixed bed flume

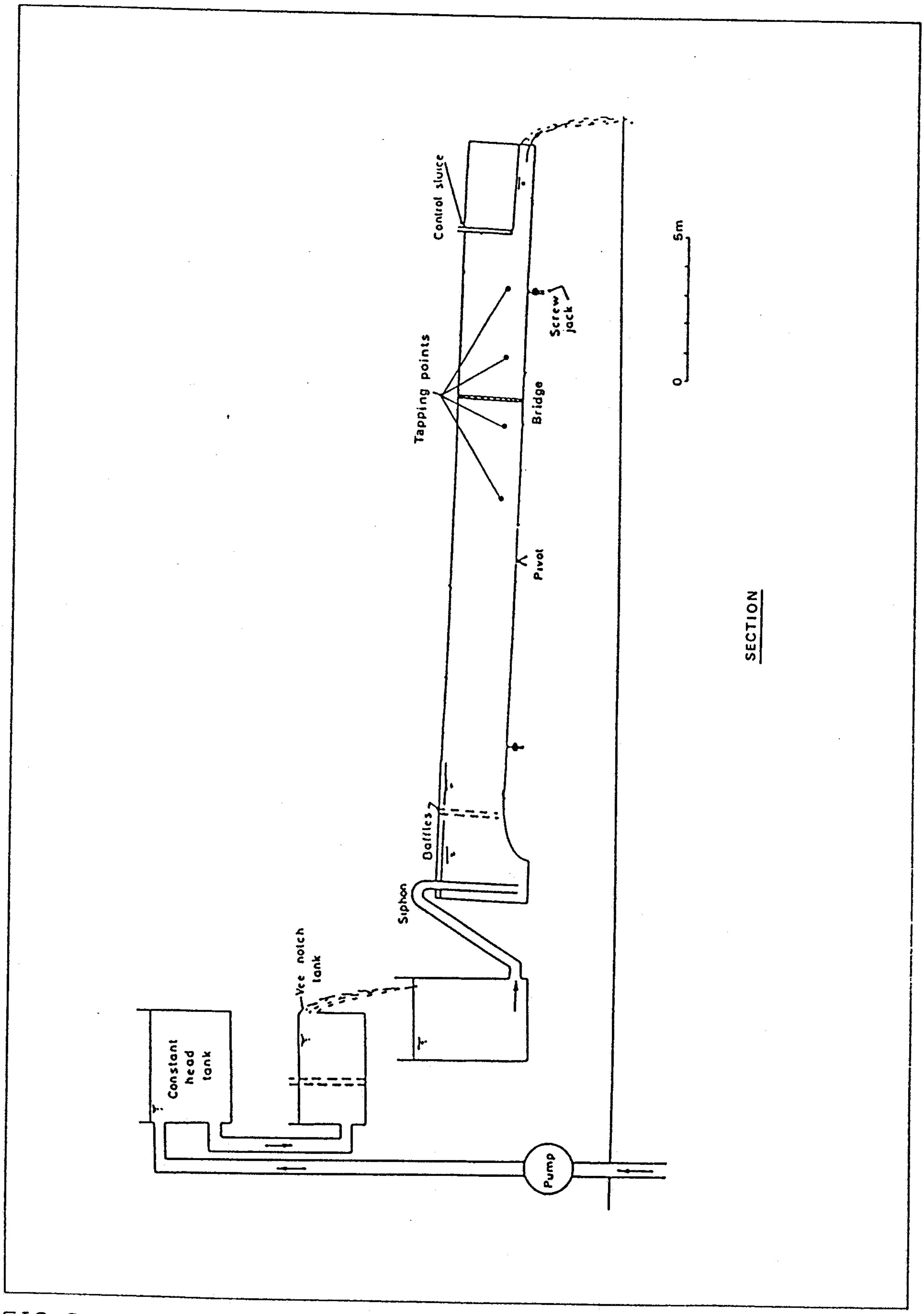


FIG 2 Layout of adjustable bed flume

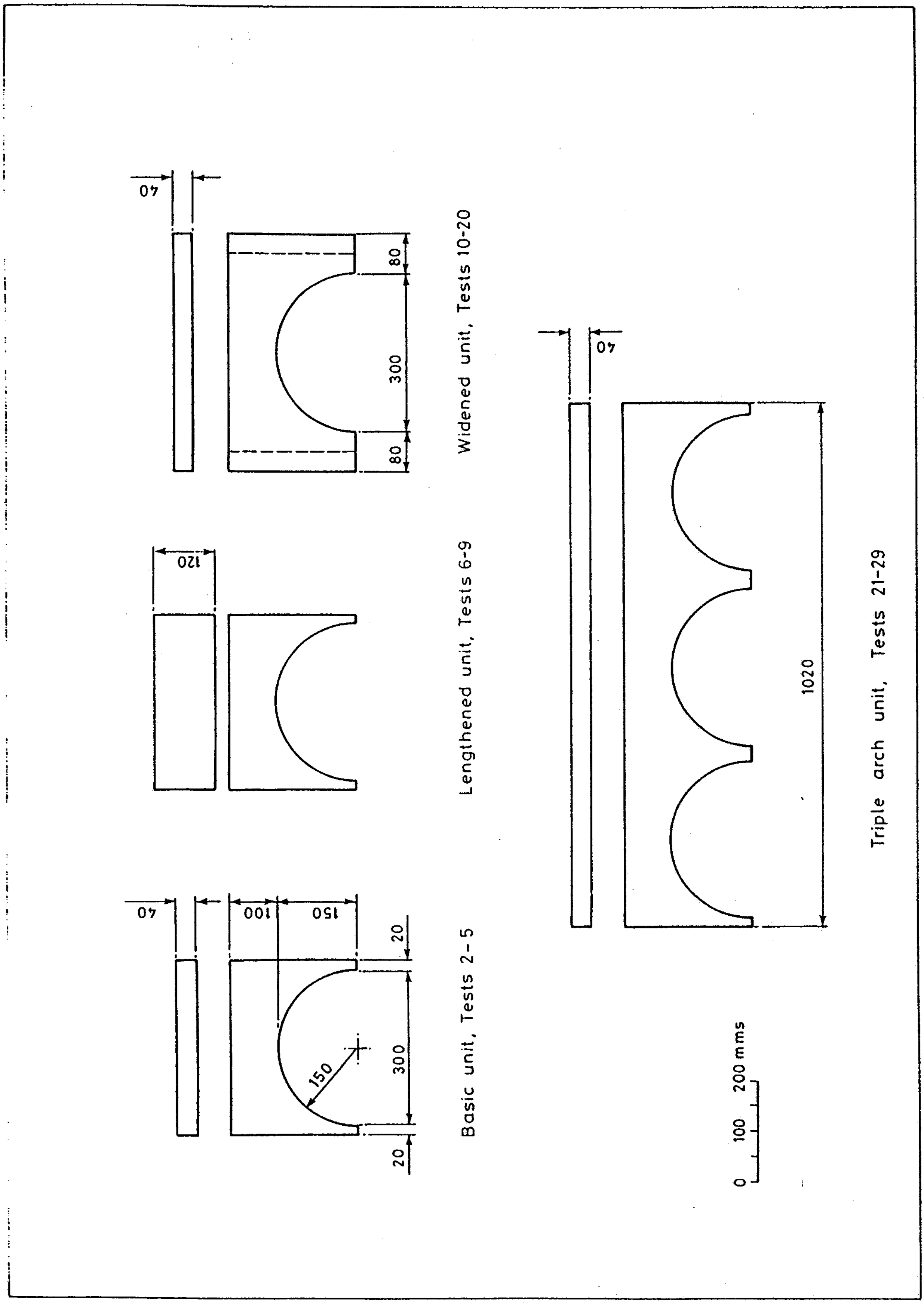


Fig 3 Semi-circular arch bridges

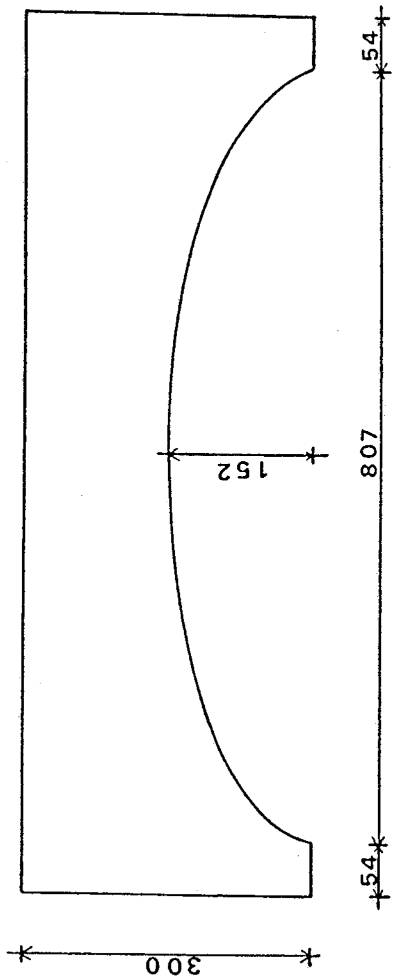


FIG 4 Elliptical arch bridge

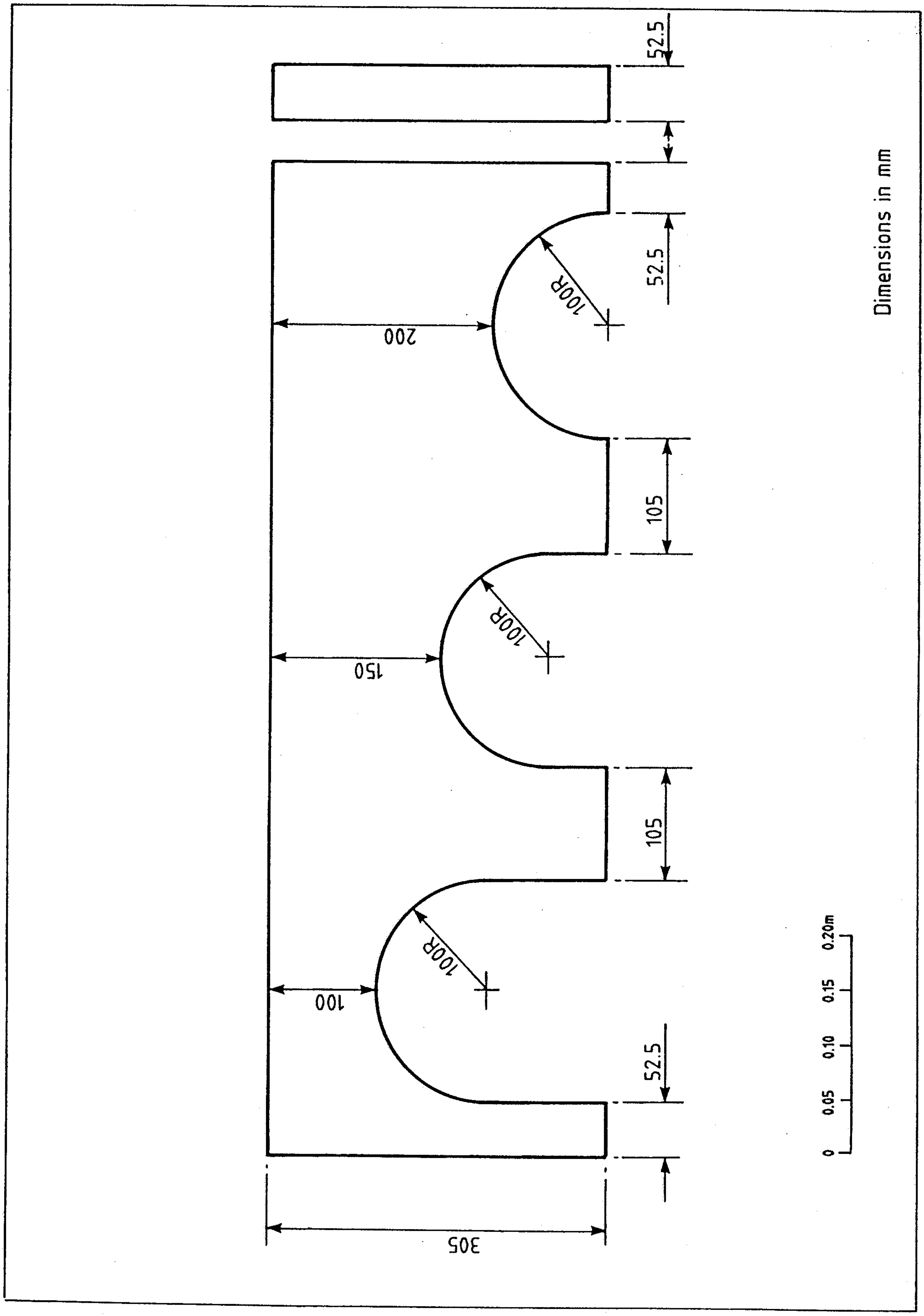


Fig 5 Multiple semi-circular arched bridge with different soffit levels

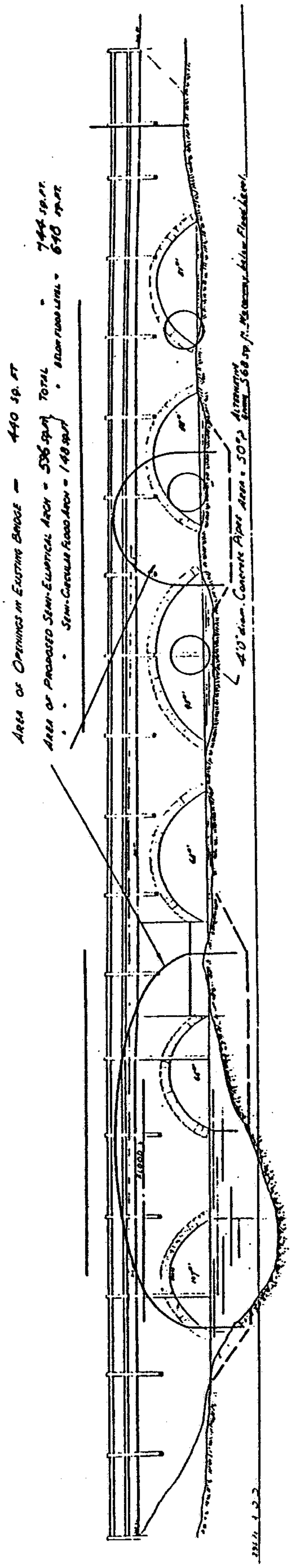


Fig 6 Dow bridge, River Avon, Severn Trent Water Authority

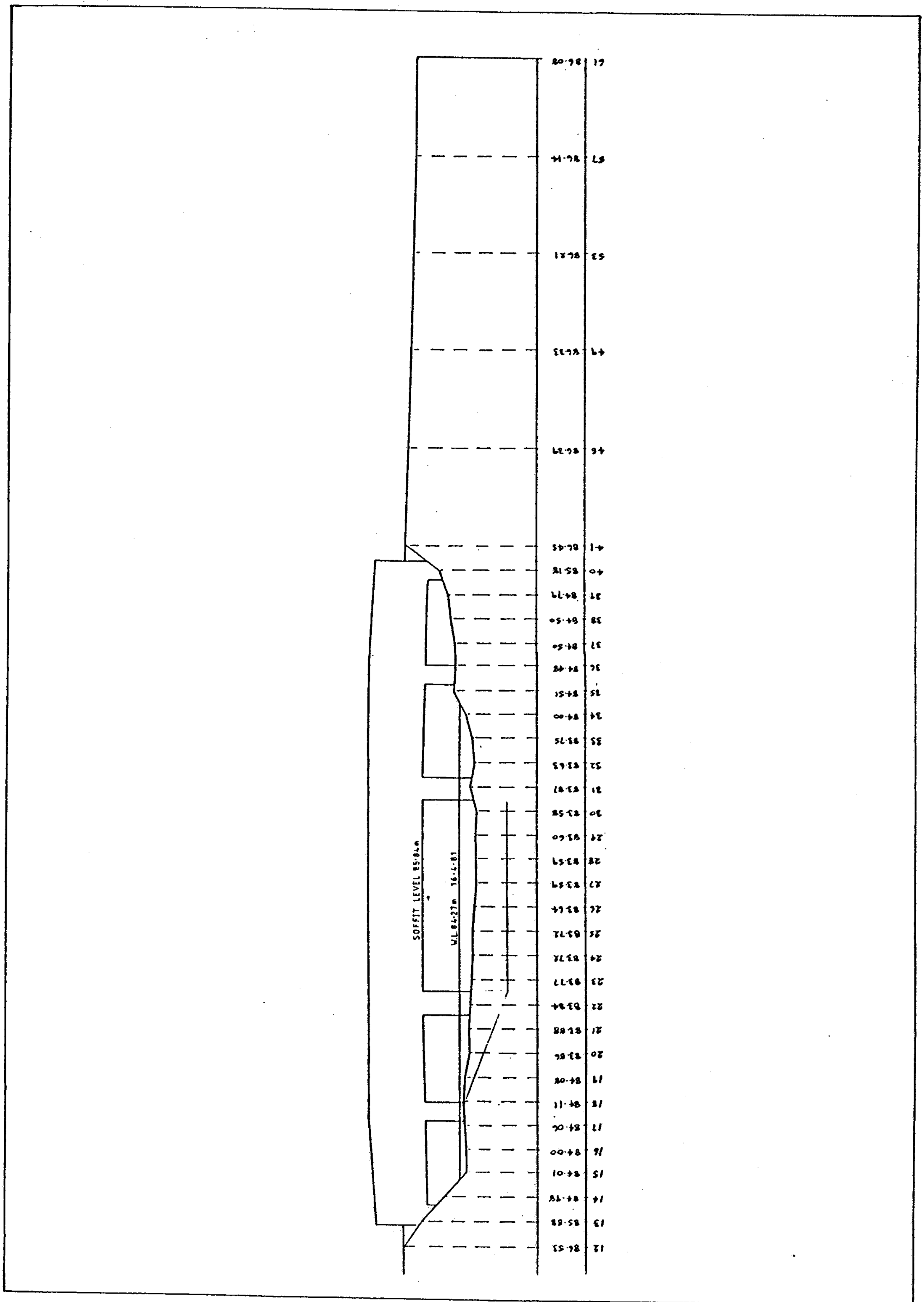


Fig 7 Boughton Road bridge, River Avon, Severn Trent Water Authority

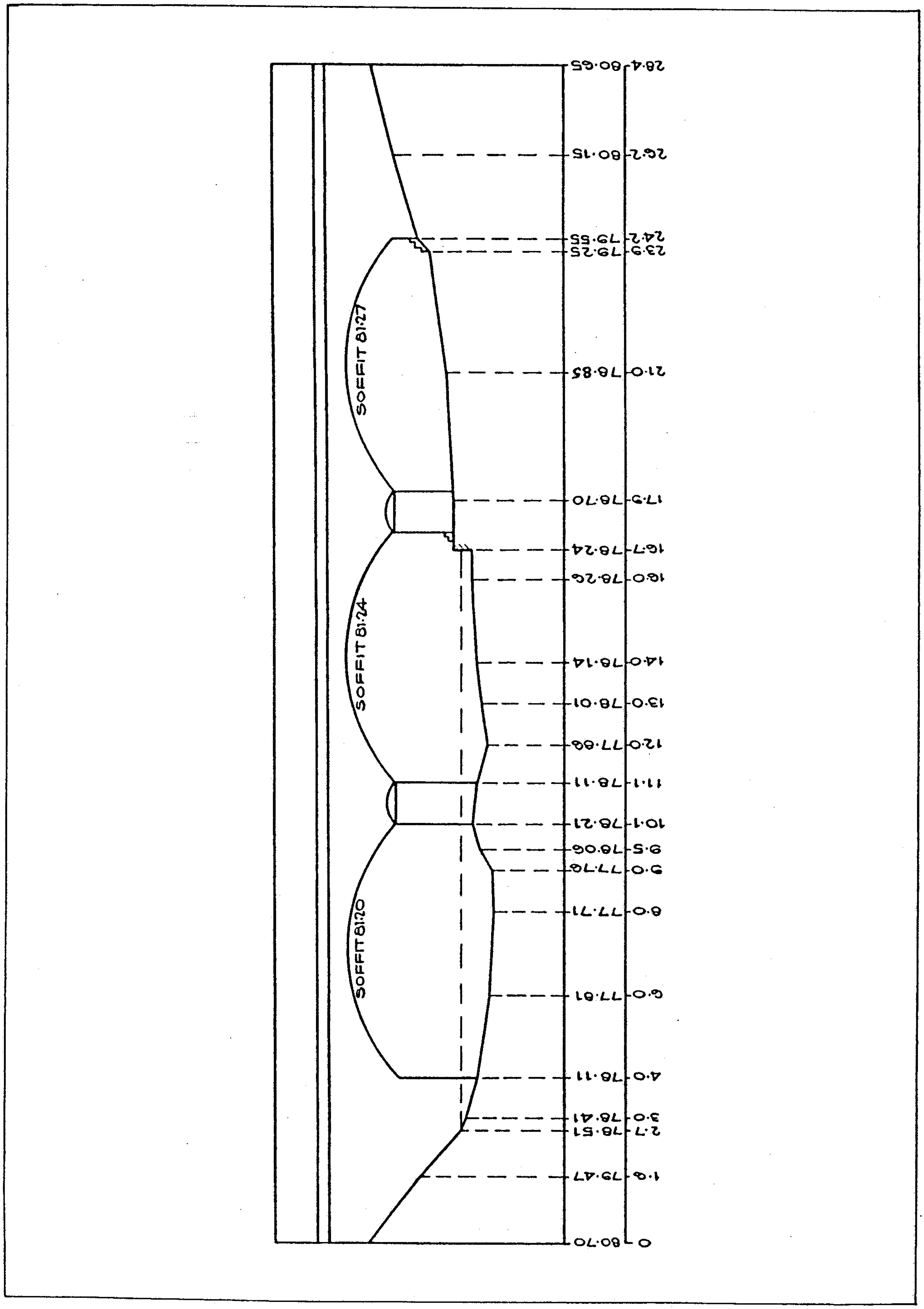


Fig 8 Lea Crescent bridge, River Avon, Severn Trent Water Authority

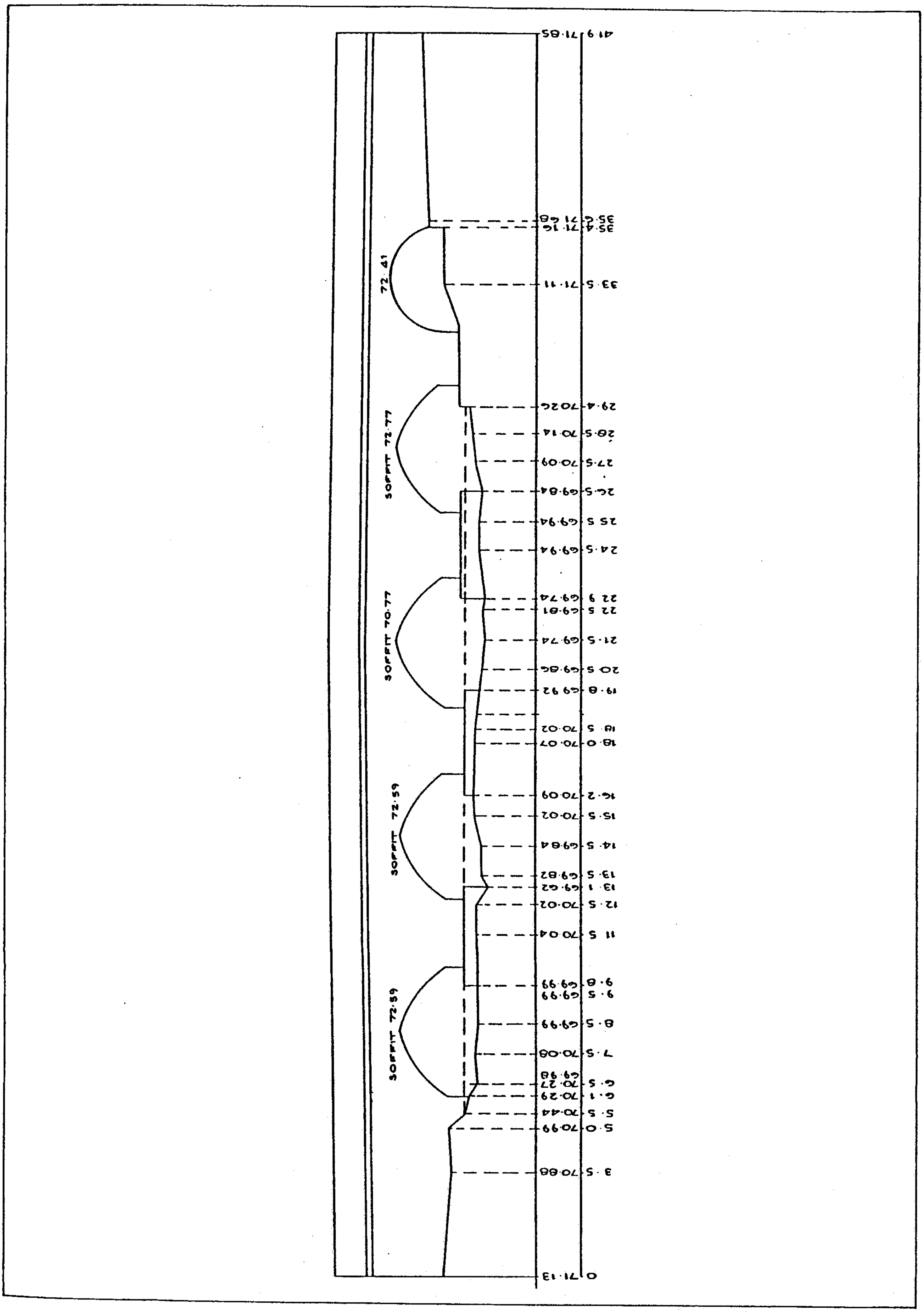


Fig 9 Bretford bridge, River Avon, Severn Trent Water Authority

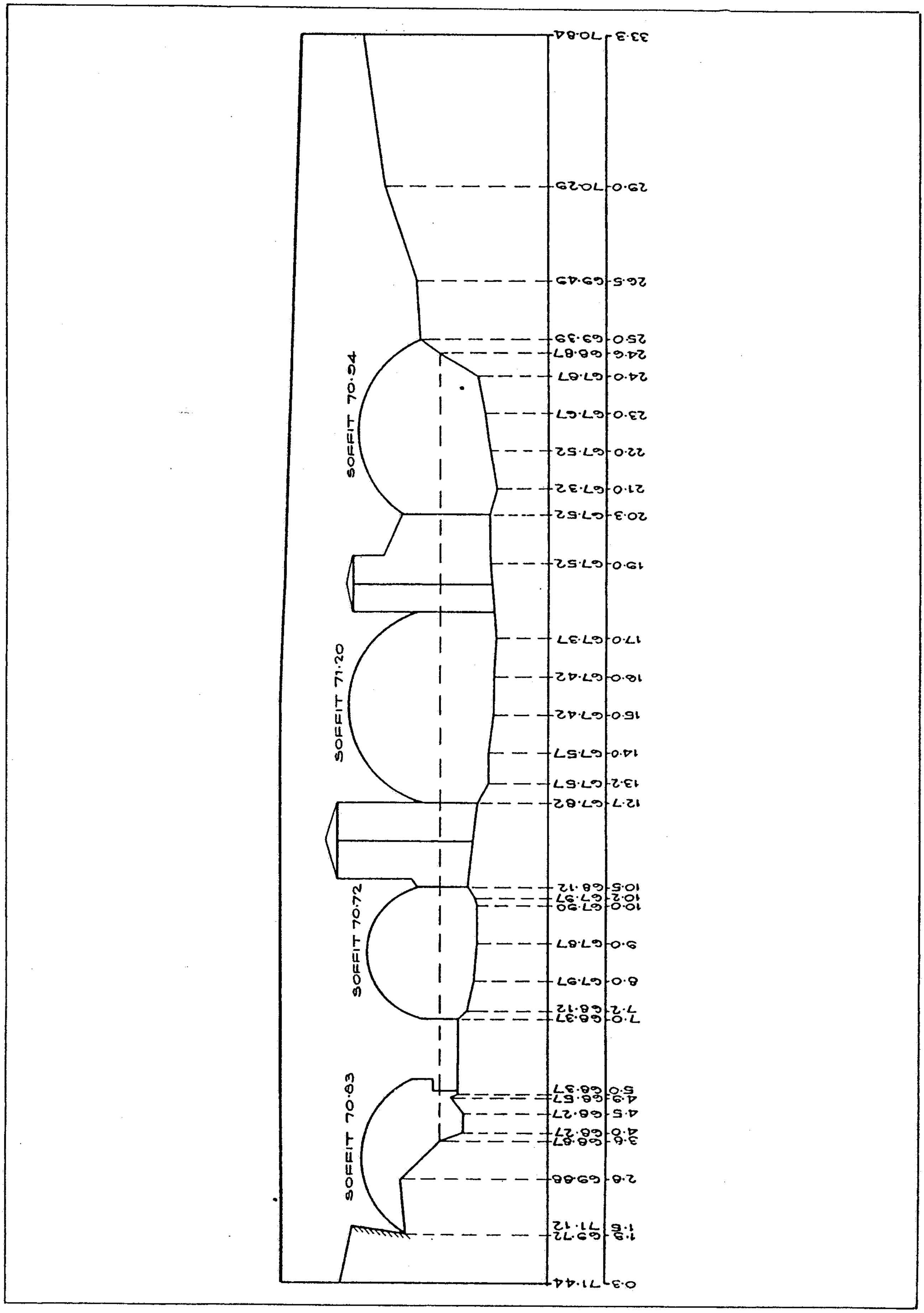


Fig 10 Wolston bridge, River Avon, Severn Trent Water Authority

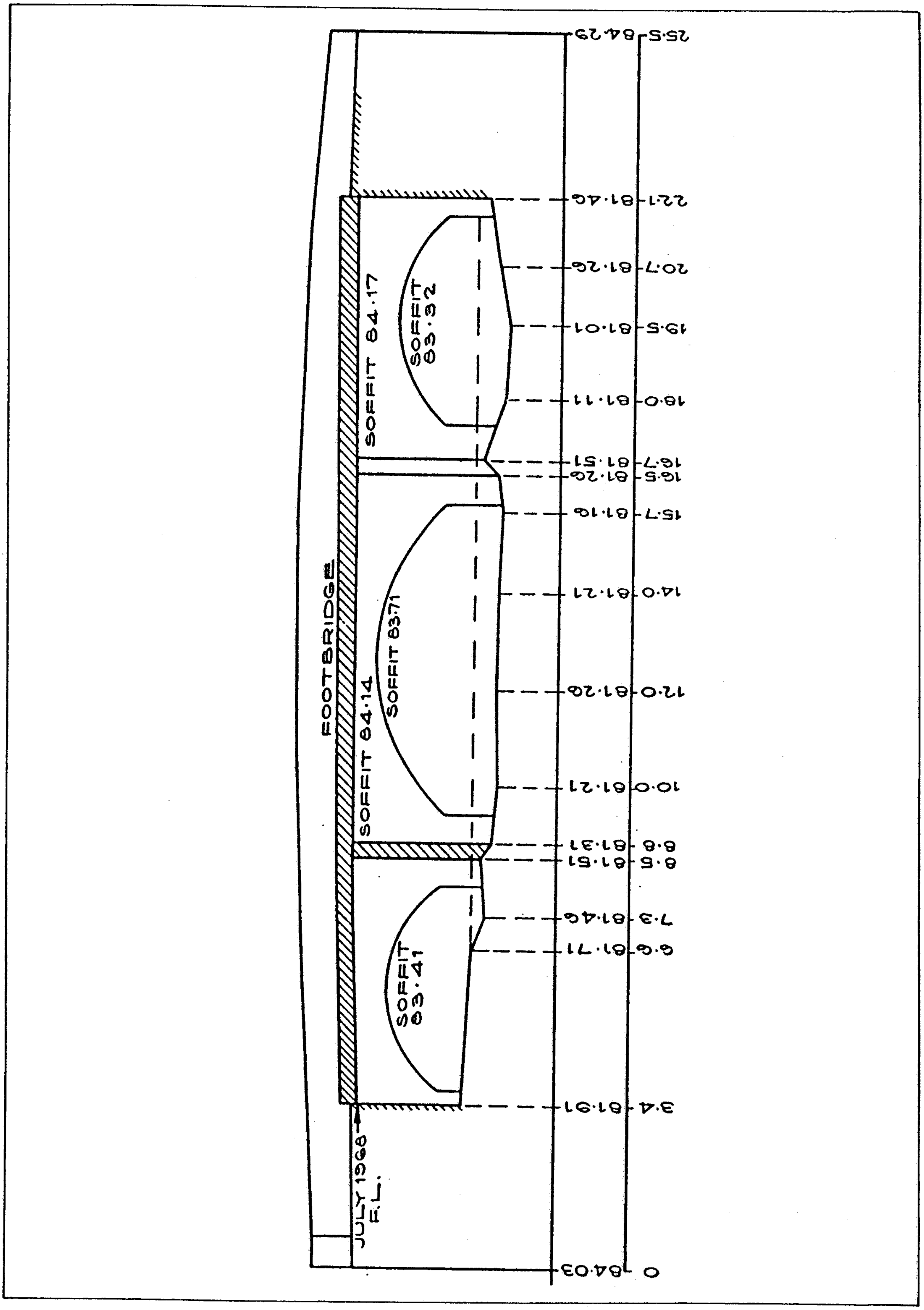


Fig 11 Avon Mill bridge, River Avon, Severn Trent Water Authority

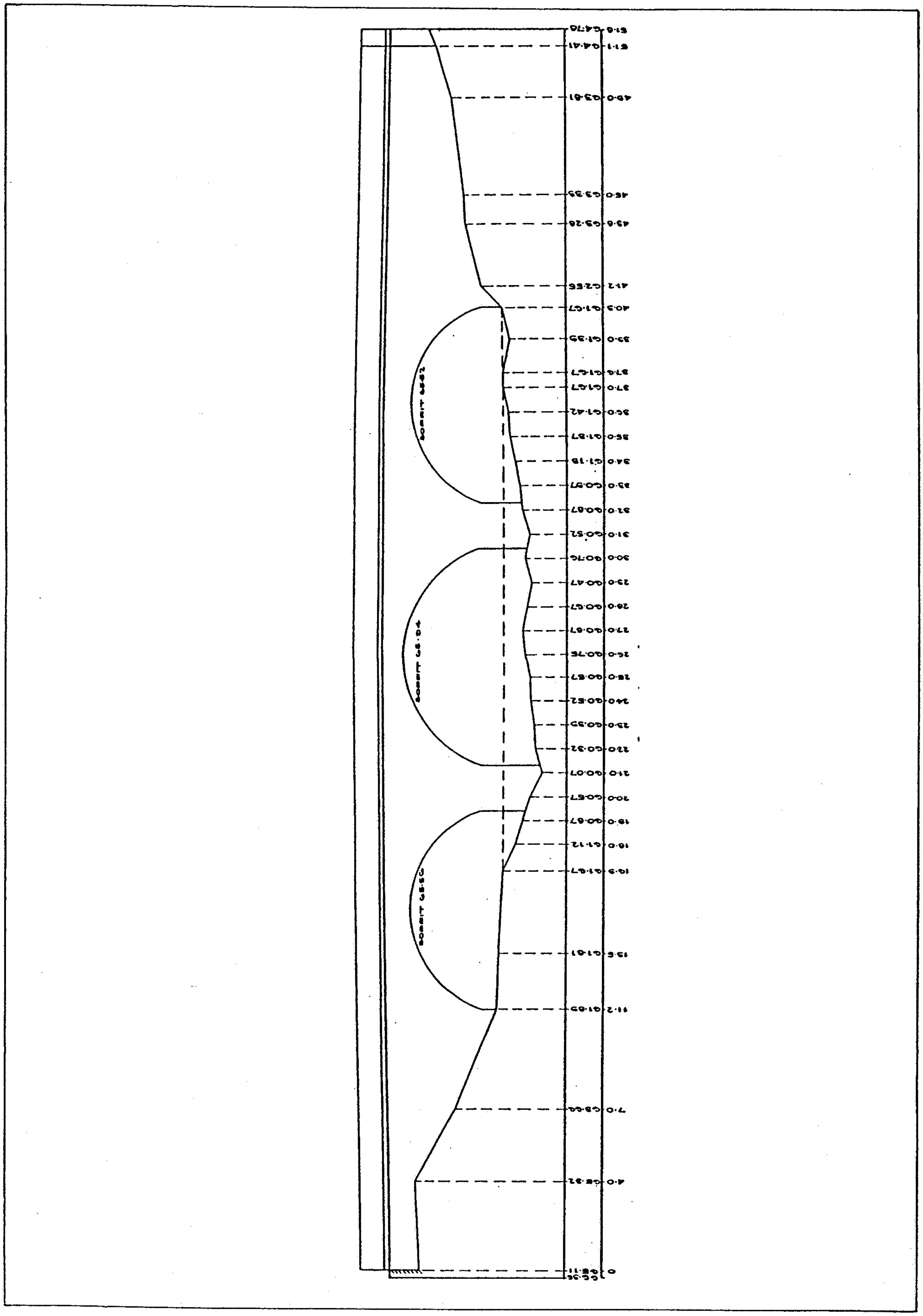


Fig 12 Ryton bridge, River Avon, Severn Trent Water Authority

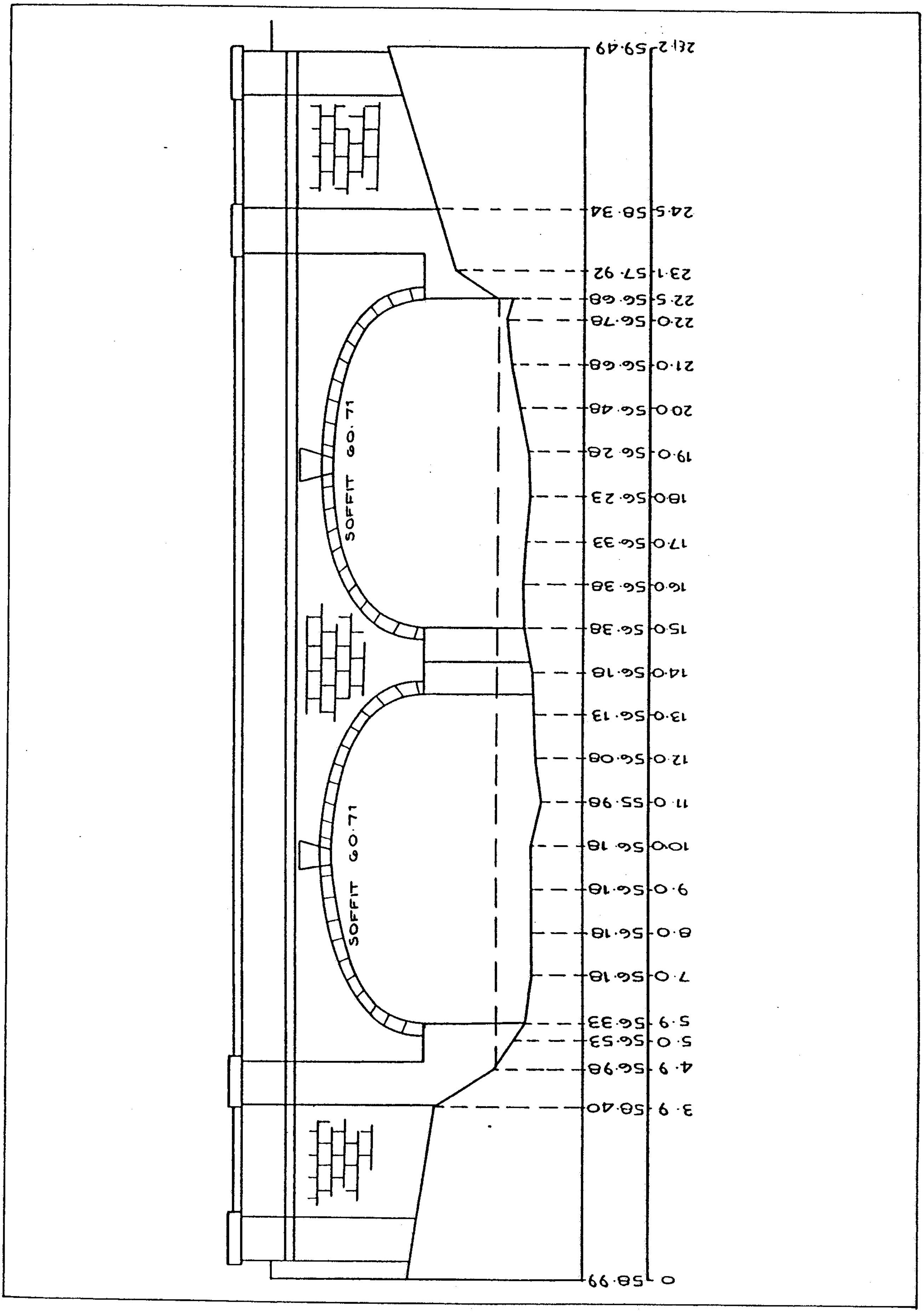


Fig 13 Bubbenhall bridge, River Avon, Severn Trent Water Authority

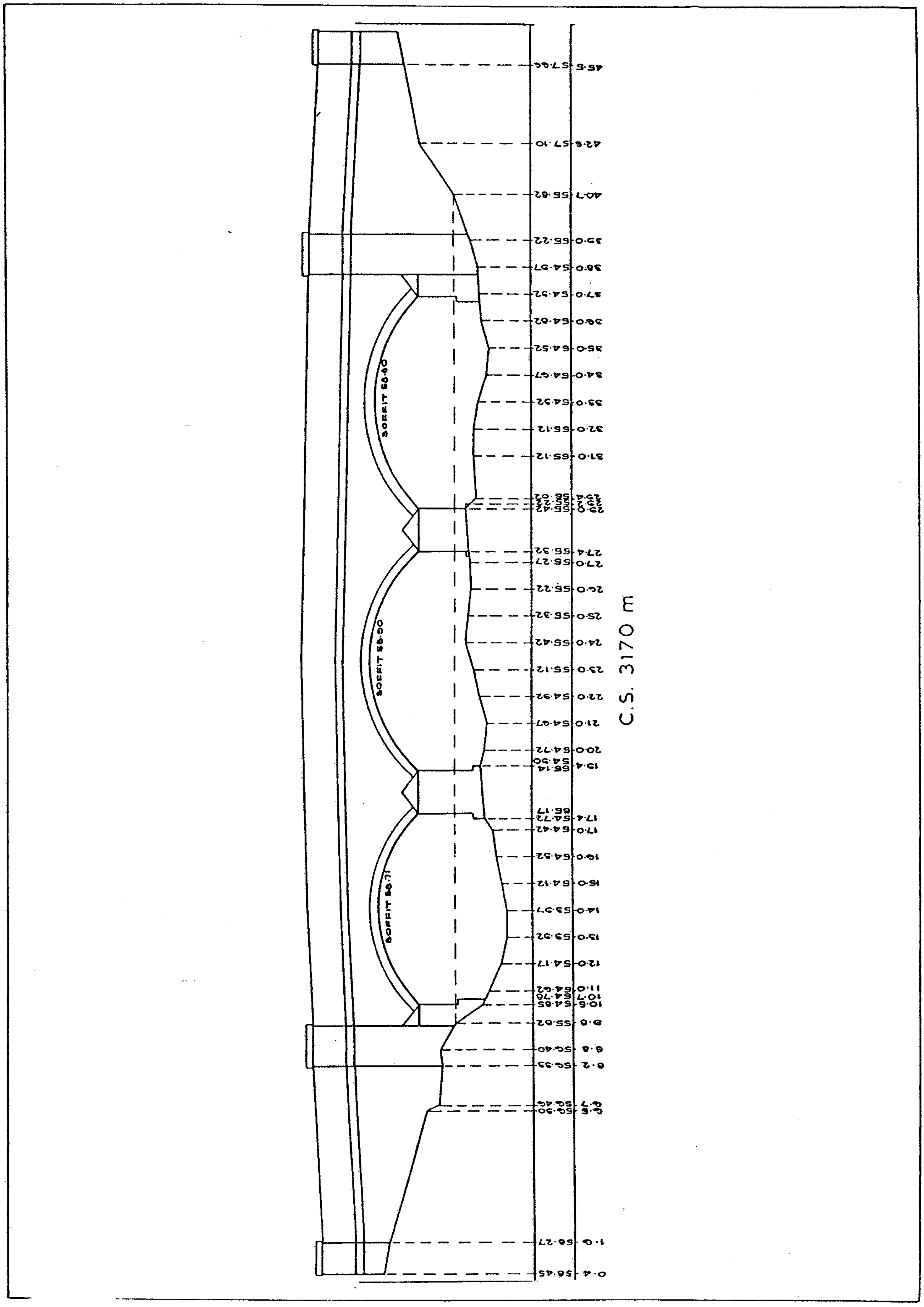


Fig 14 Cloud bridge, River Avon, Severn Trent Water Authority

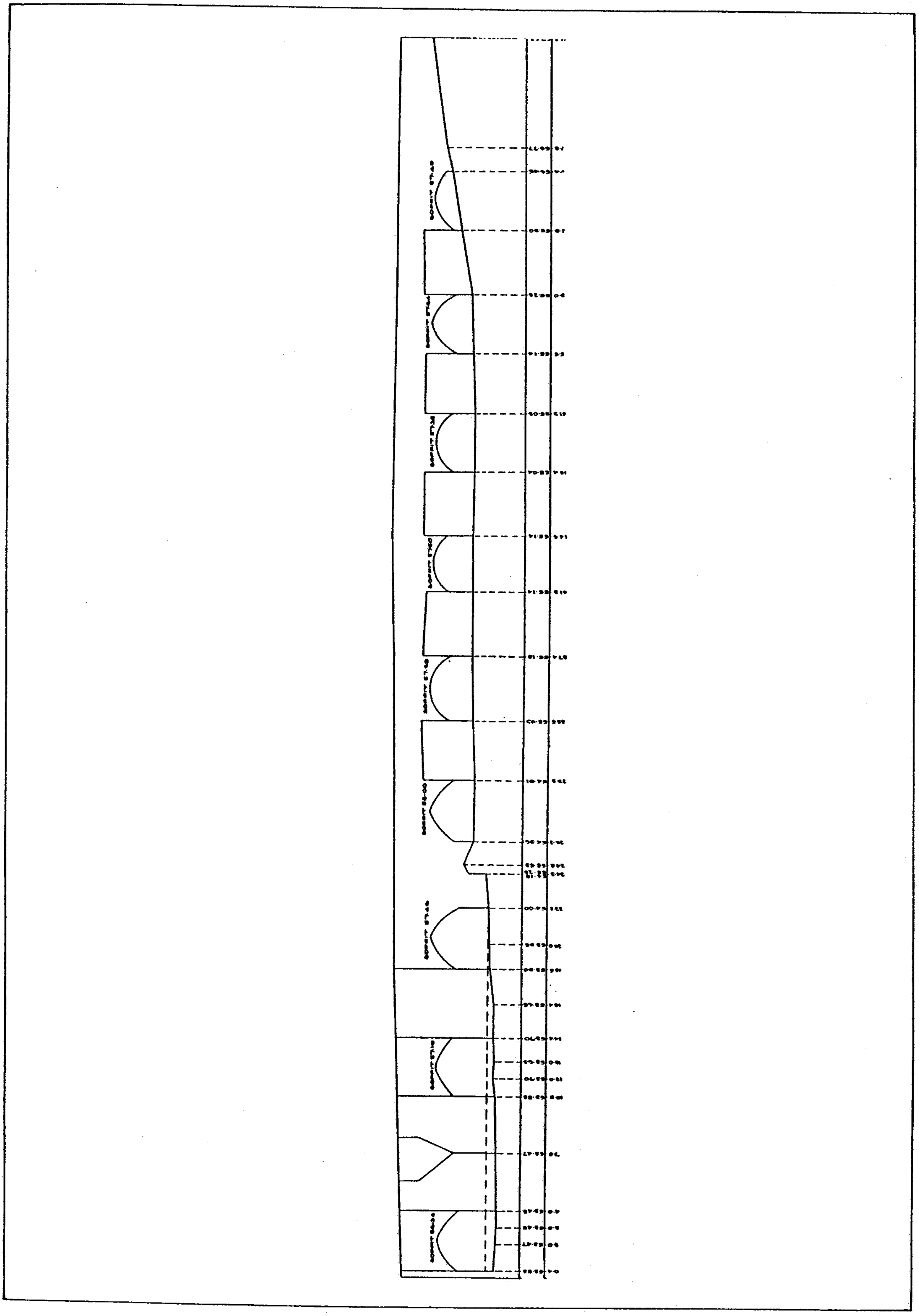


Fig 15 Stare bridge, River Avon, Severn Trent Water Authority

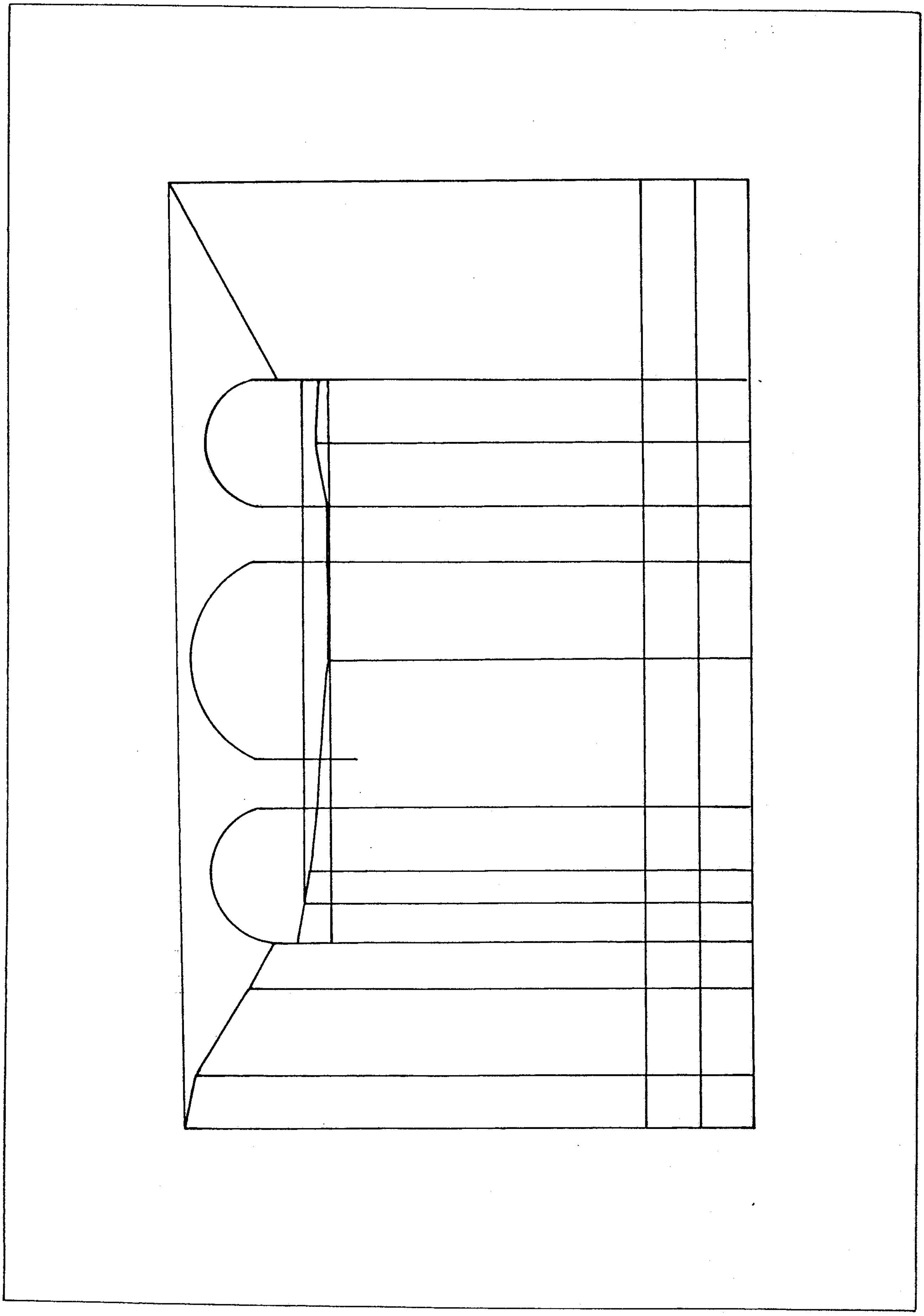


Fig 16 Stanton Gate bridge, River Erewash, Severn Trent Water Authority

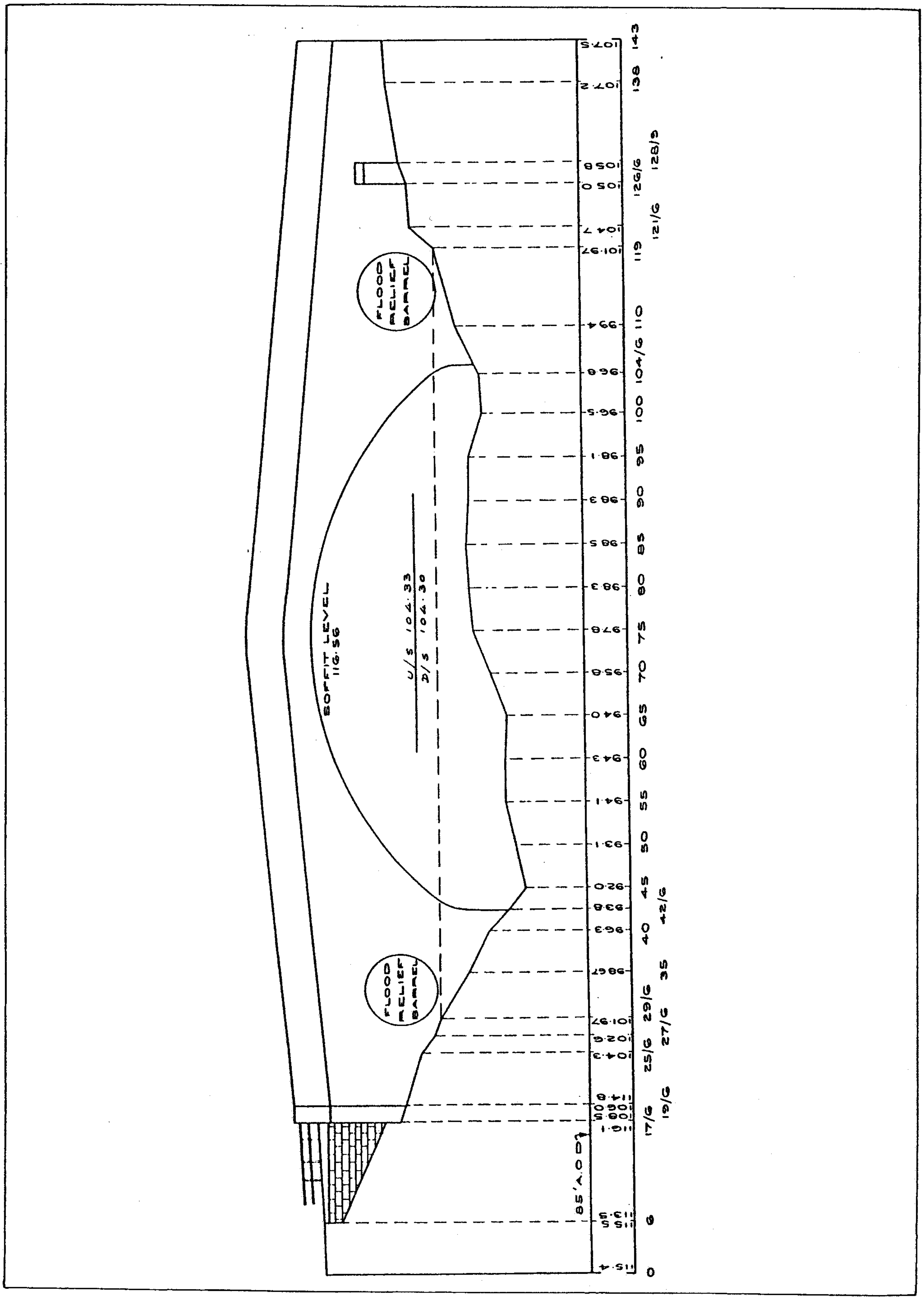


Fig 17 Wixford bridge; River Arrow, Severn Trent Water Authority

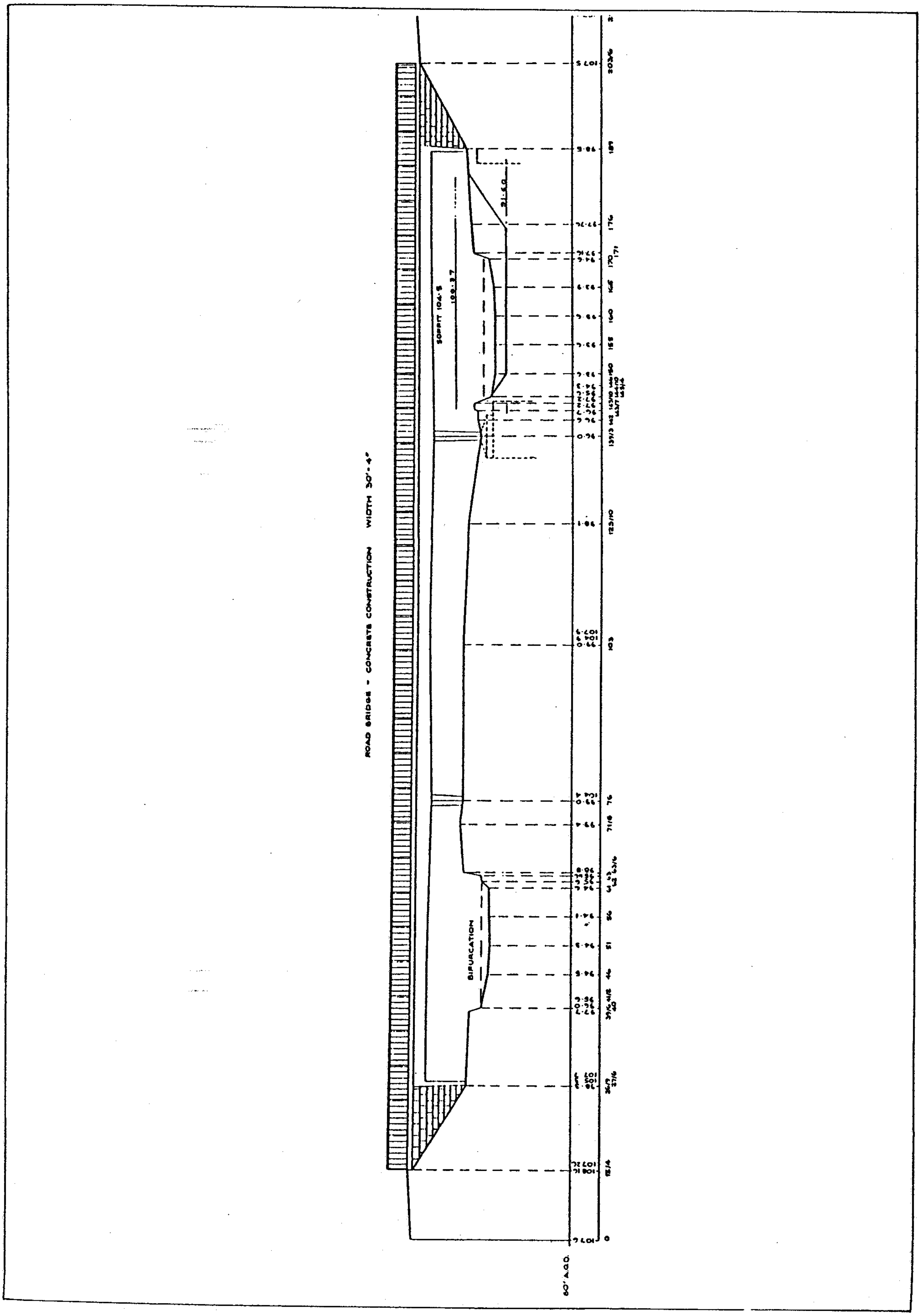


Fig 18 Broom bridge, River Arrow, Severn Trent Water Authority

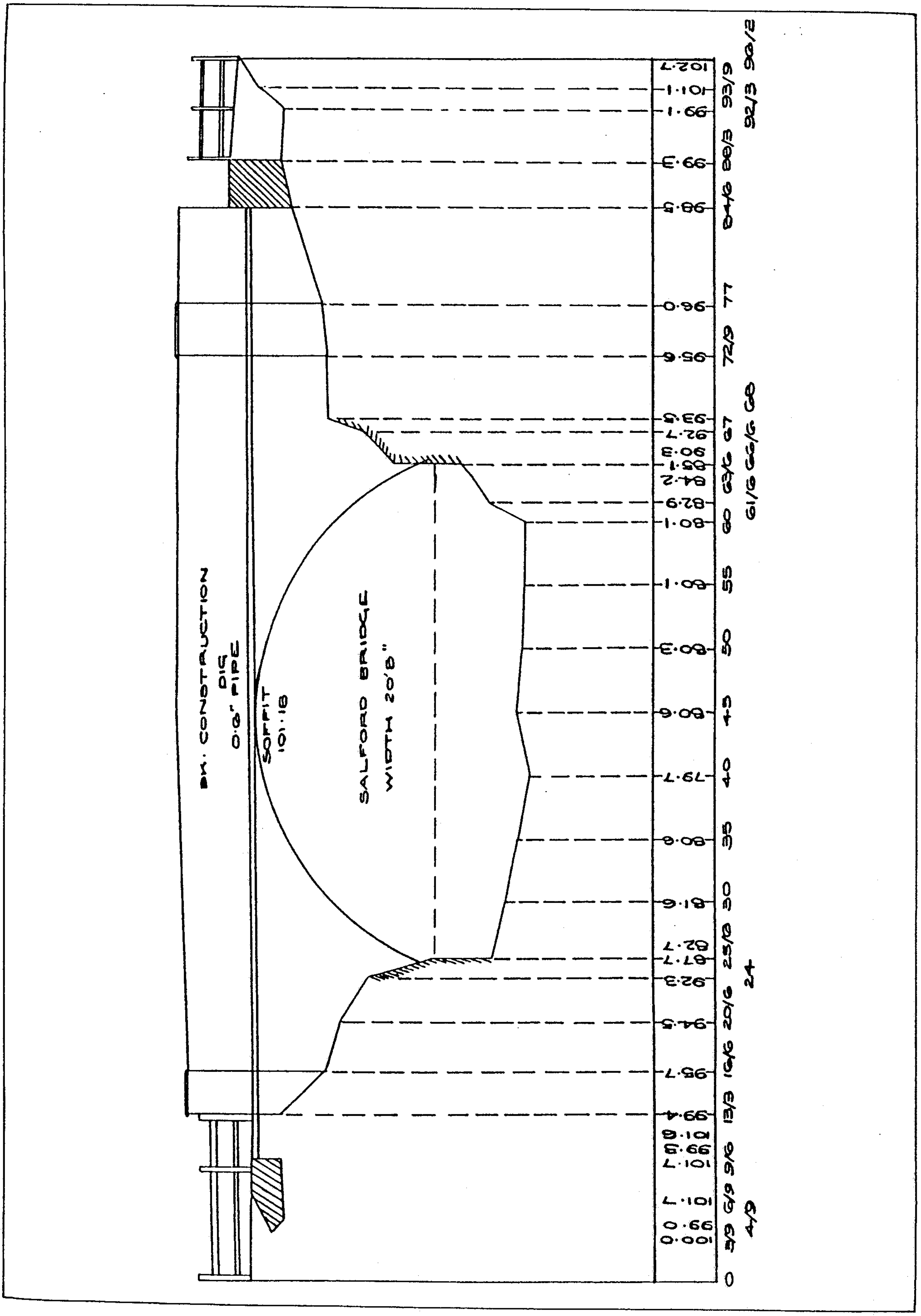


Fig 19 Salford bridge, River Arrow, Severn Trent Water Authority

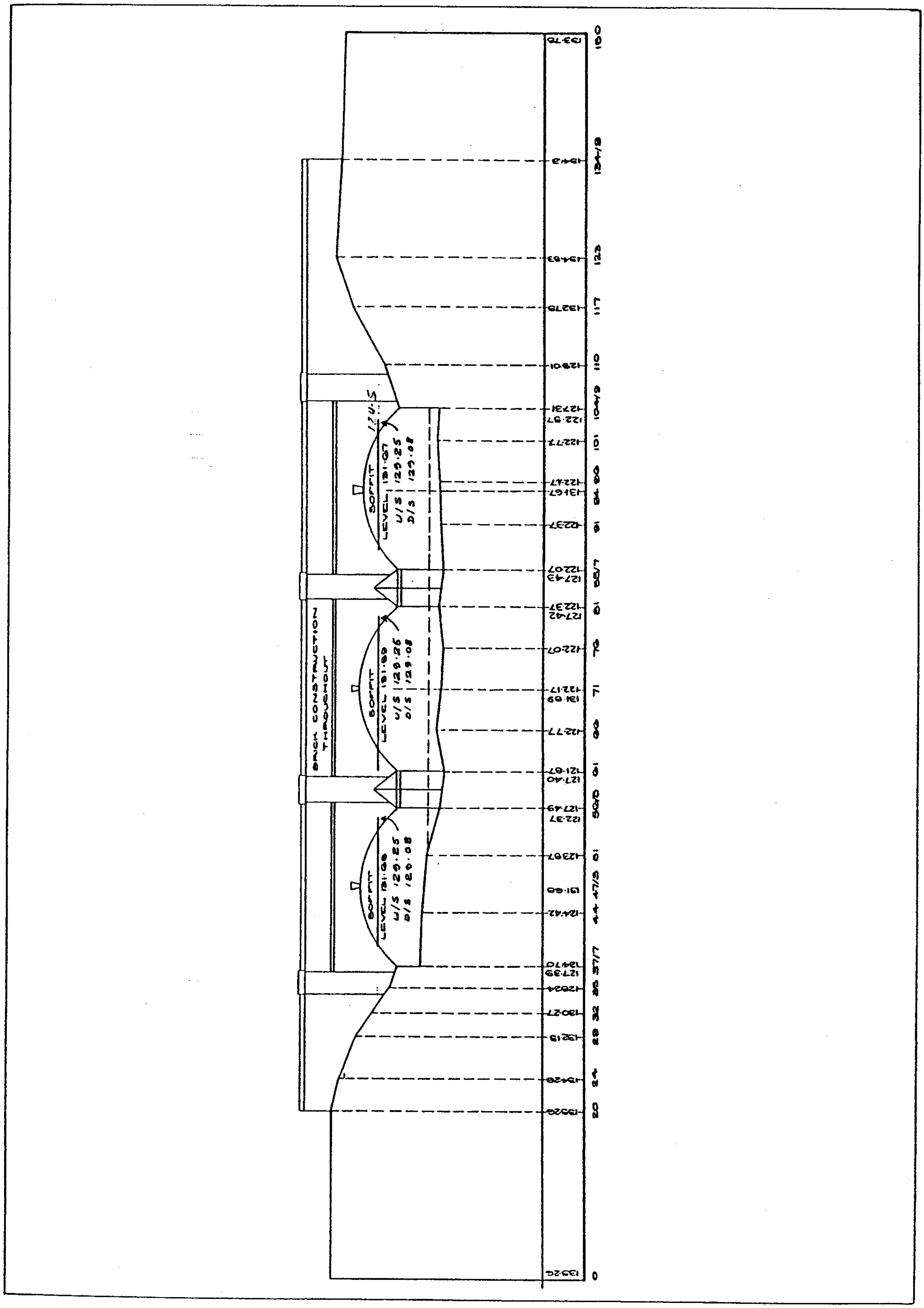


Fig 20 Gunnings bridge, River Arrow, Severn Trent Water Authority

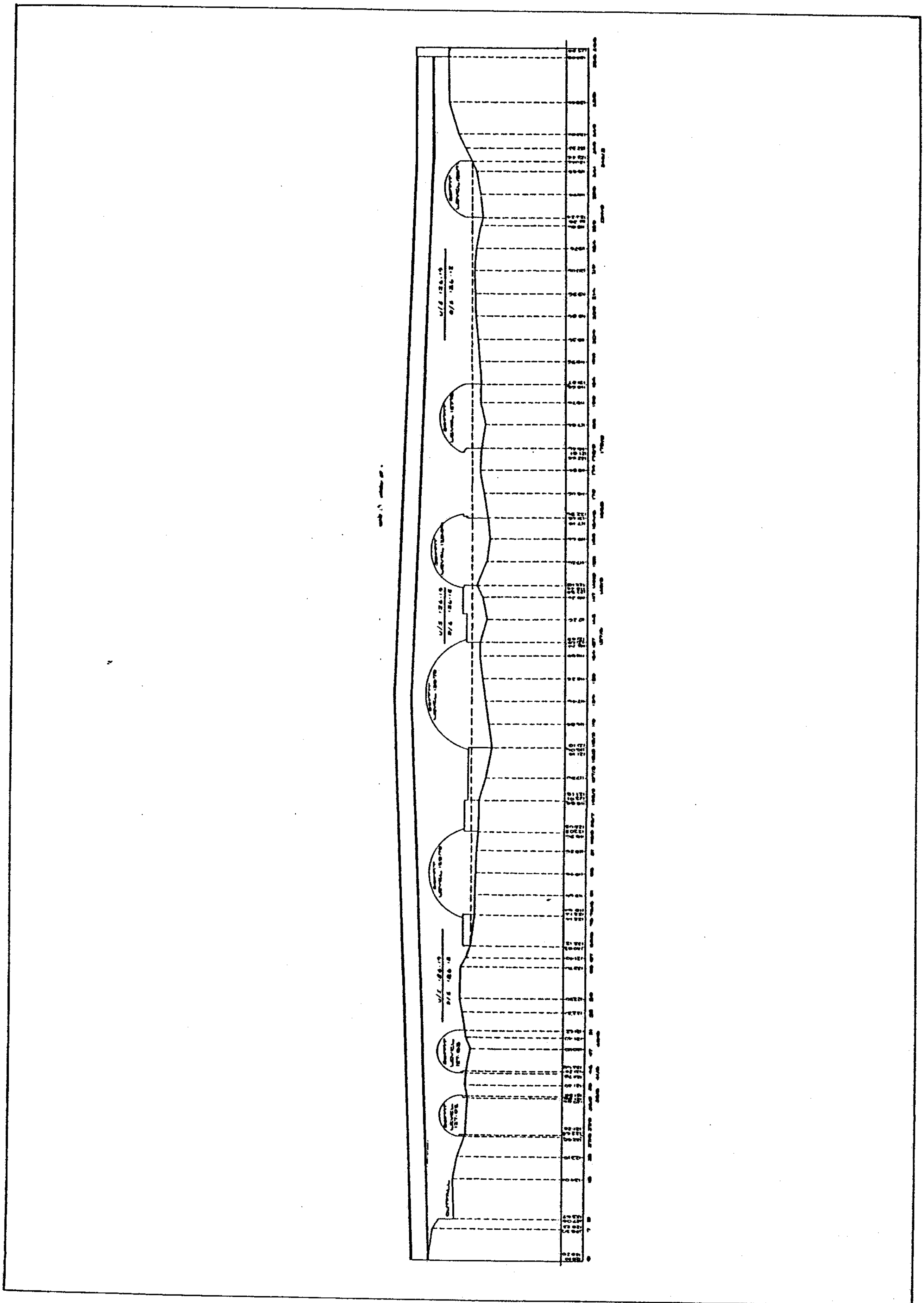


Fig 21 Oversley bridge, River Arrow, Severn Trent Water Authority

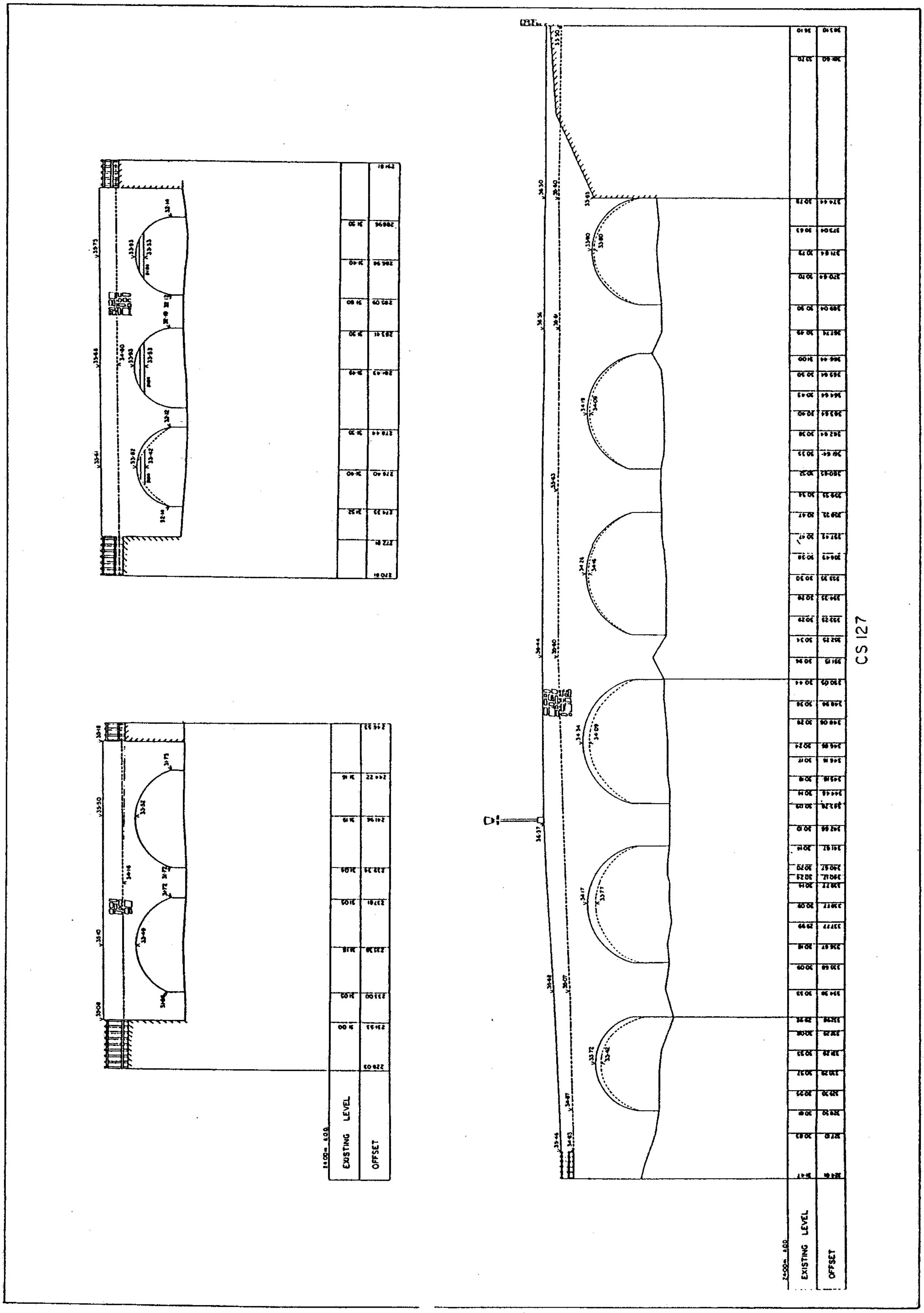


Fig 22 Blandford bridge, River Stour, Wessex Water Authority

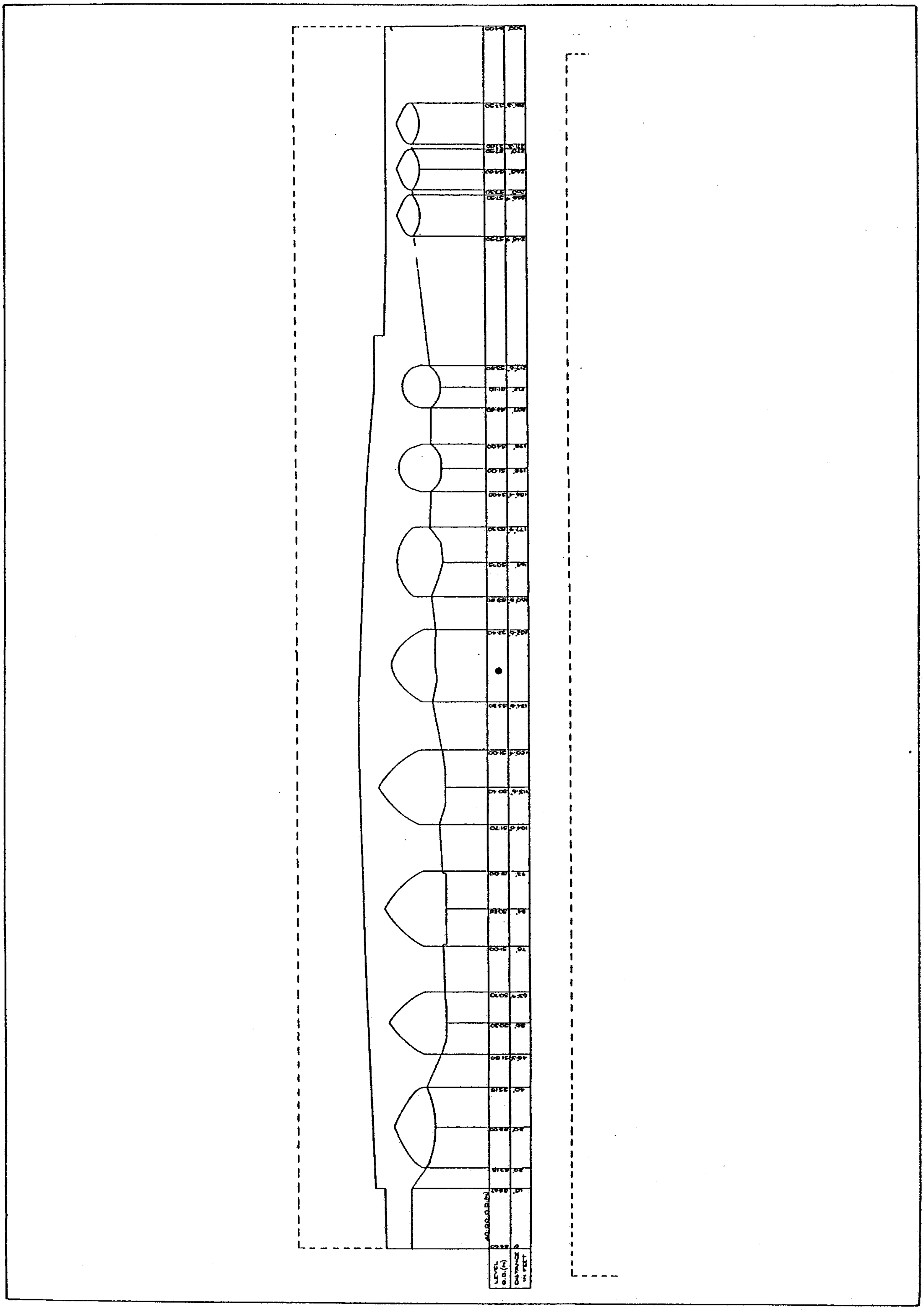


Fig 23 Julians bridge, River Stour, Wessex Water Authority

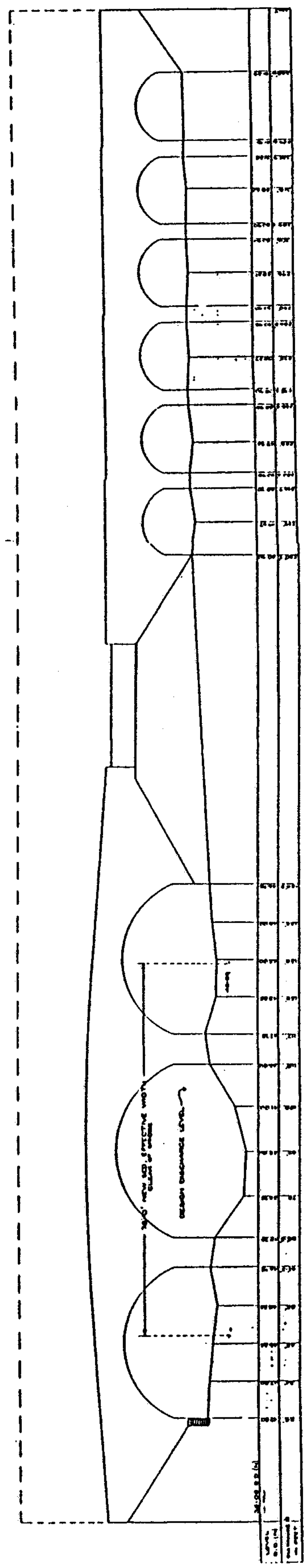


Fig 24 Canford bridge, River Stour, Wessex Water Authority

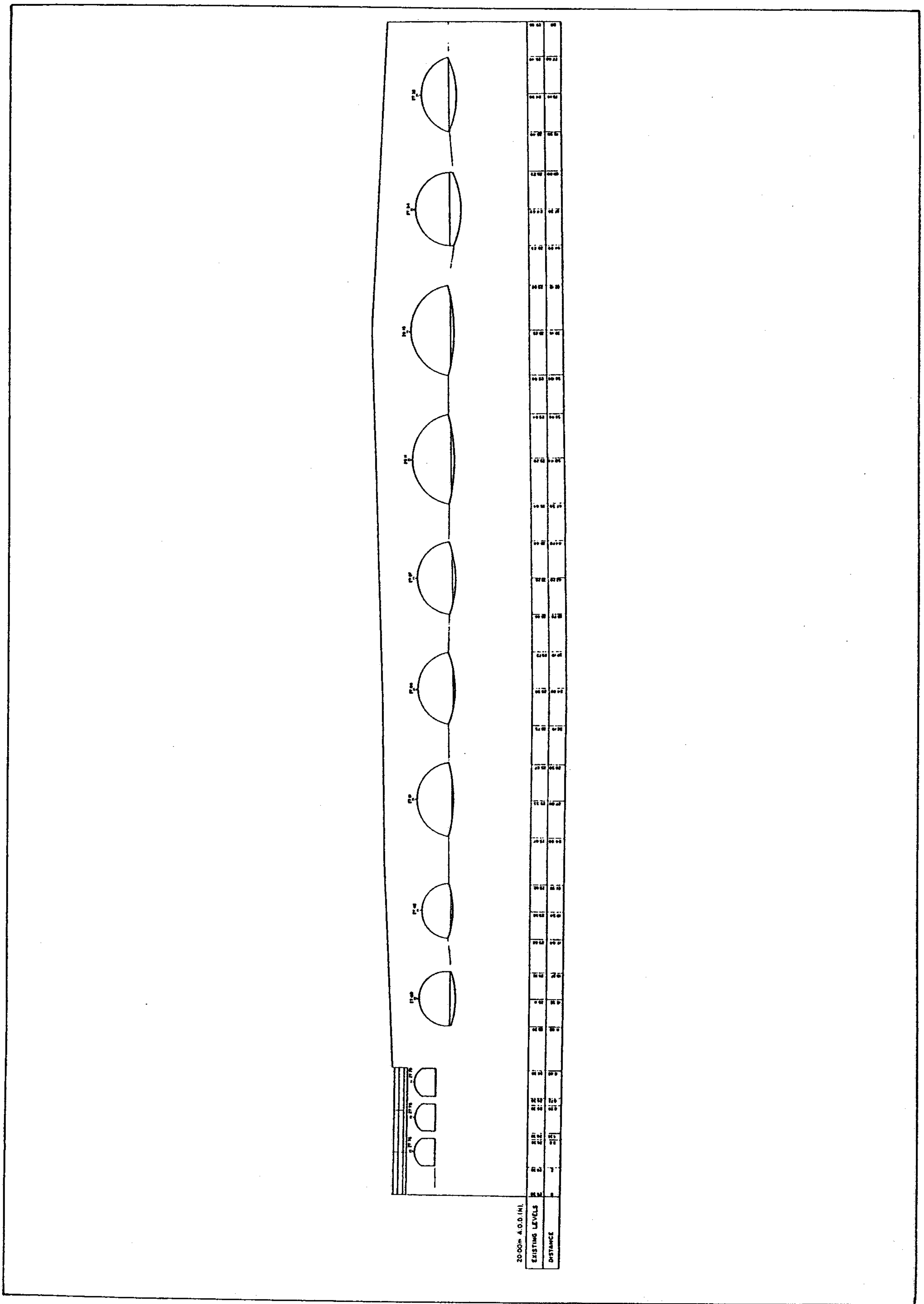


Fig 25 Crawford bridge, River Stour, Wessex Water Authority

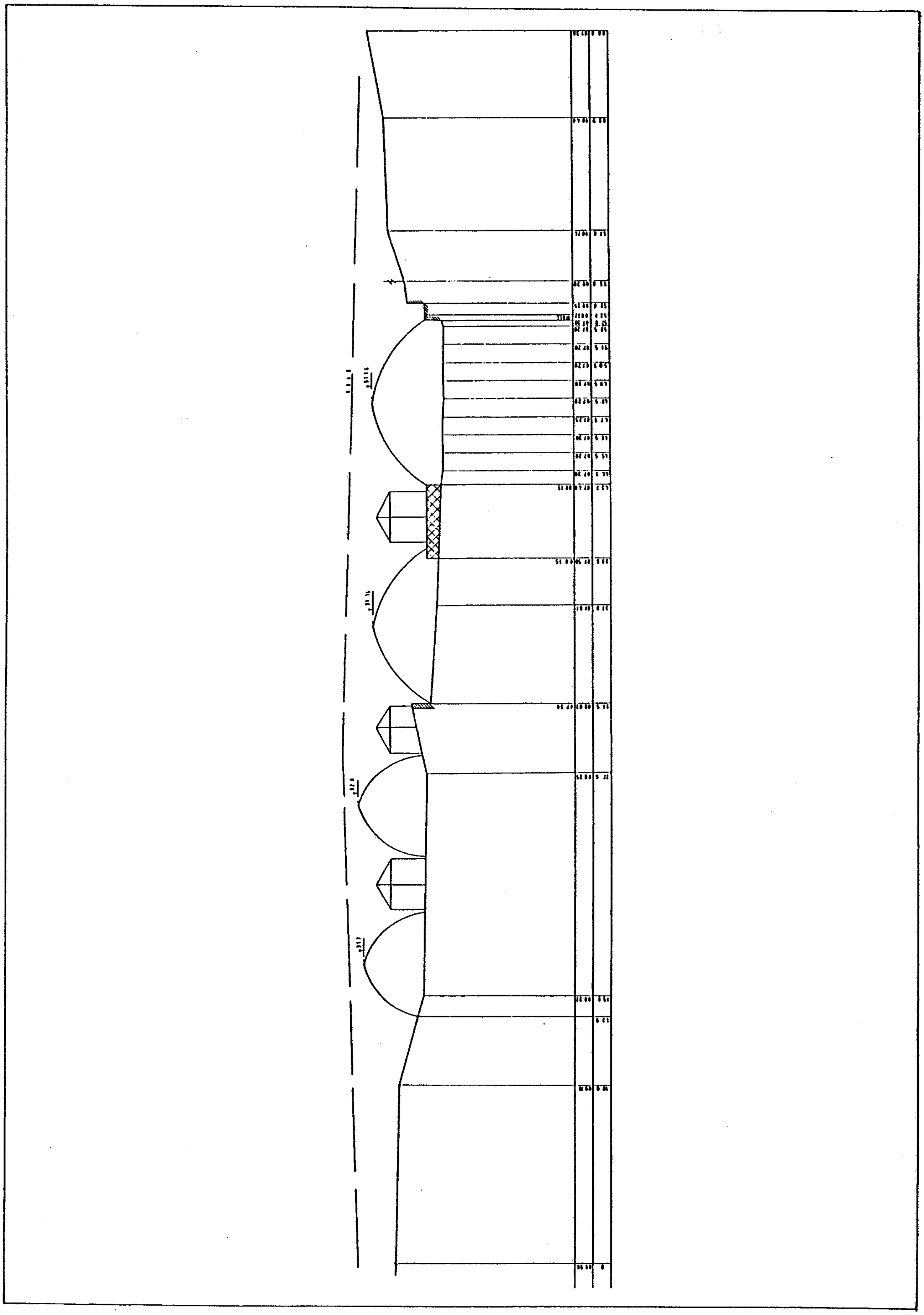


Fig 26 Kildwick bridge, River Aire, Yorkshire Water Authority

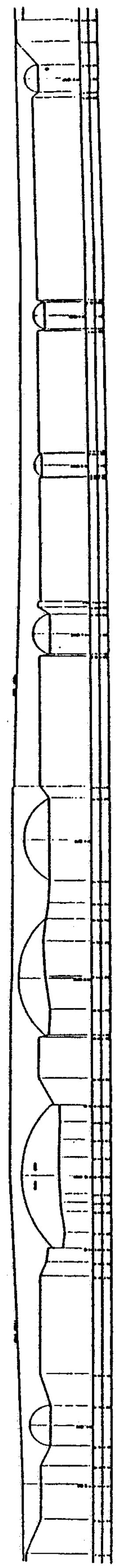


Fig 27 Inghey bridge, River Aire, Yorkshire Water Authority

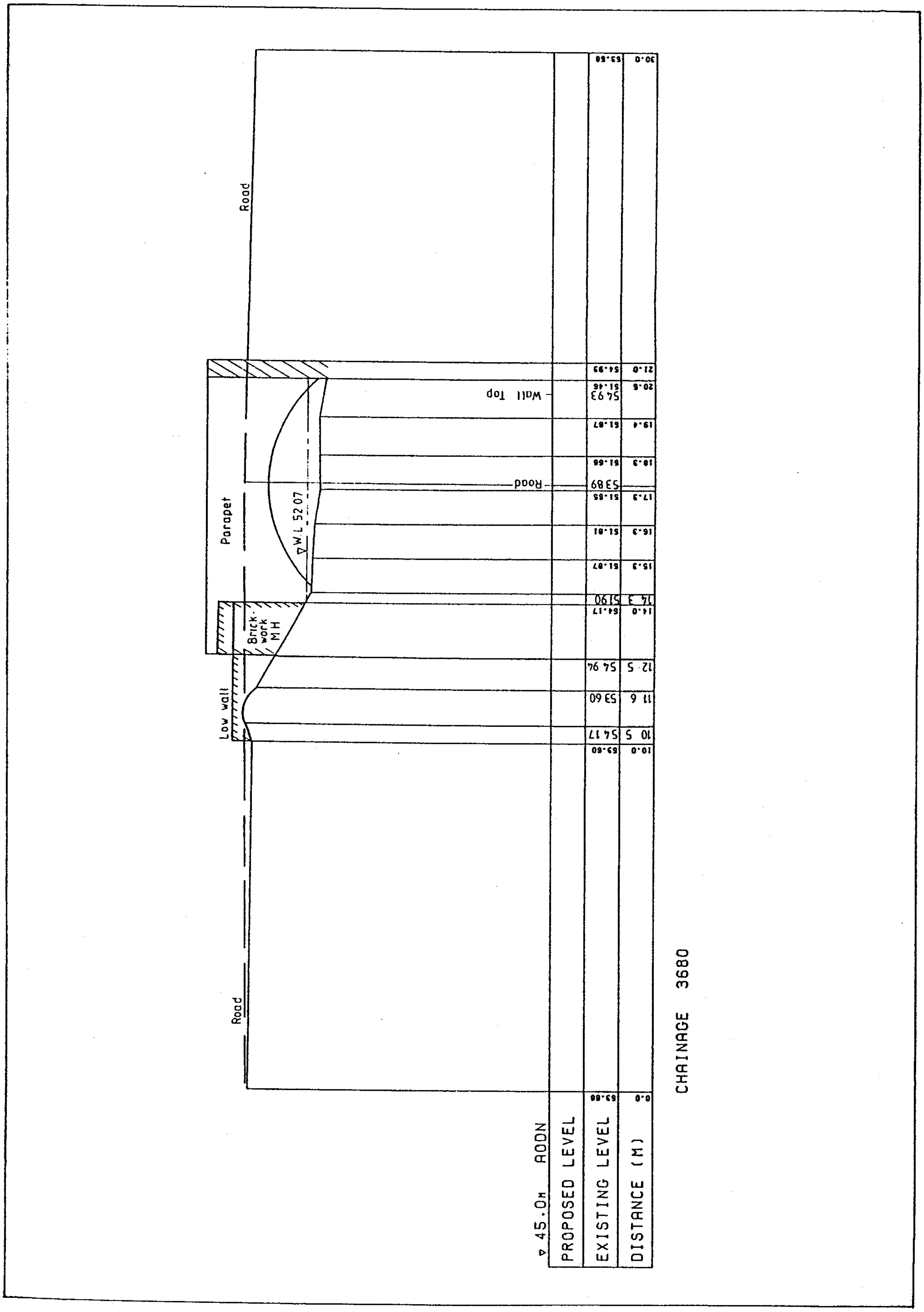


Fig 28 Station Road bridge; River Spen, Yorkshire Water Authority

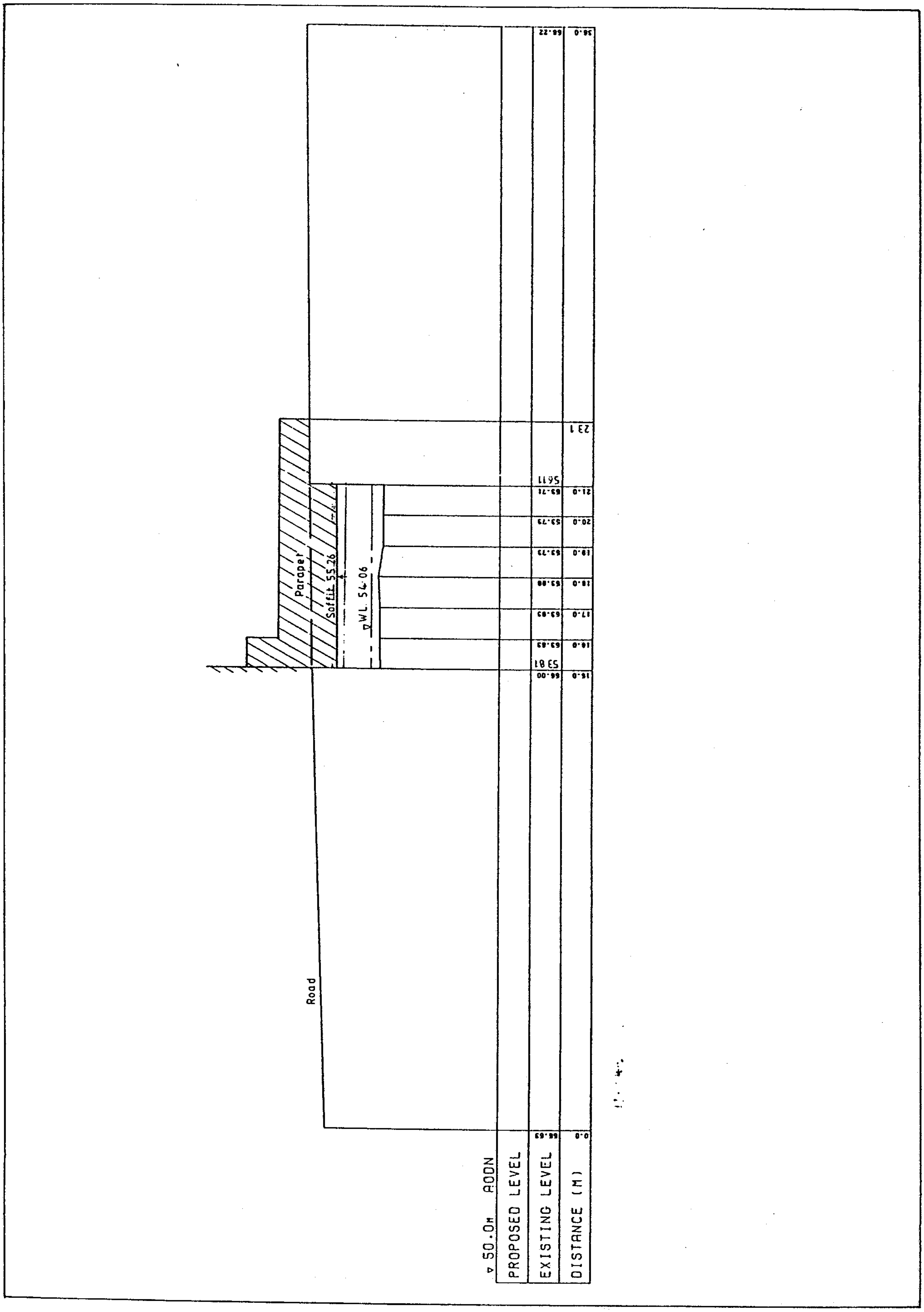


Fig 29 Union Street bridge, River Spen, Yorkshire Water Authority

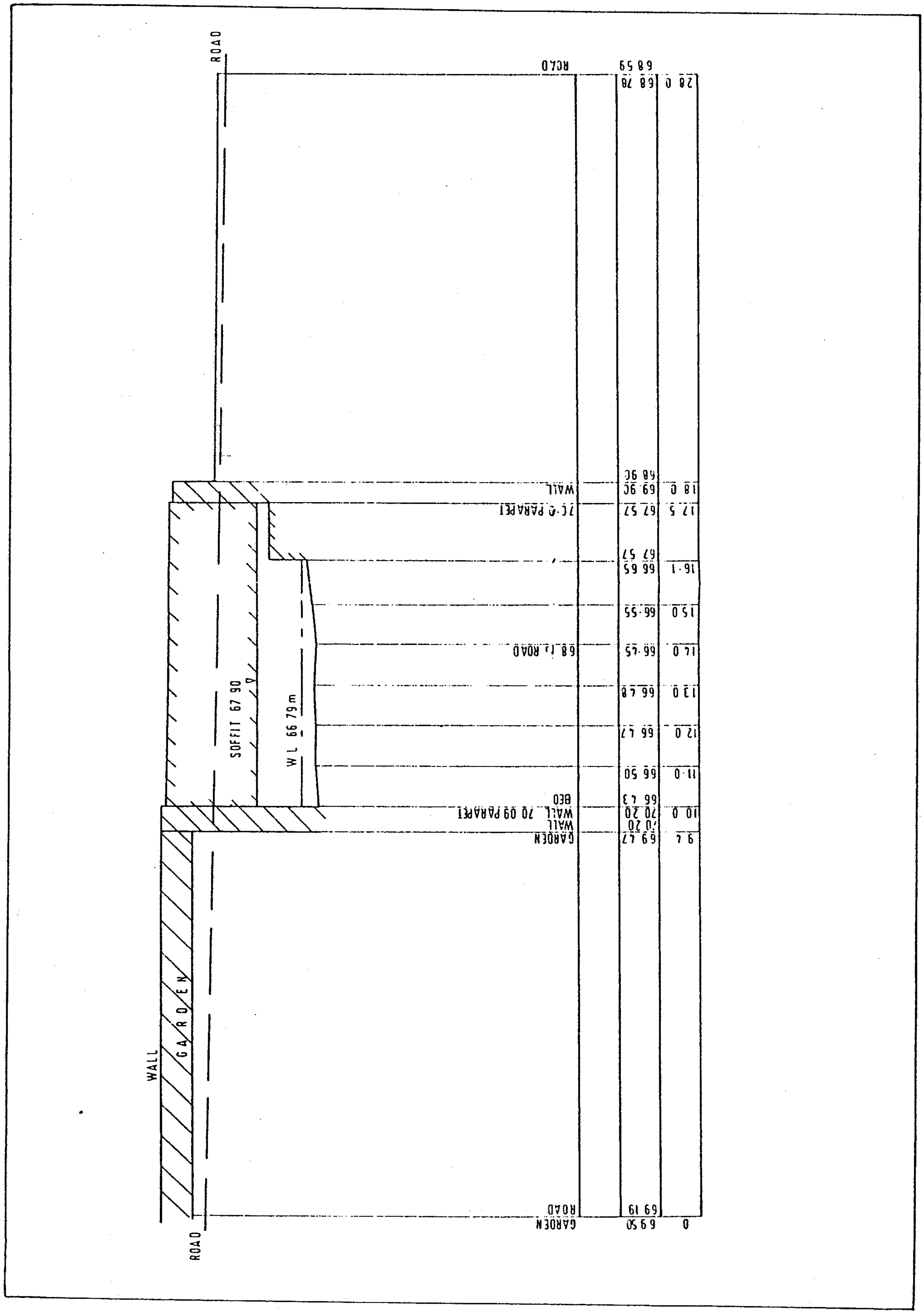


Fig 30 Rawfolds bridge, River Spen, Yorkshire Water Authority

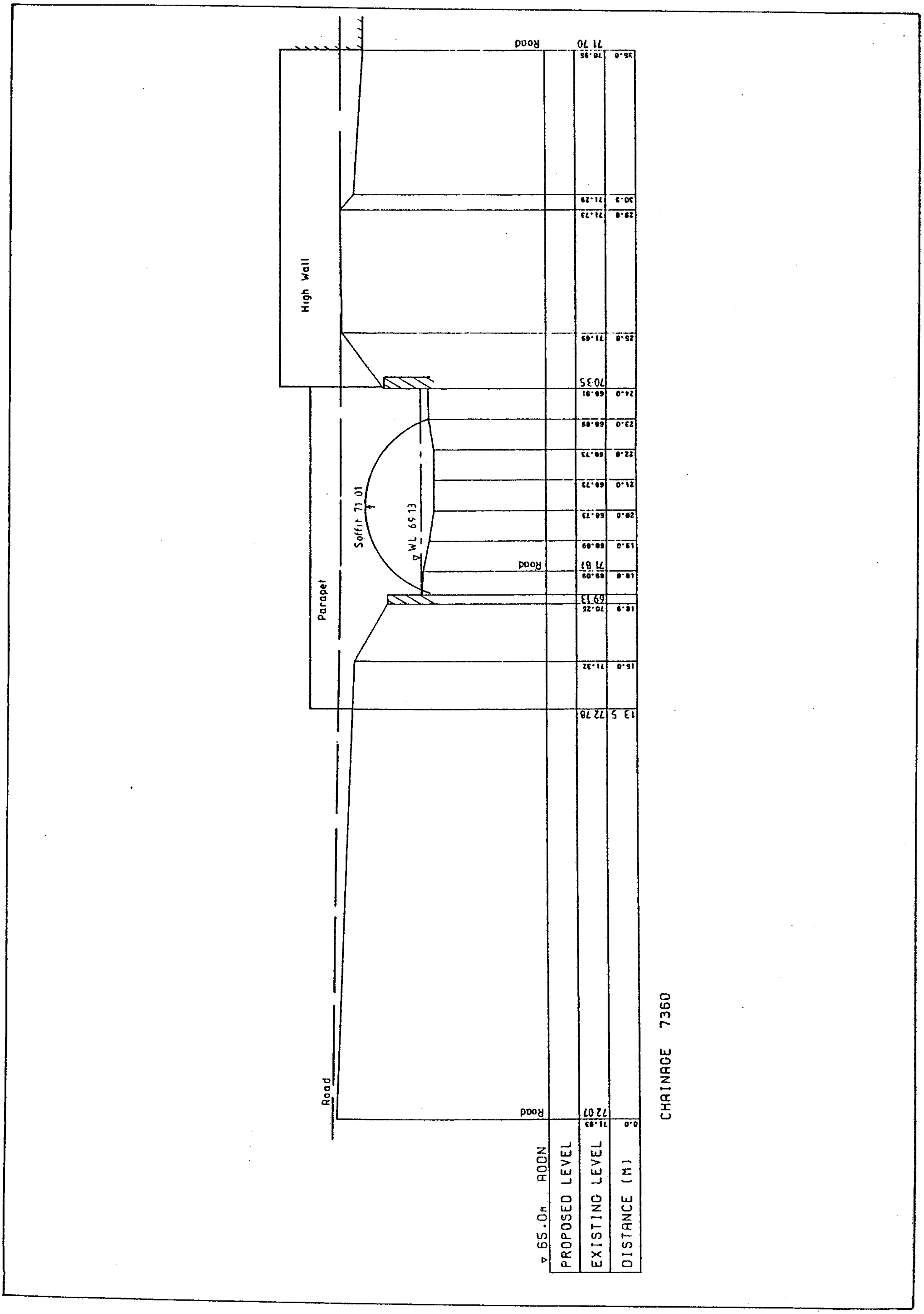


Fig 31 St Pegs bridge, River Spen, Yorkshire Water Authority

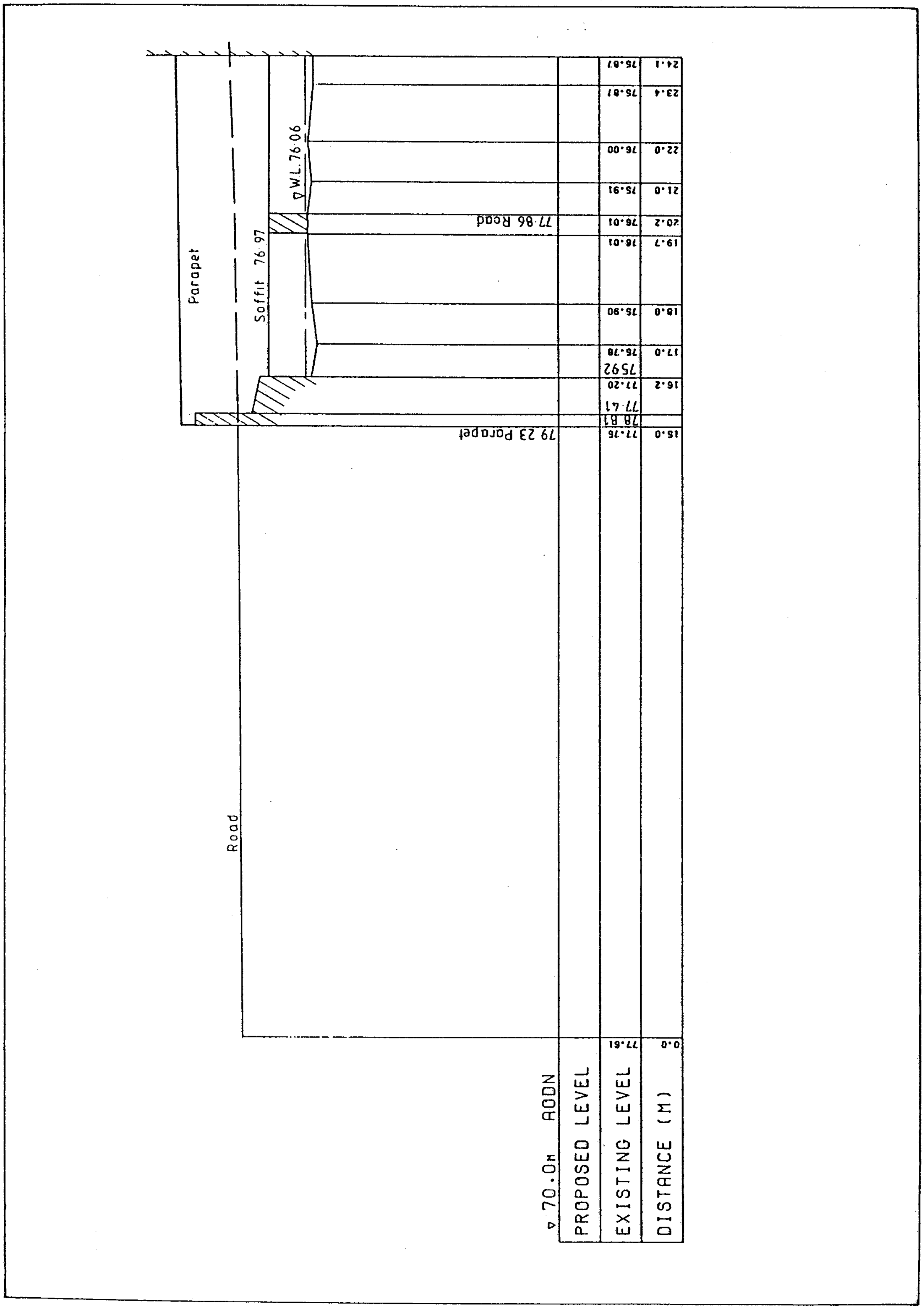


Fig 32 Balme Road bridge, River Spen, Yorkshire Water Authority

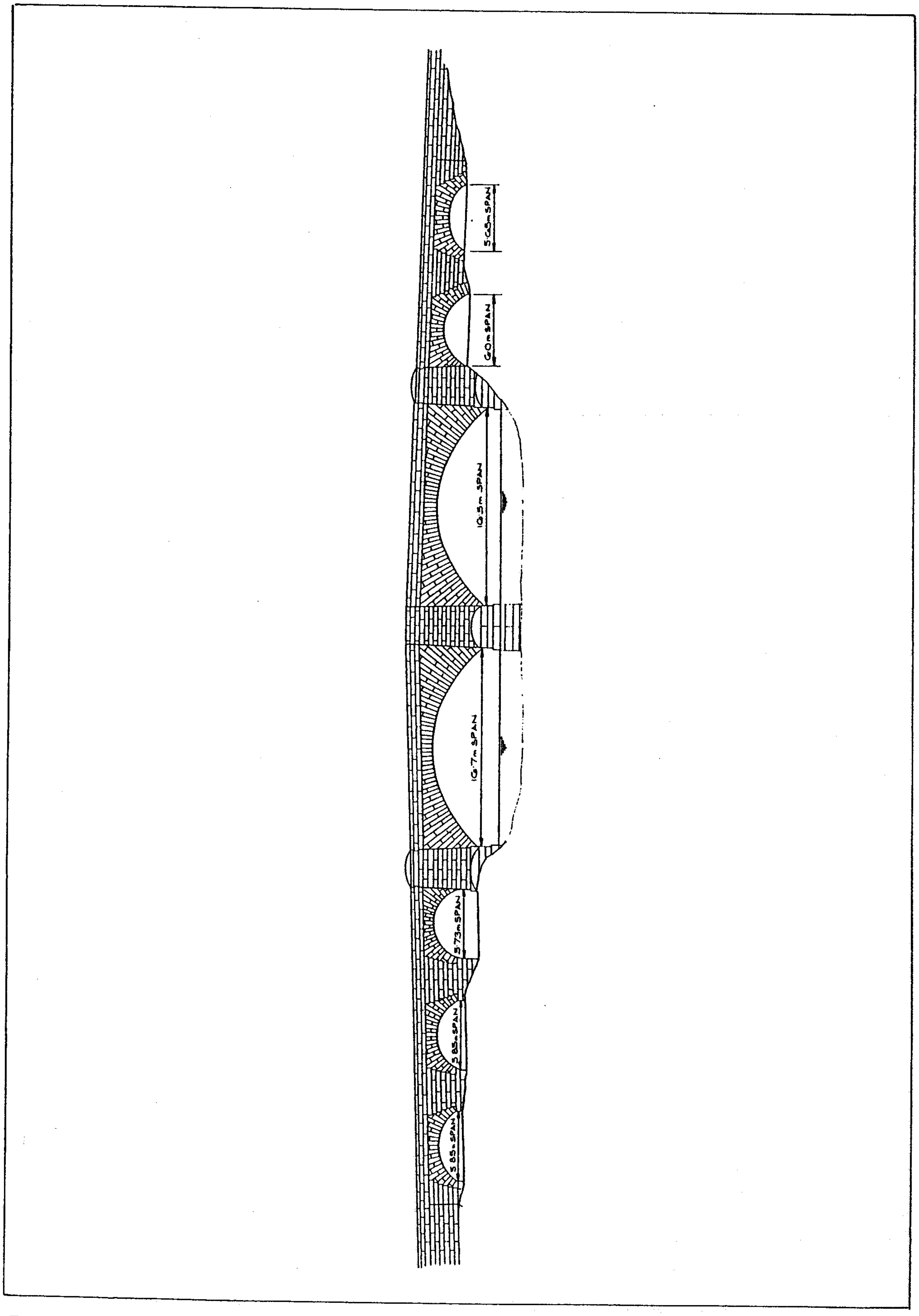


Fig 33 Pool bridge, River Wharfe, Yorkshire Water Authority

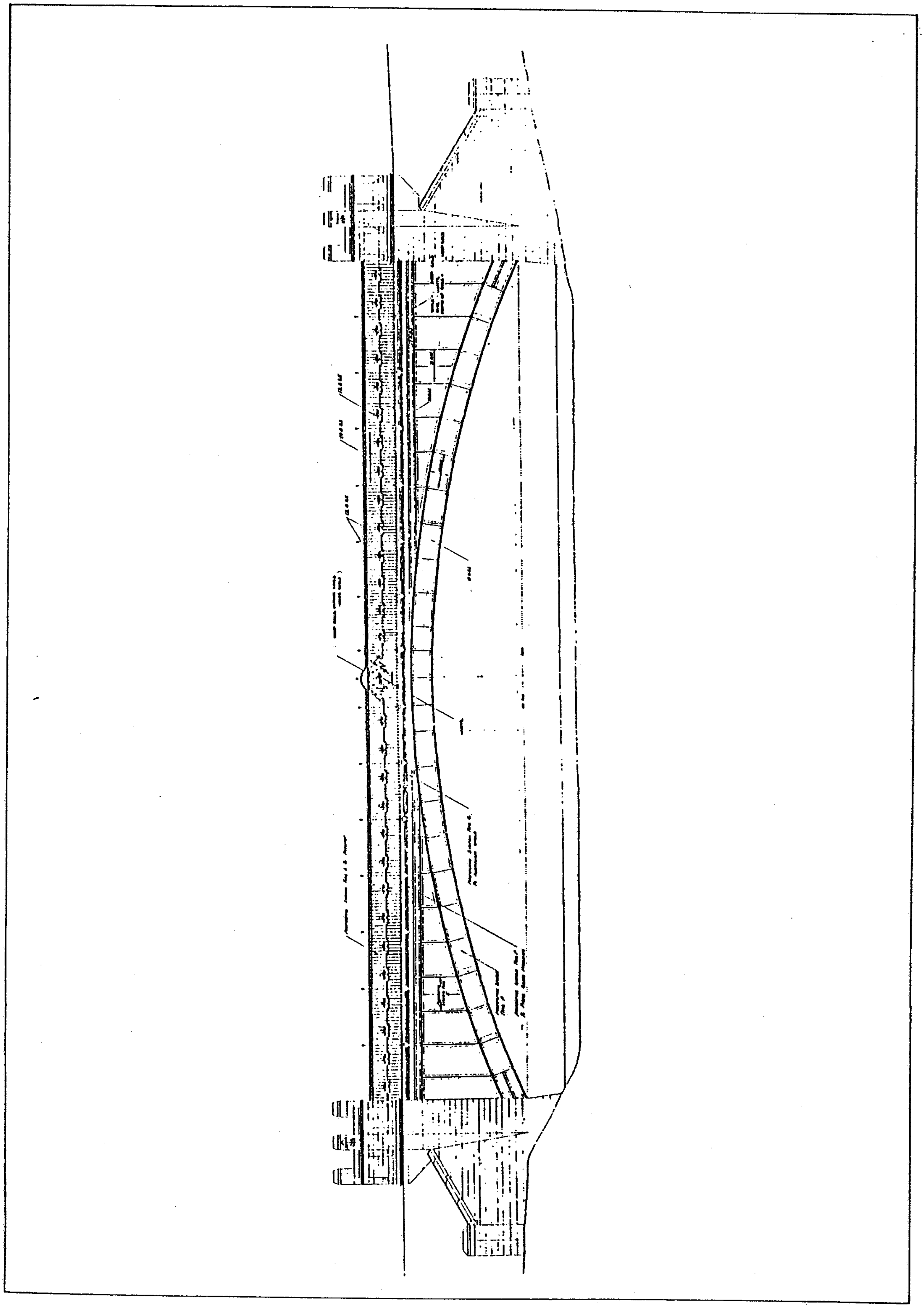


Fig 34 Ilkley bridge, River Wharfe, Yorkshire Water Authority

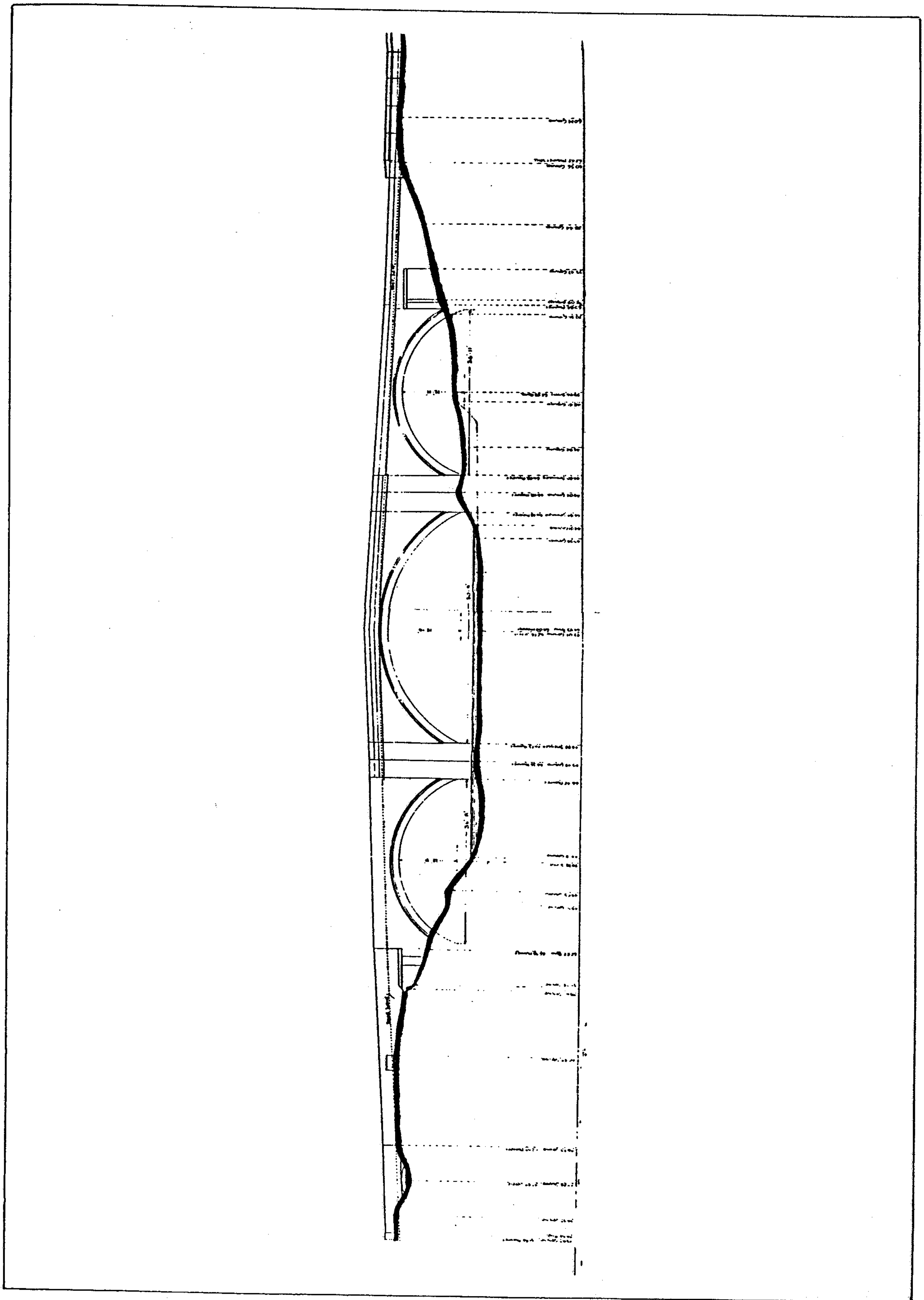


Fig 35 Cattal bridge, River Nidd, Yorkshire Water Authority

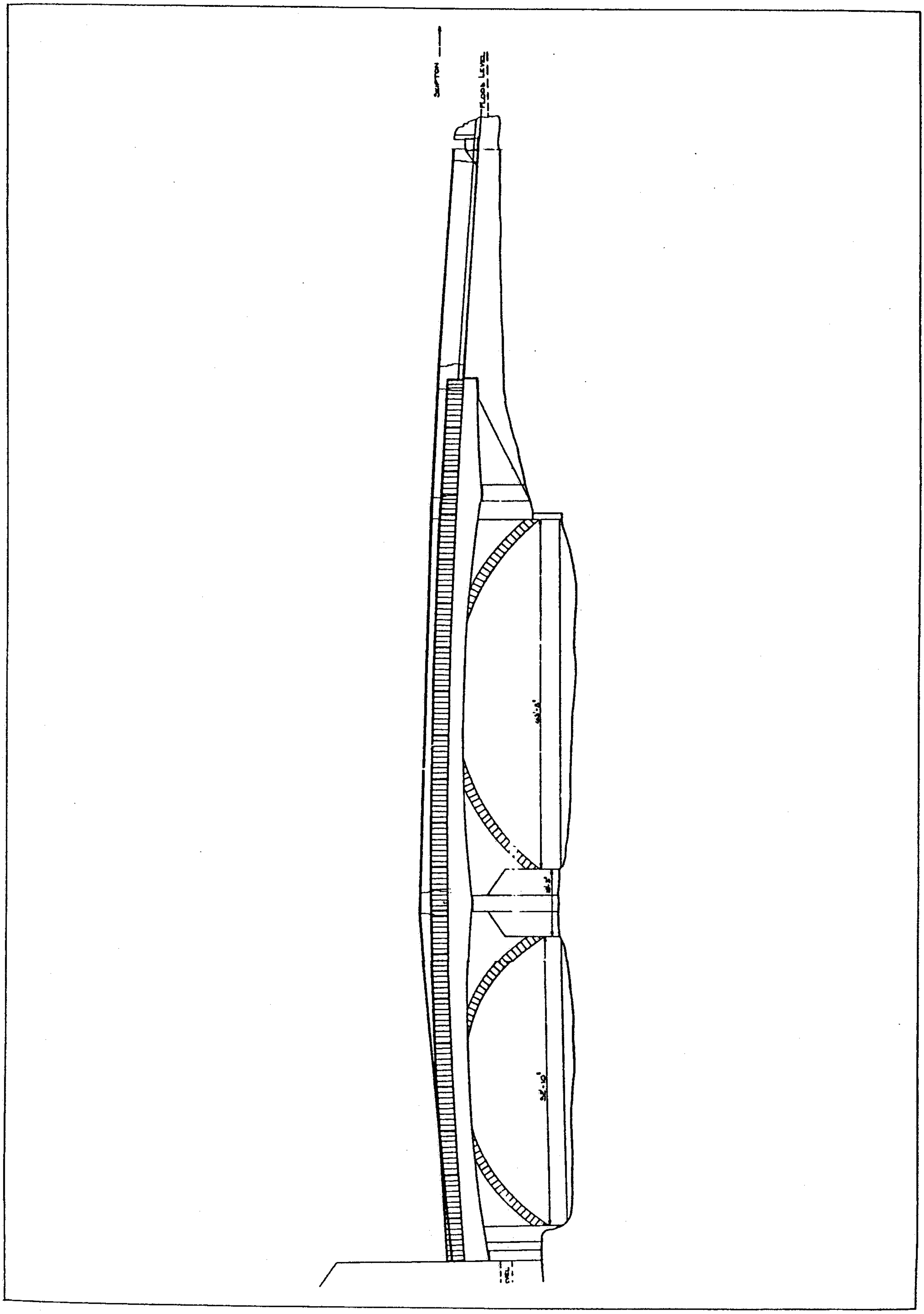


Fig 36 Bolton bridge, River Wharfe, Yorkshire Water Authority

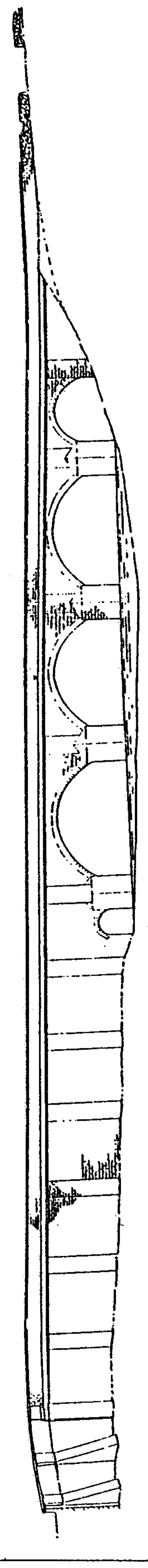


Fig 37 Grassington bridge, River Wharfe, Yorkshire Water Authority

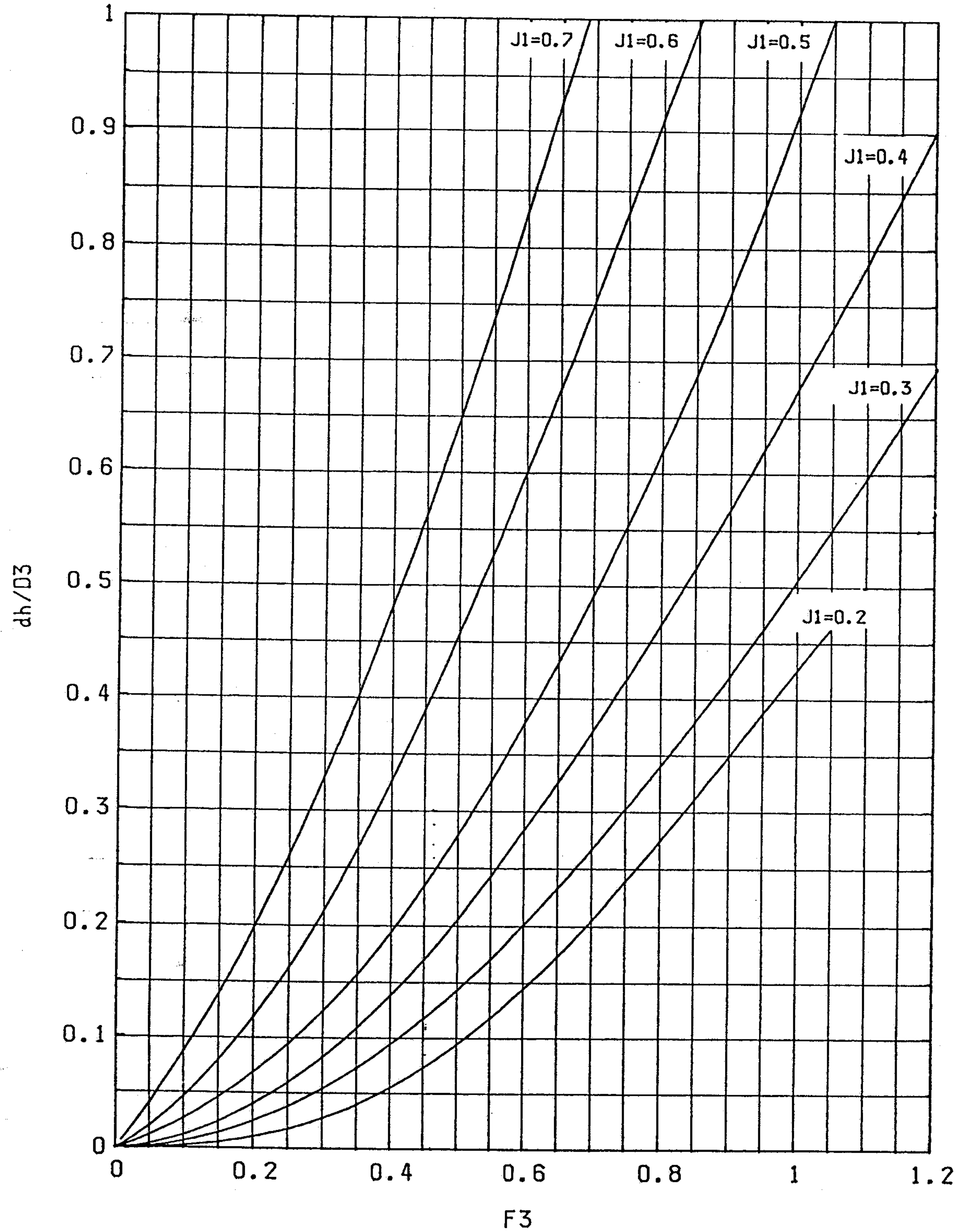


FIG 38   PLOT OF dh/D3 VRS F3 AND J1 FOR ALL SINGLE ARCHES

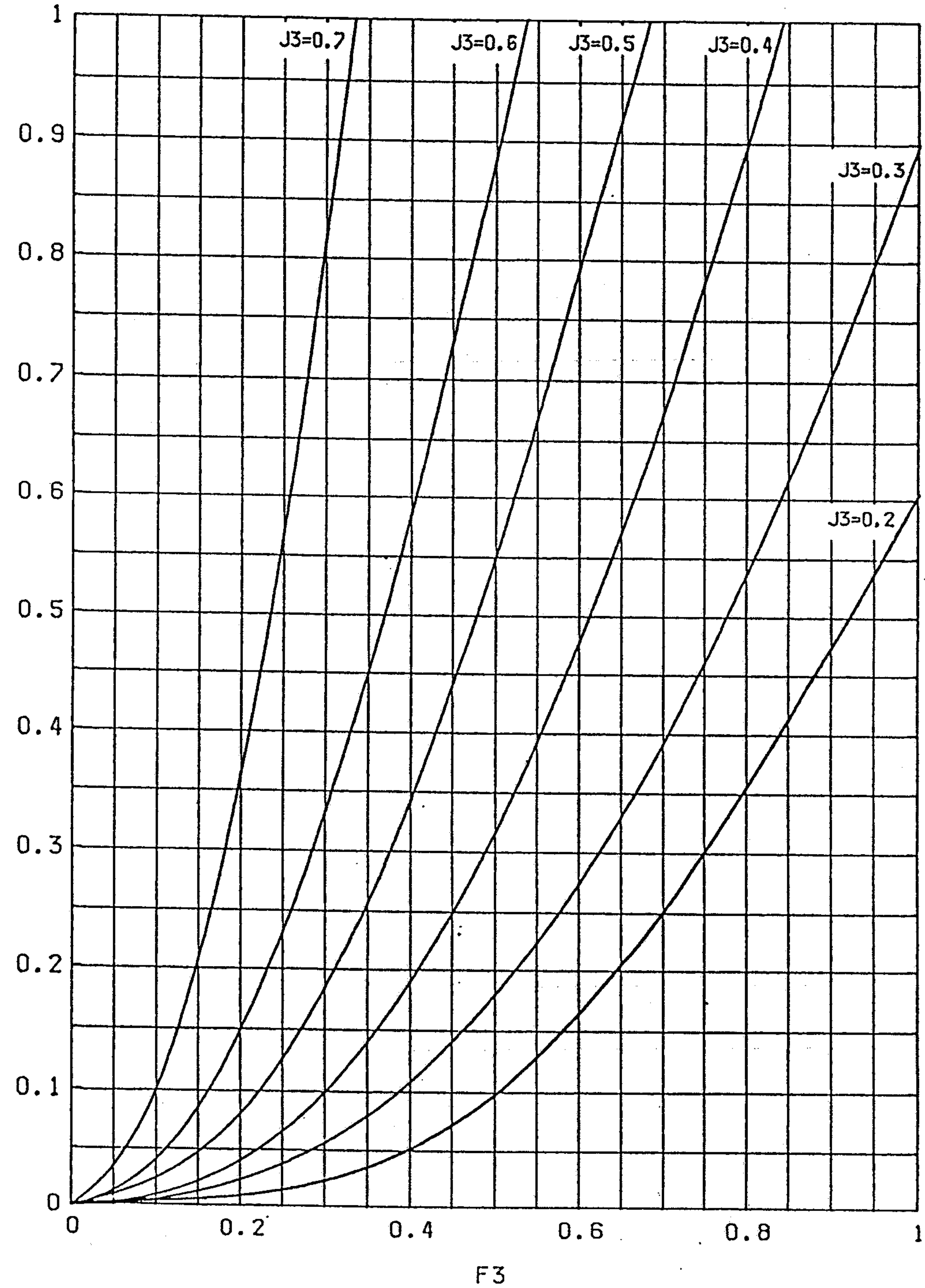


FIG 39 PLOT OF dh/D3 VRS F3 AND J3 FOR ALL BRIDGES

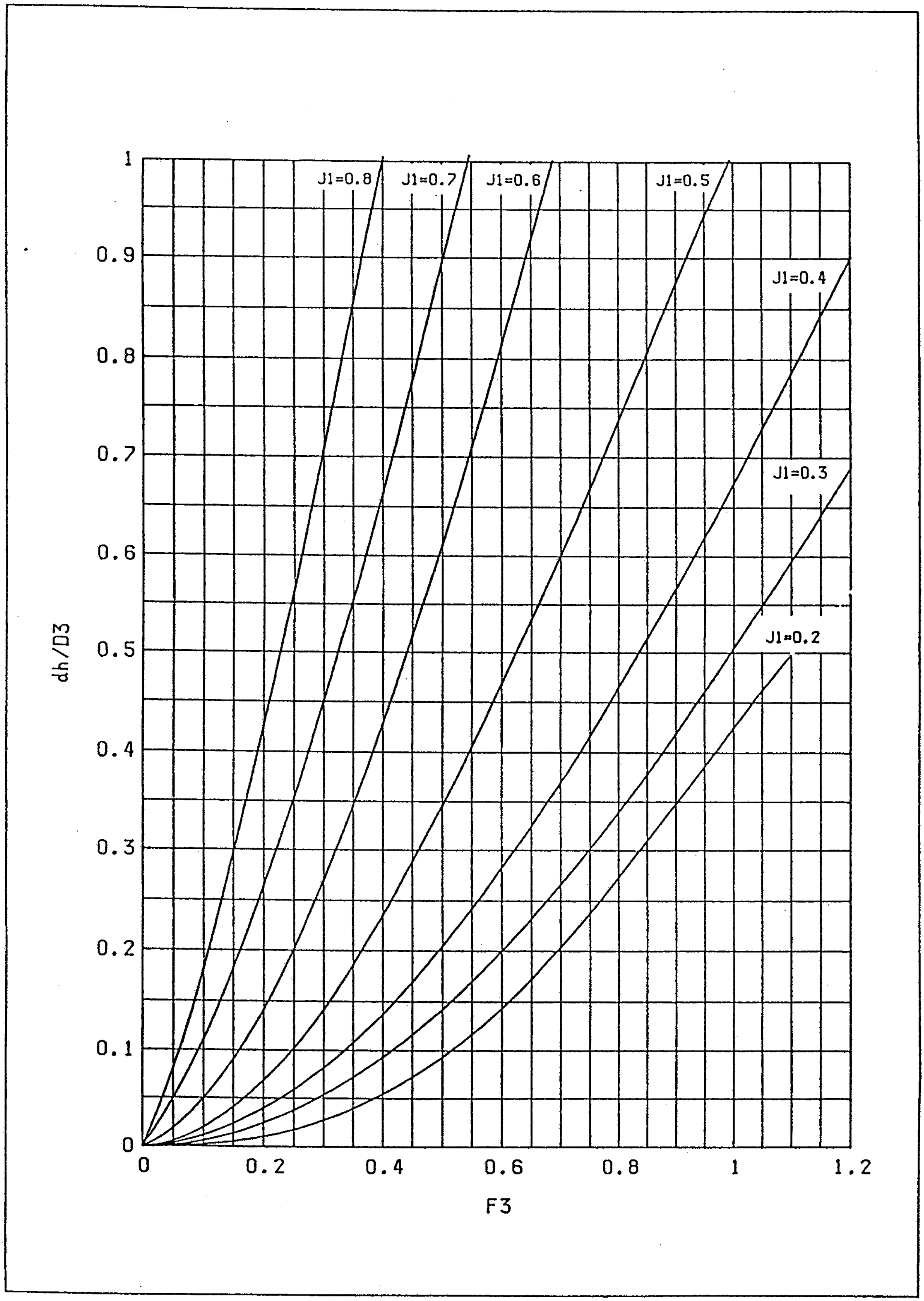


FIG 40 PLOT OF dh/D3 VRS F3 AND J1 FOR MULTIPLE ARCHES

PLATES.

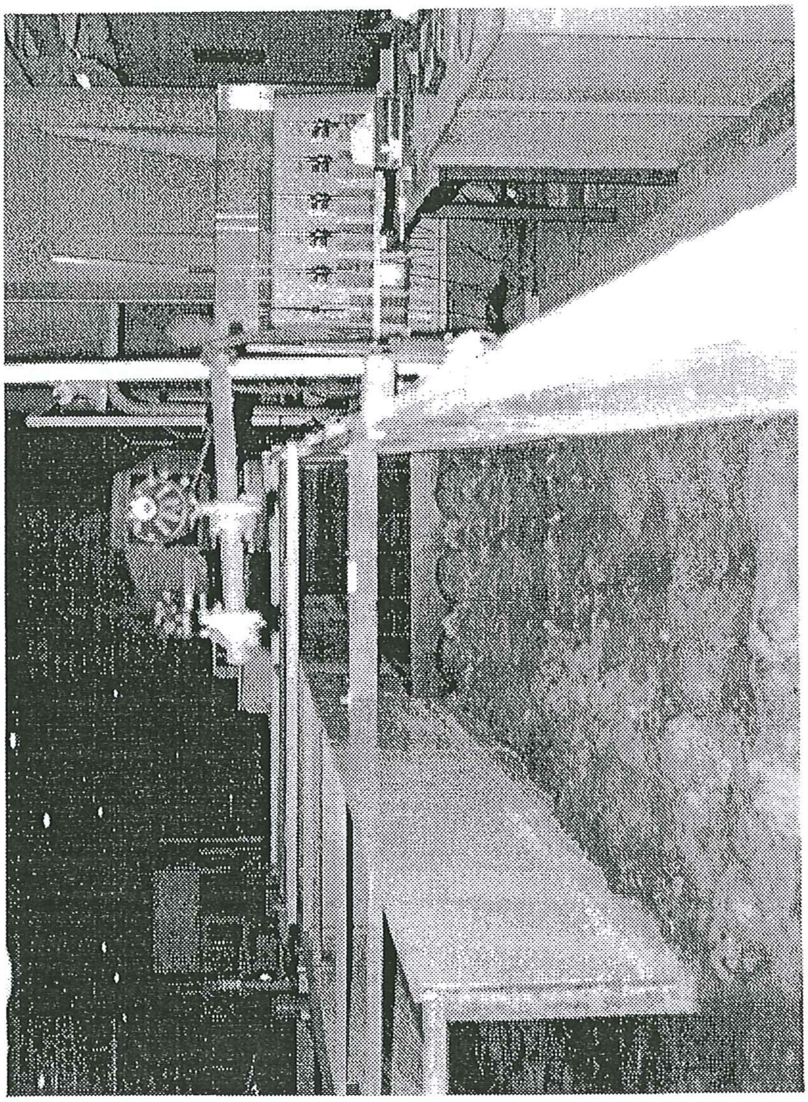


PLATE 1 FIXED BED FLUME

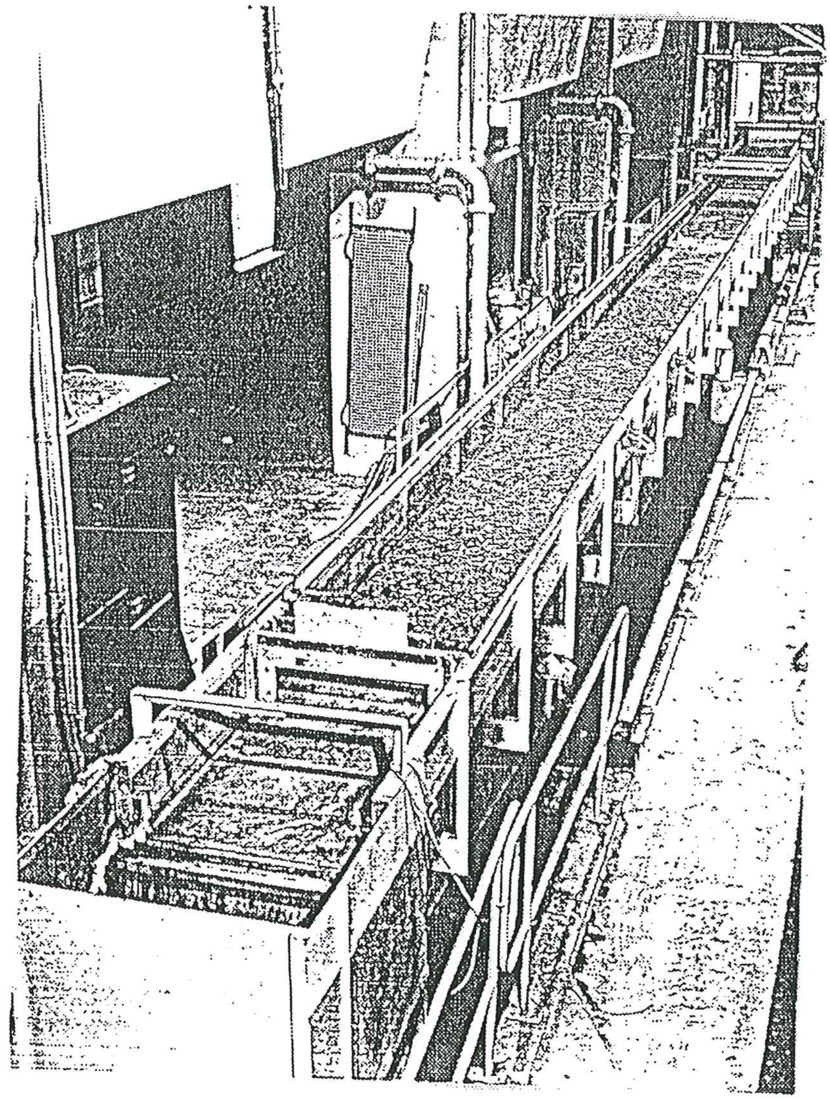


PLATE 2 ADJUSTABLE BED FLUME

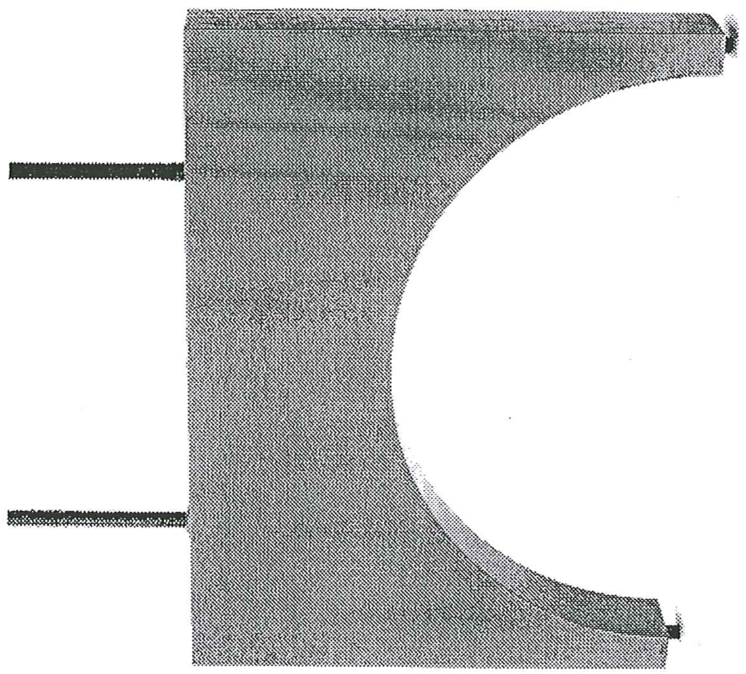


PLATE 3 SINGLE SEMI-CIRCULAR ARCHED BRIDGE

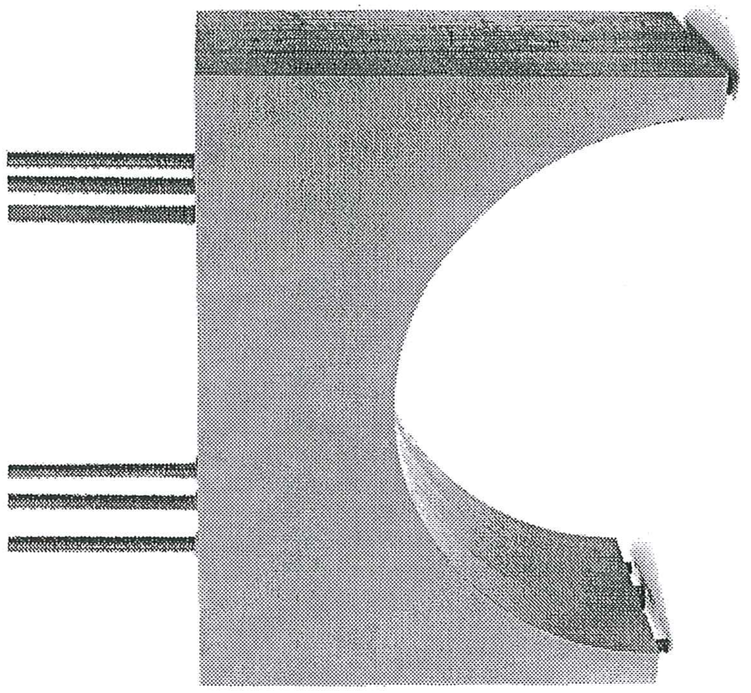


PLATE 4 SINGLE SEMI-CIRCULAR ARCHED BRIDGE
LENGTHENED IN DIRECTION OF FLOW

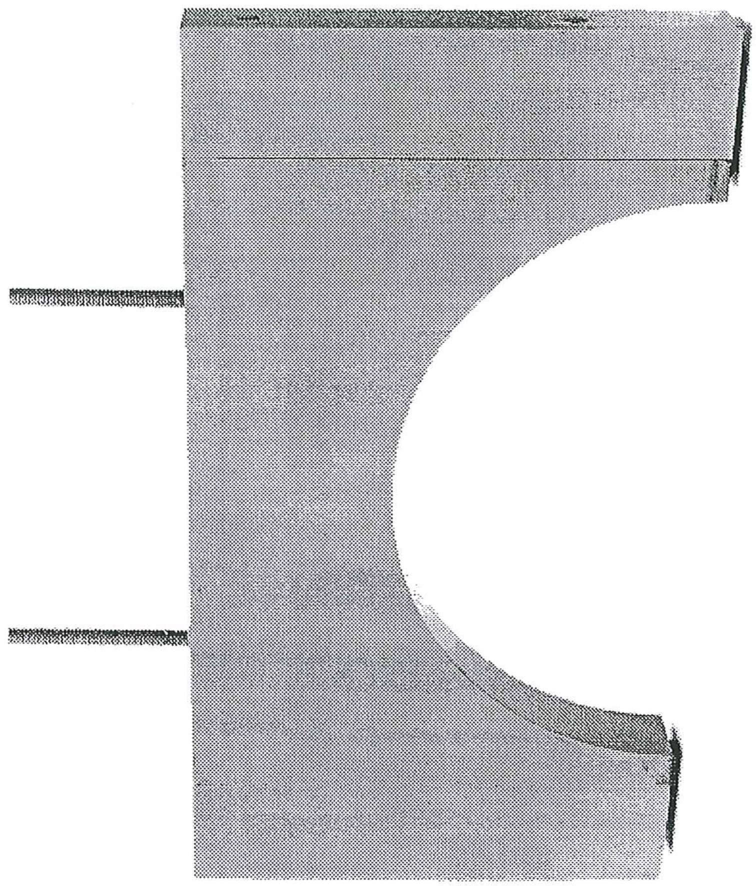


PLATE 5 SINGLE SEMI-CIRCULAR ARCHED BRIDGE WITH WIDENED PIERS

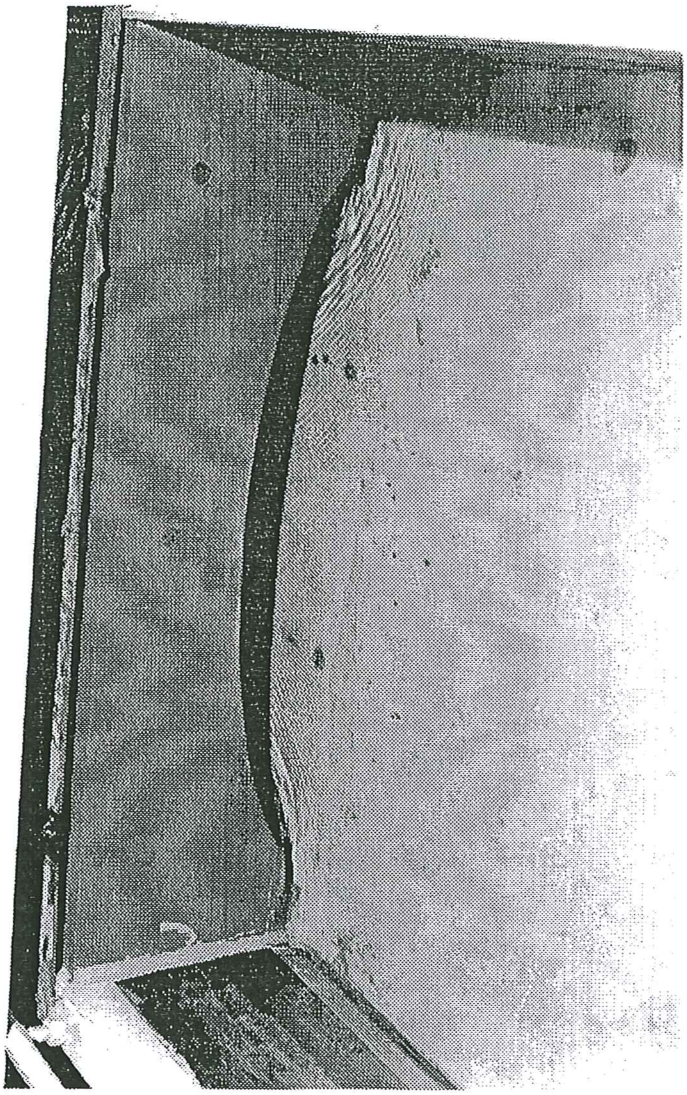


PLATE 6 ELLIPTICAL ARCHED BRIDGE UPSTREAM VIEW

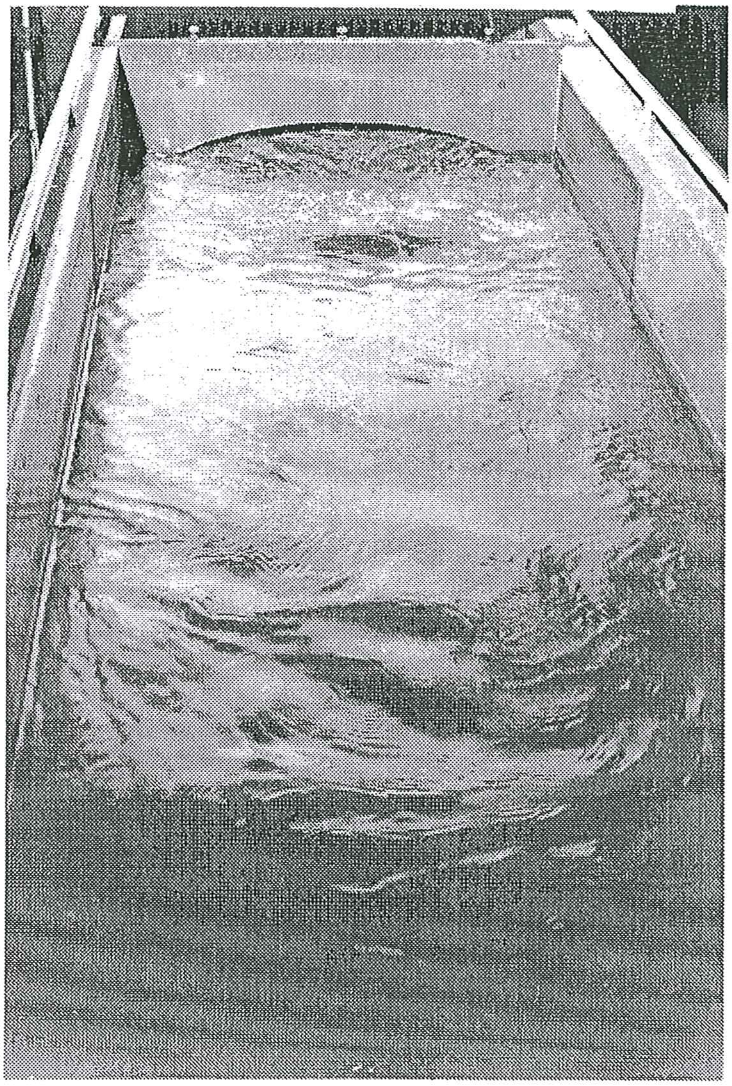


PLATE 7   ELLIPTICAL ARCHED BRIDGE DOWNSTREAM VIEW

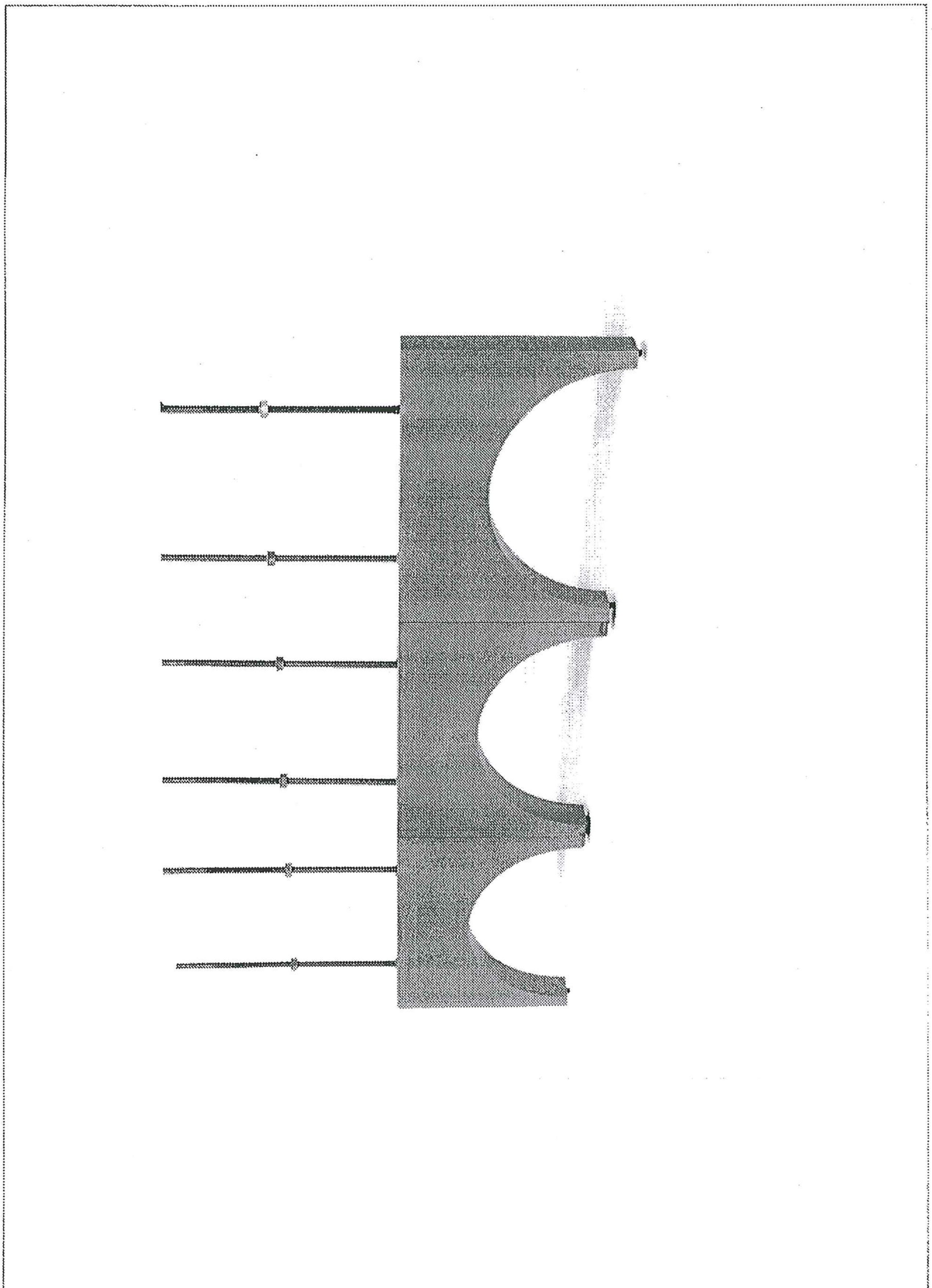


PLATE 8 MULTIPLE SEMI-CIRCULAR ARCHED BRIDGE

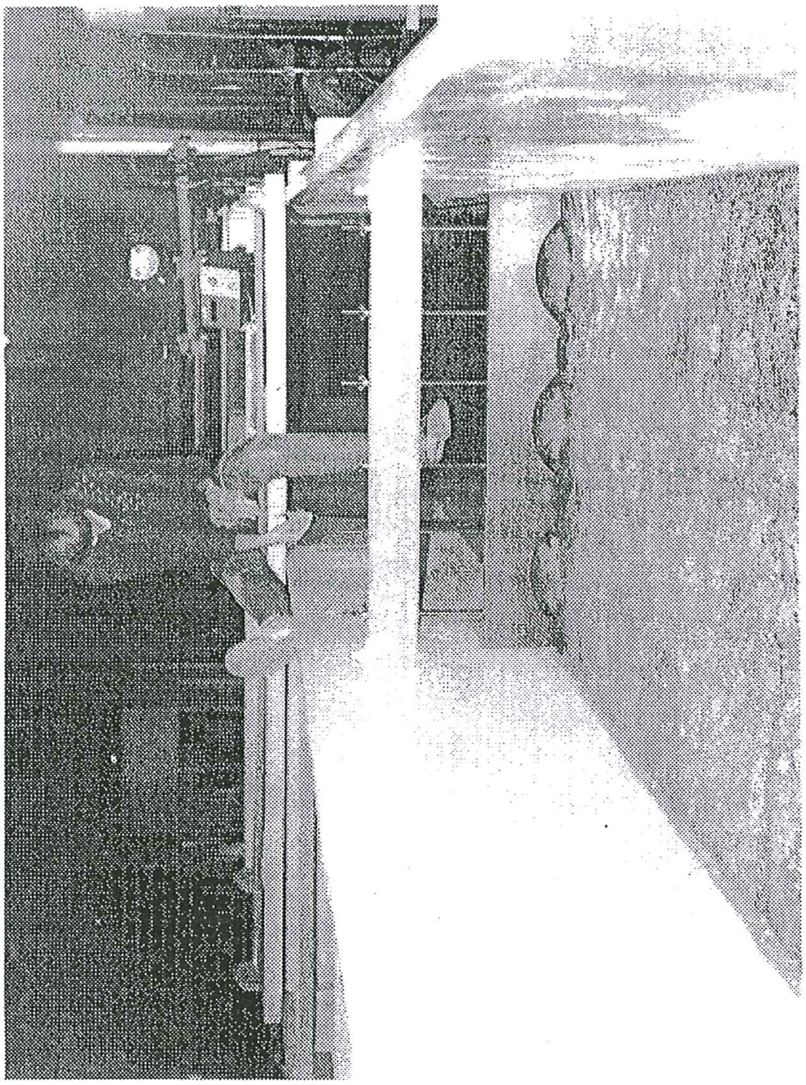


PLATE 9 MULTIPLE SEMI-CIRCULAR ARCHED BRIDGE DURING TESTING

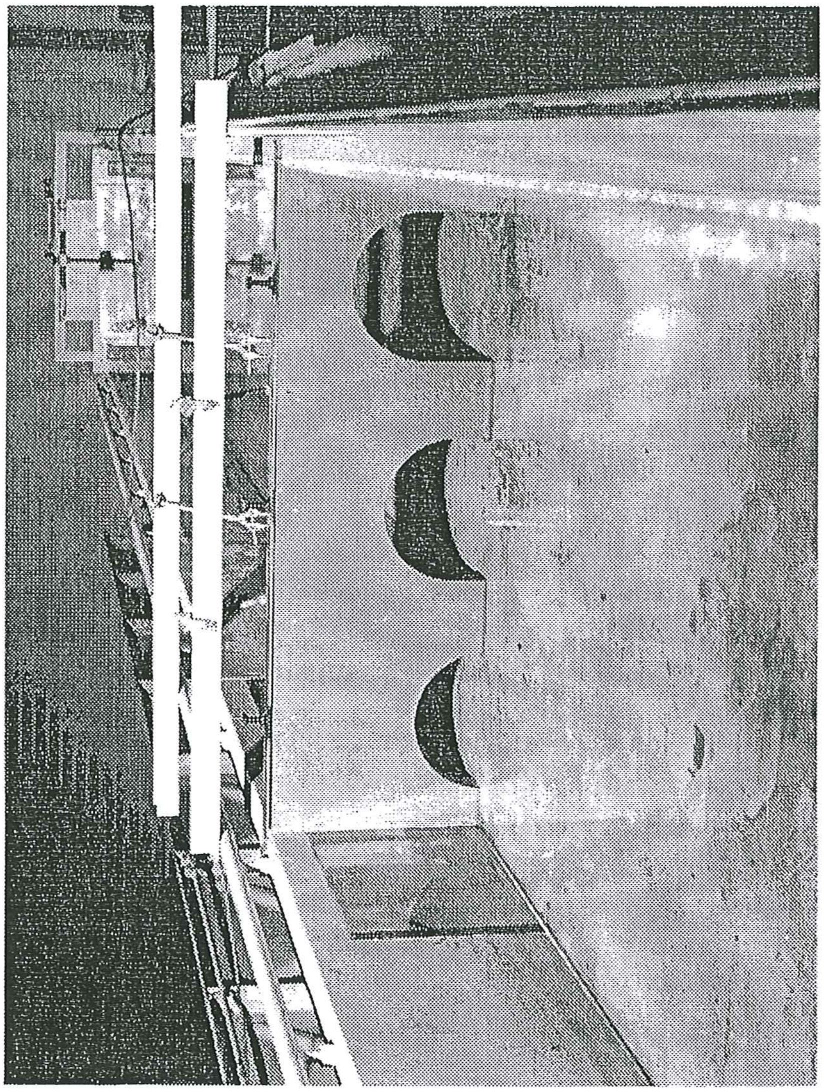


PLATE 10   MULTIPLE ARCHED BRIDGE WITH DIFFERENT SOFFIT LEVELS

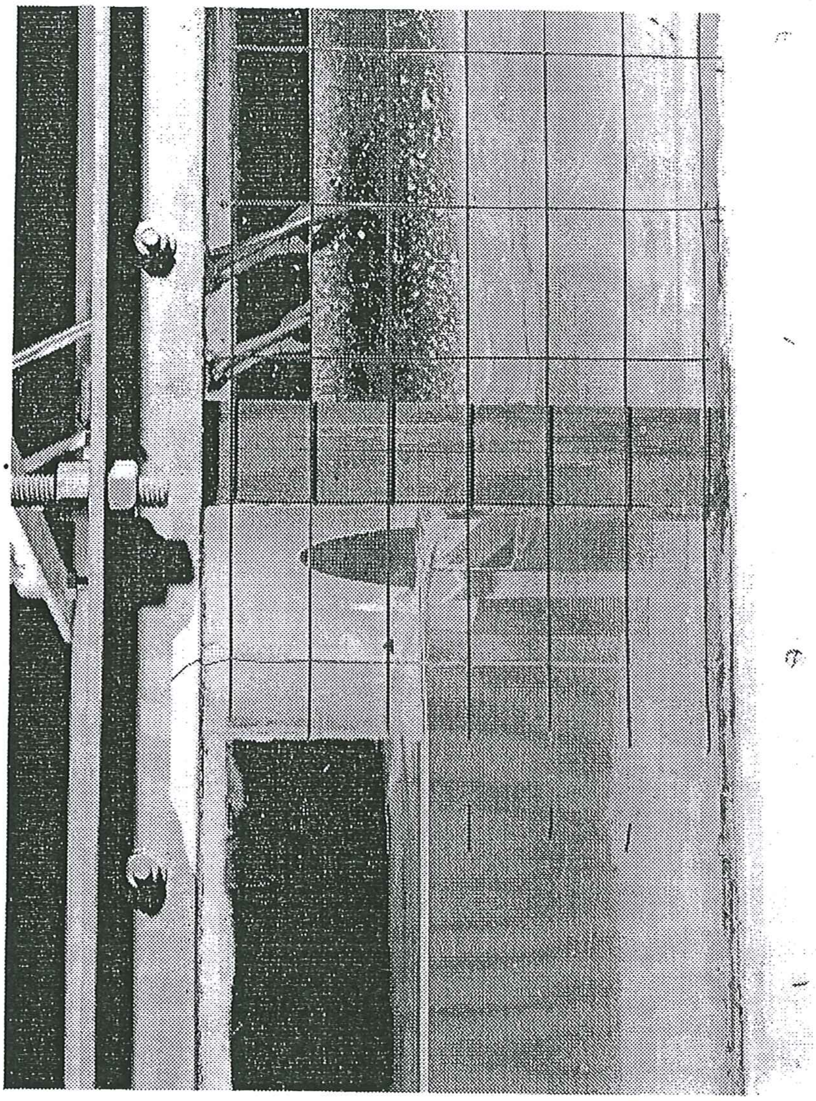


PLATE 11   MULTIPLE ARCHED BRIDGE DURING TESTING

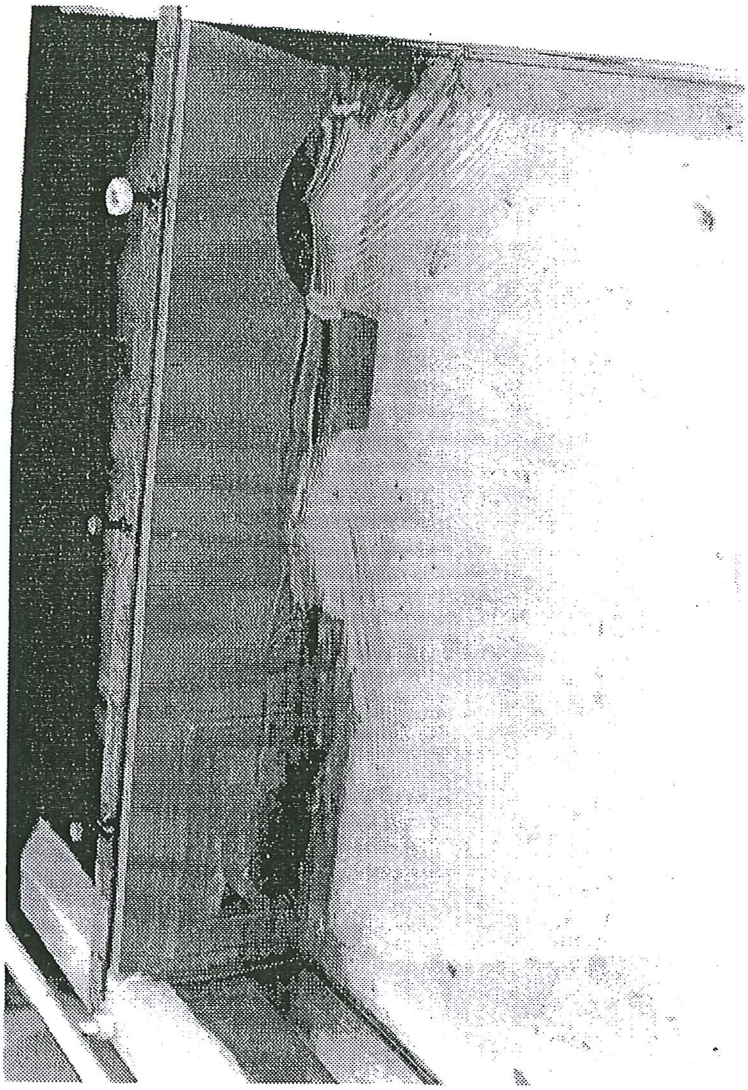
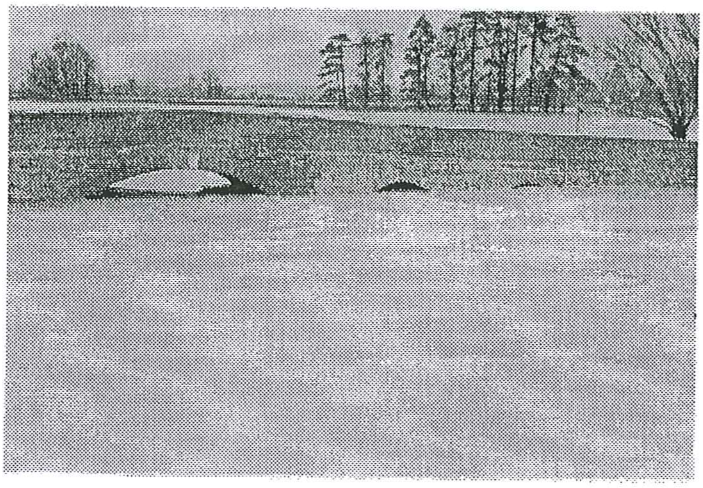


PLATE 12 MULTIPLE ARCHED BRIDGE, SMALL ARCH BLOCKED

PLATE 13 MULTIPLE ARCHED BRIDGE CENTRE ARCH BLOCKED



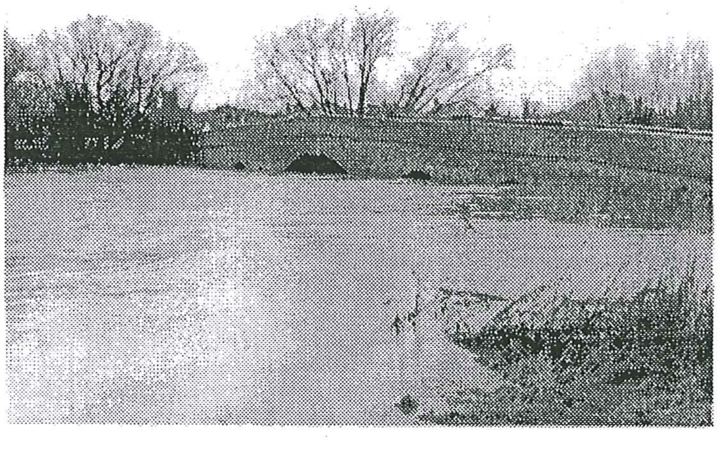
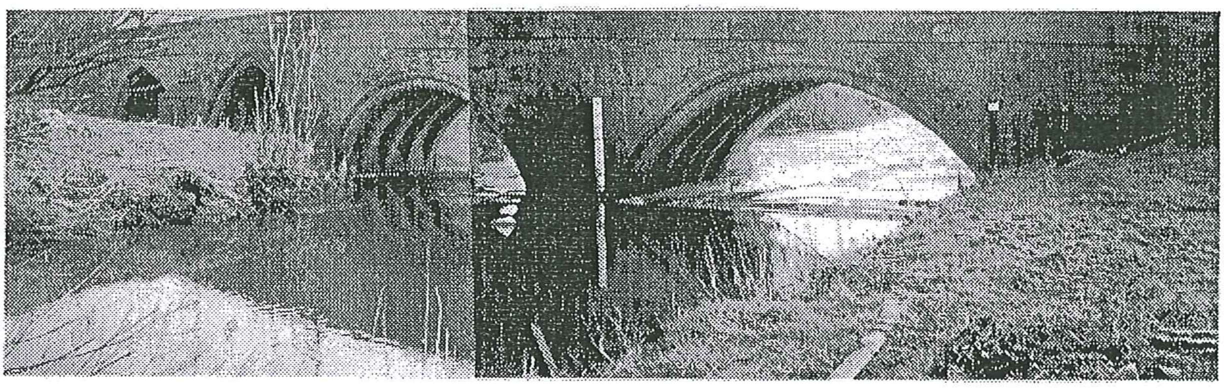


PLATE 14 FLOOD CONDITIONS AT TWO BRIDGE SITES



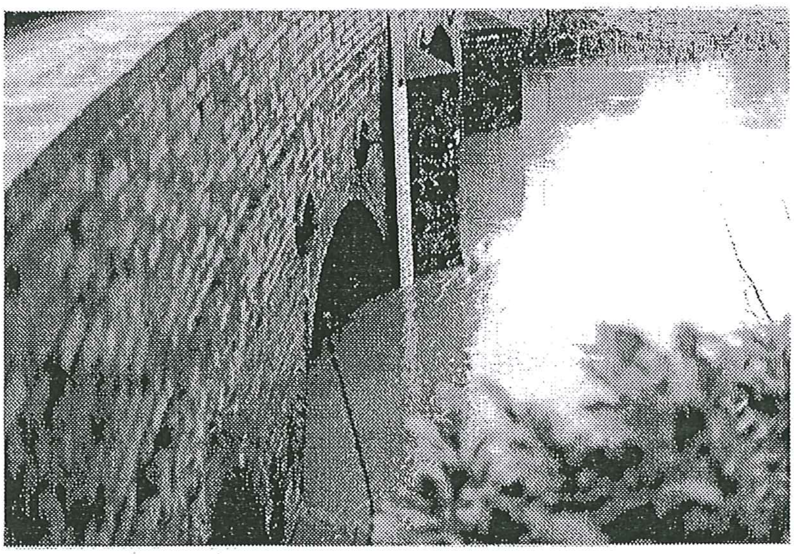


PLATE 15 SITING OF GAUGE BOARDS

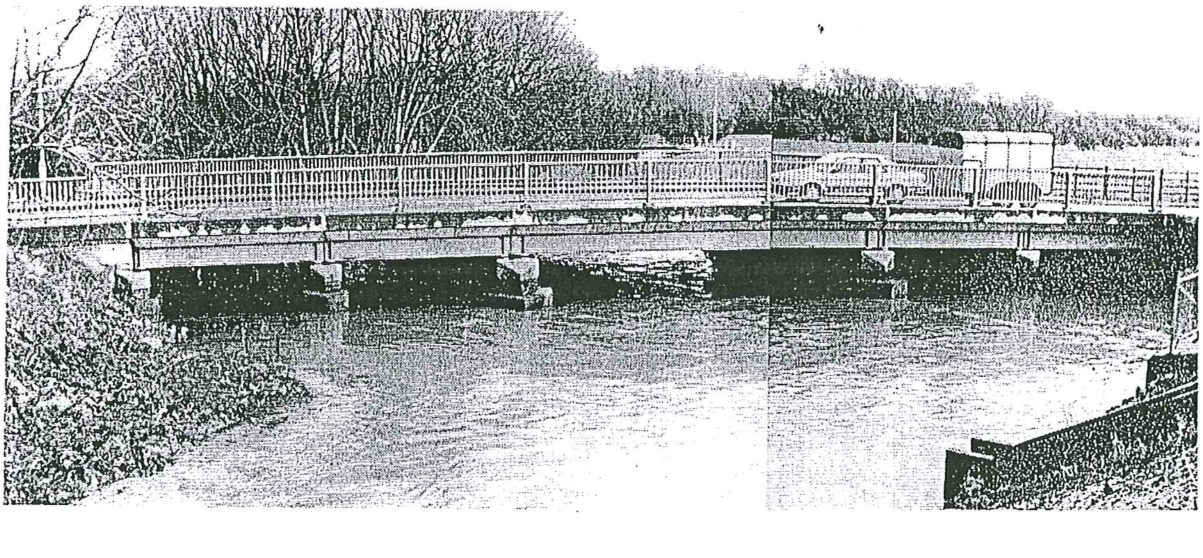
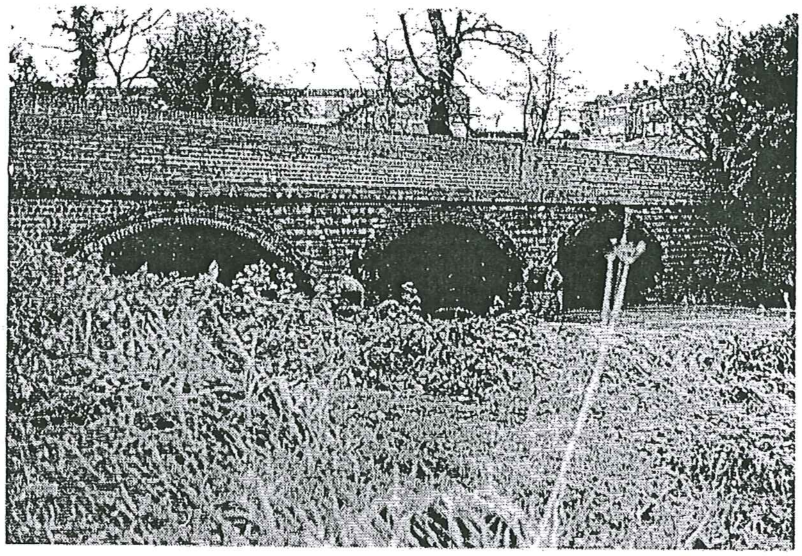


PLATE 16 DOW BRIDGE AND BOUGHTON ROAD BRIDGE



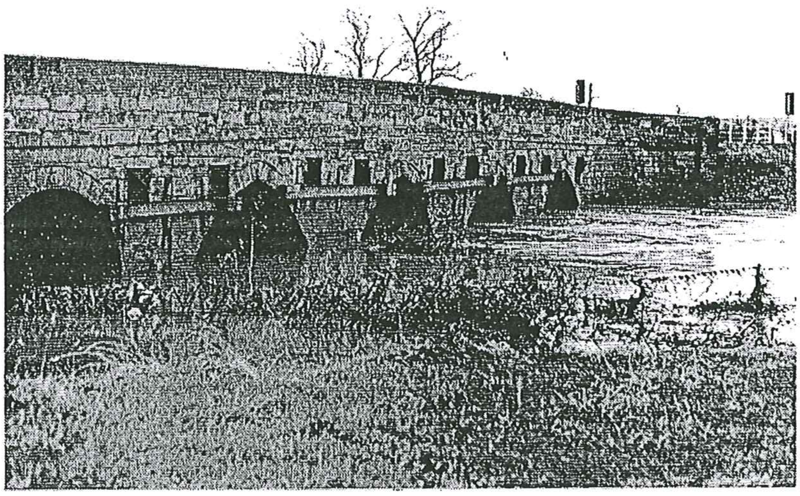


PLATE 17 LEA CRESCENT BRIDGE AND BRETFORD BRIDGE

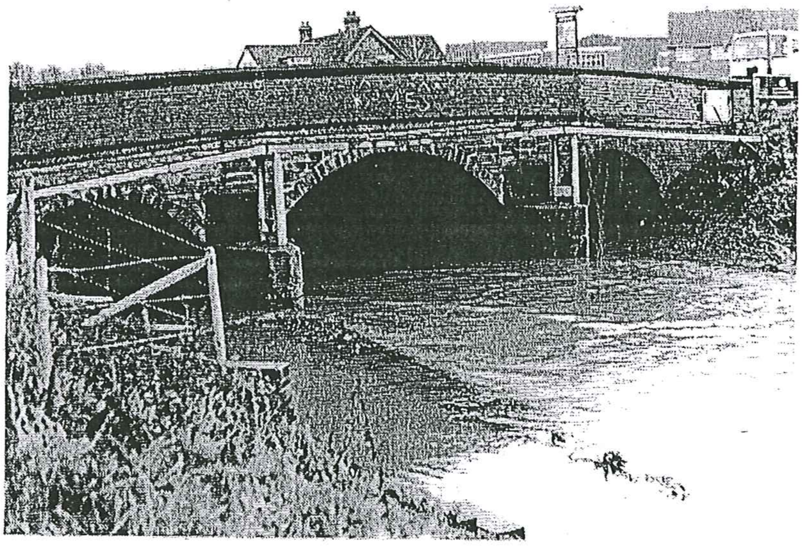
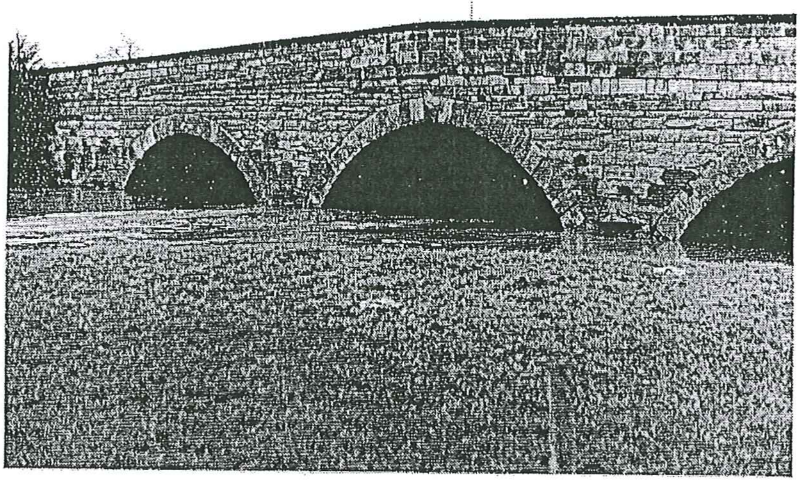


PLATE 18 WOLSTON BRIDGE AND AVON MILL BRIDGE



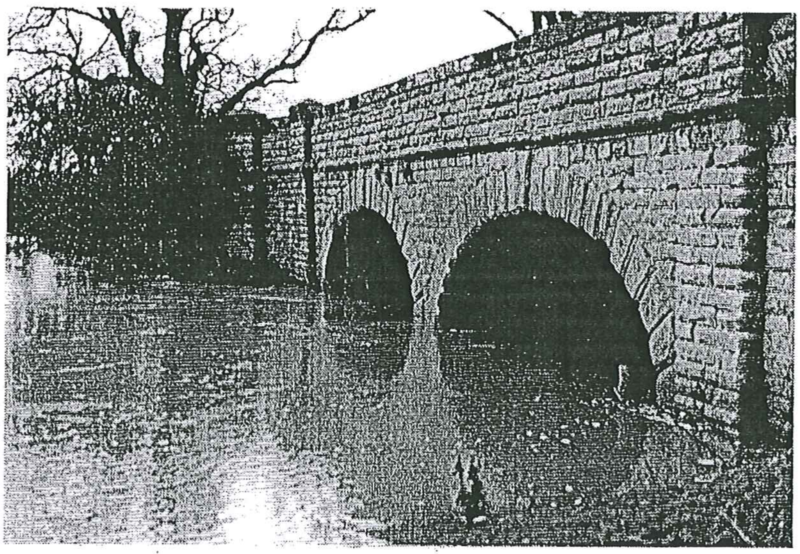


PLATE 19 RYTON BRIDGE AND BUBBENHALL BRIDGE

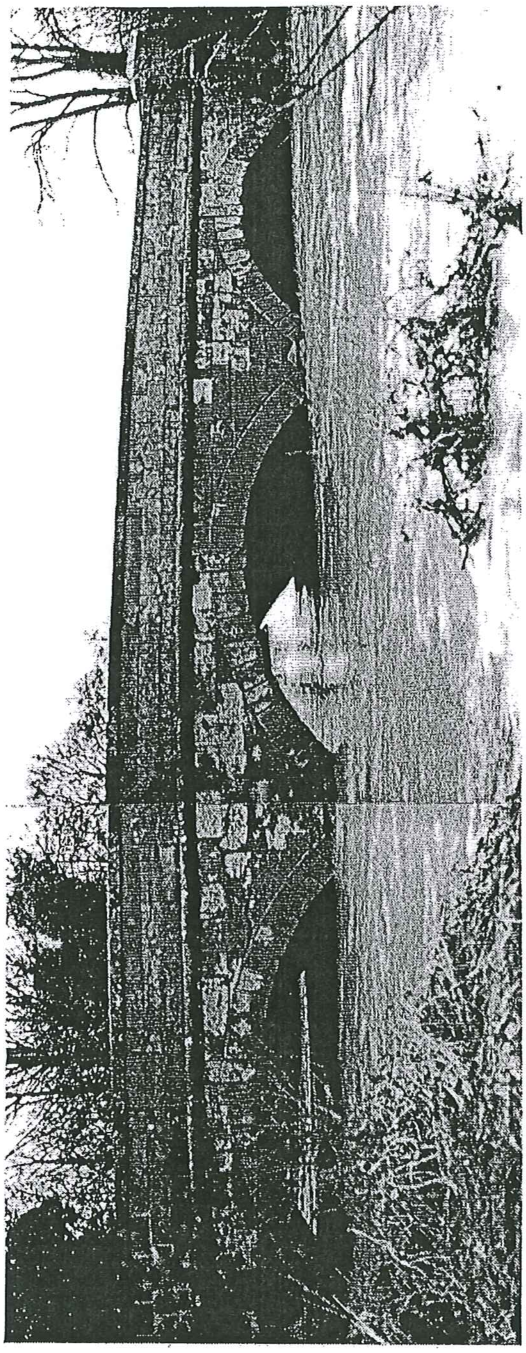


PLATE 2Ø CLOUD BRIDGE

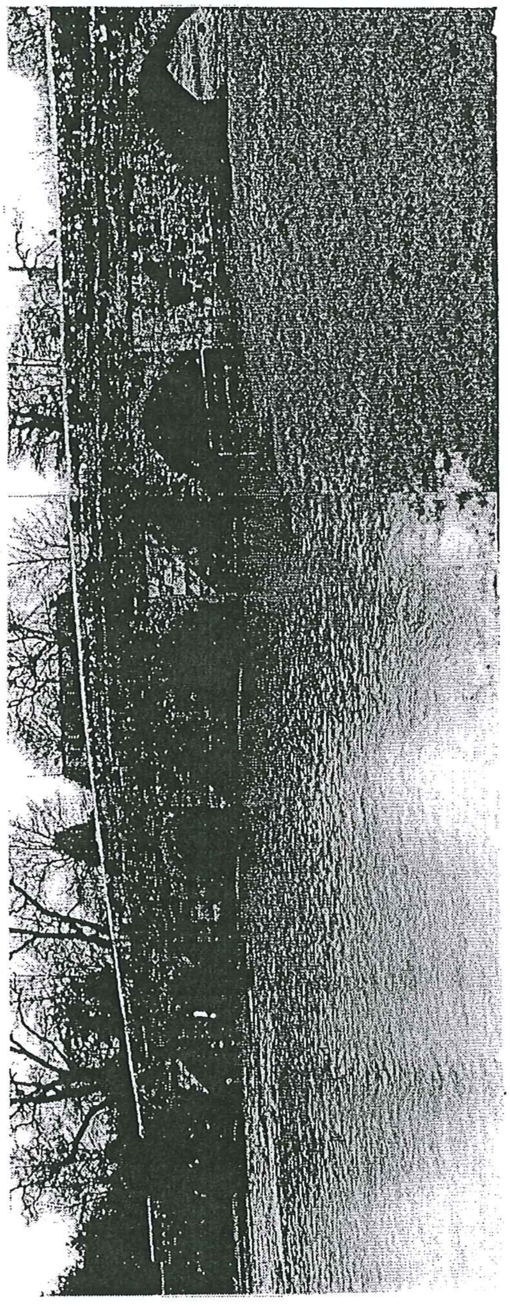


PLATE 21 STARE BRIDGE

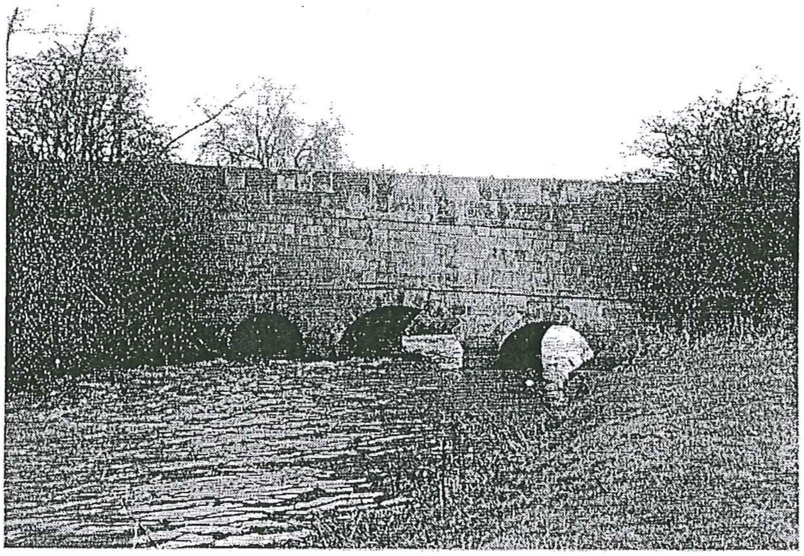


PLATE 22 STANTON GATE BRIDGE AND WIXFORD BRIDGE

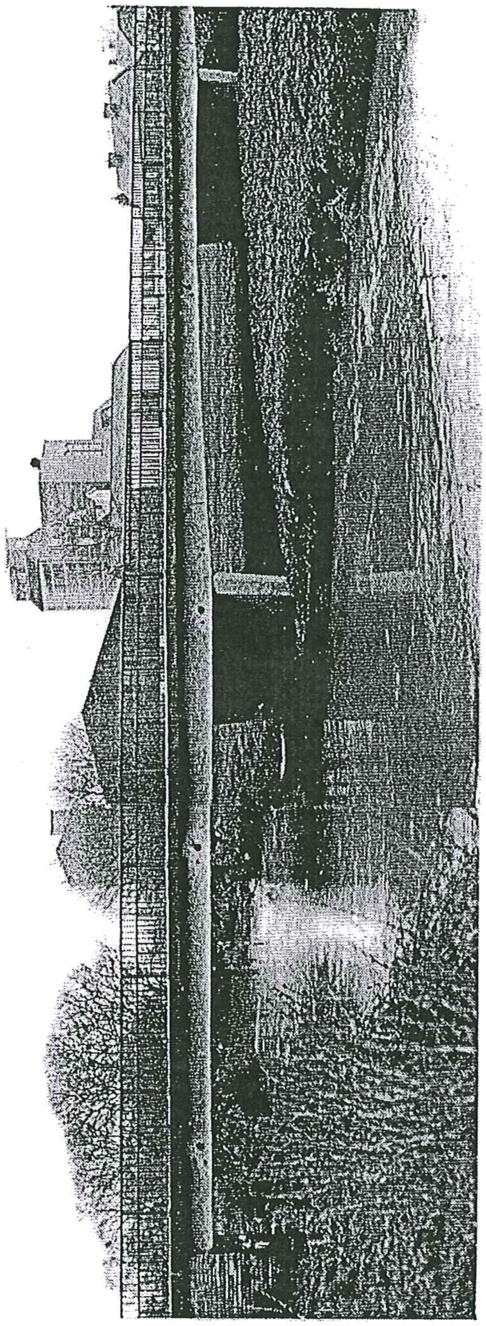


PLATE 23 BROOM BRIDGE

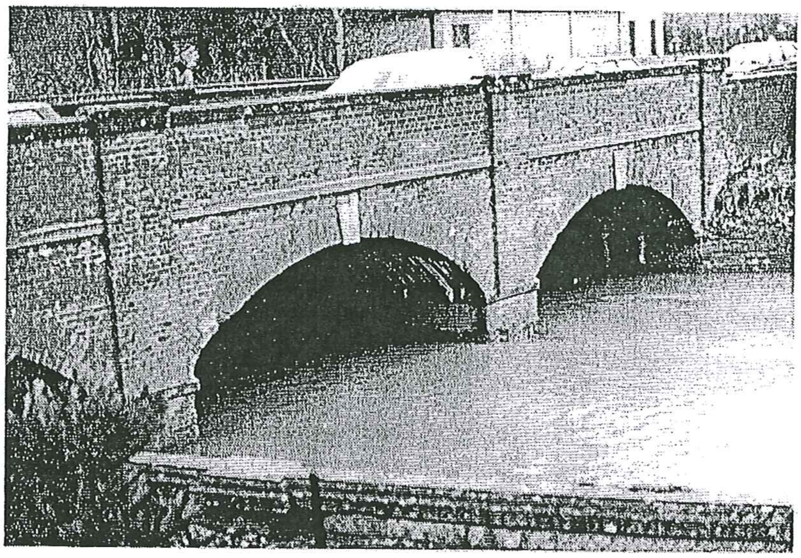


PLATE 24 GUNNINGS BRIDGE

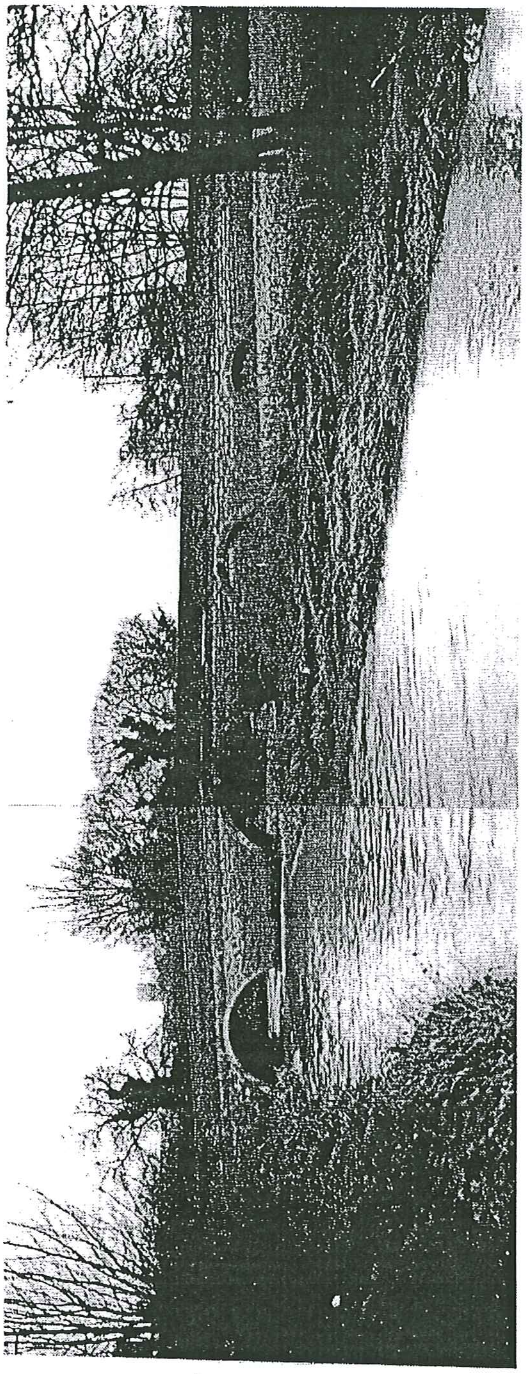


PLATE 25 OVERSLEY BRIDGE

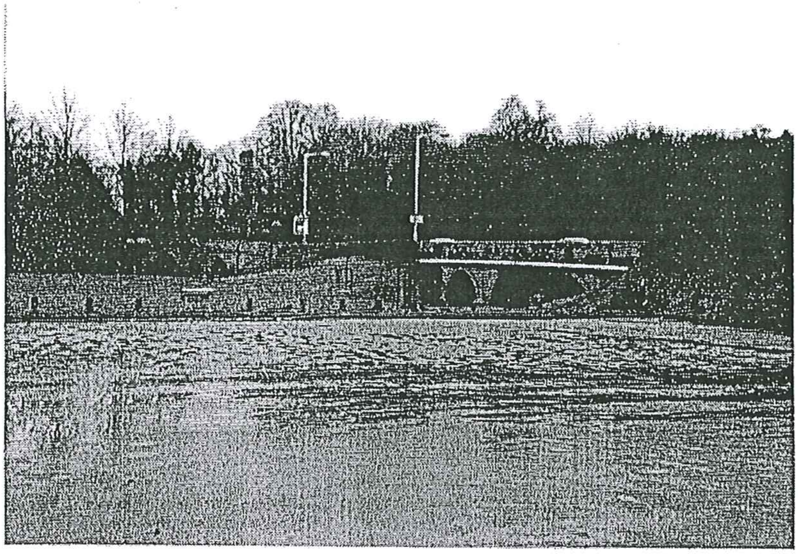


PLATE 26 BLANDFORD BRIDGE AND JULIANS BRIDGE

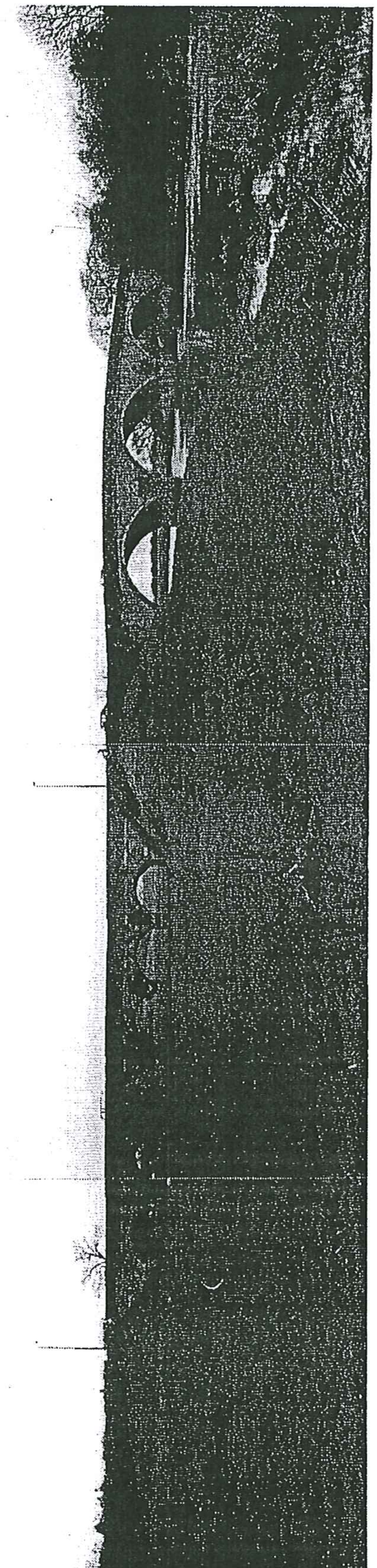


PLATE 27 CANFORD BRIDGE

PLATE 28 CRAWFORD BRIDGE

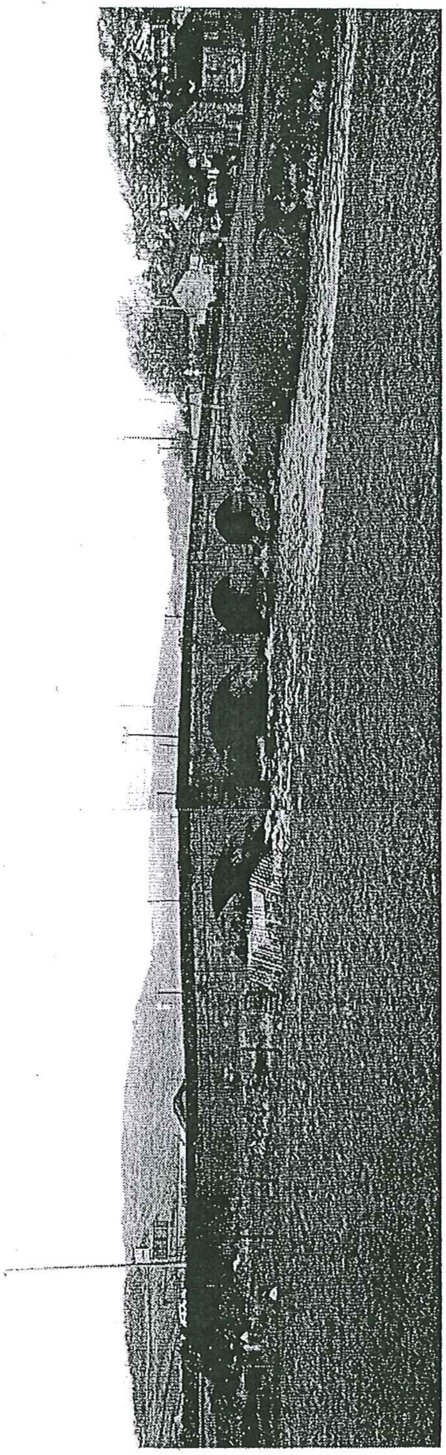


PLATE 29 KILDWICK BRIDGE

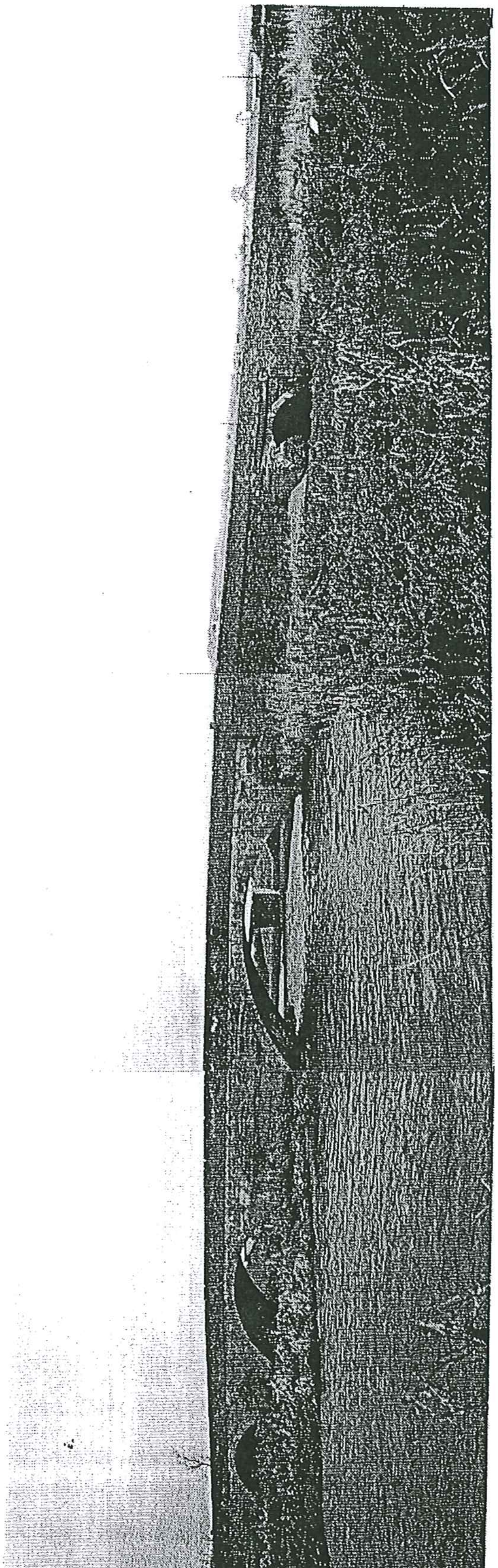
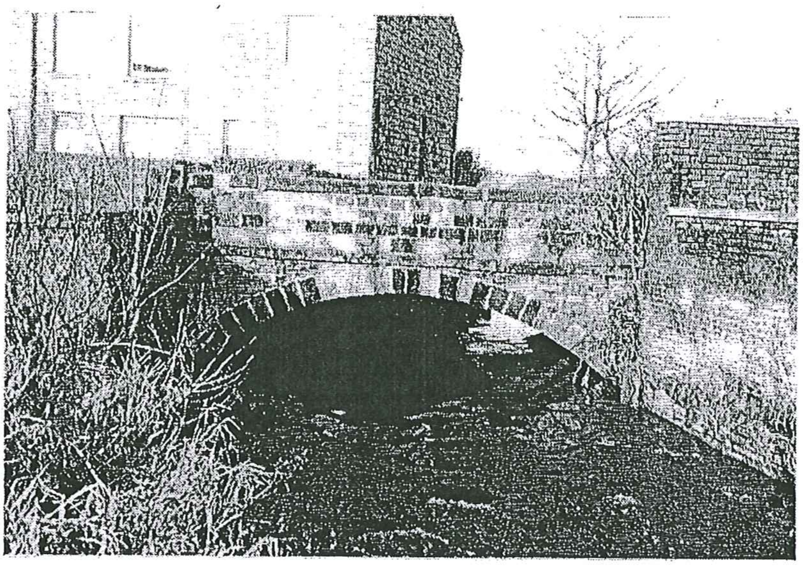


PLATE 30   INGHEY BRIDGE



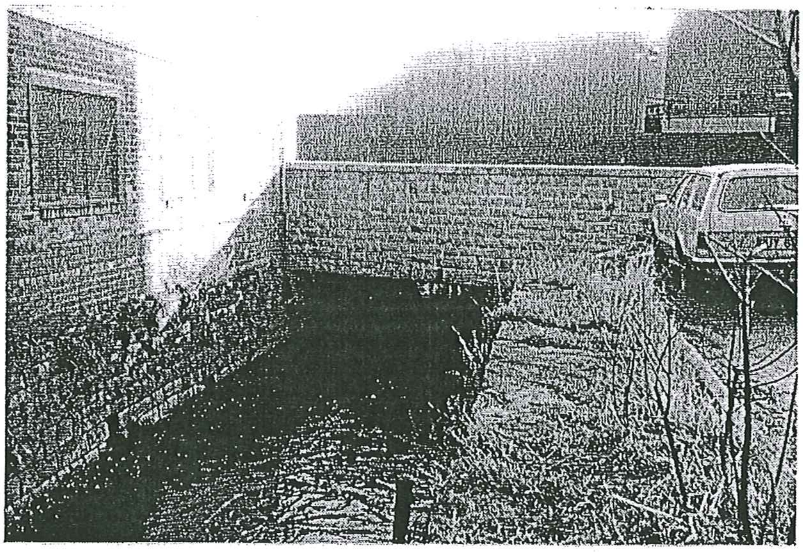


PLATE 31 STATION ROAD BRIDGE AND UNION STREET BRIDGE

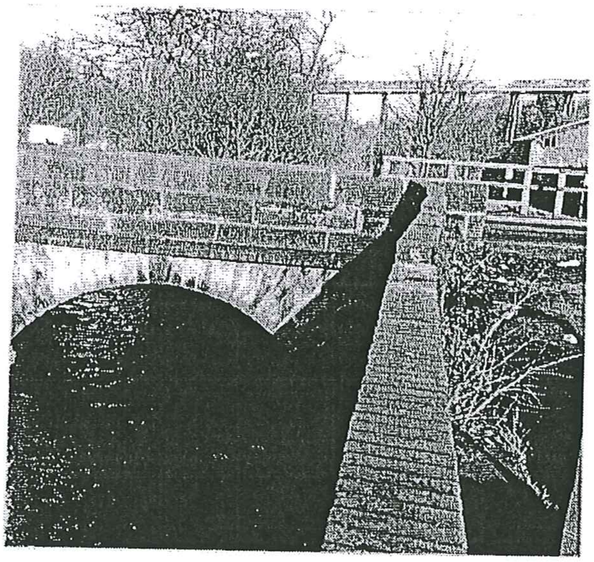
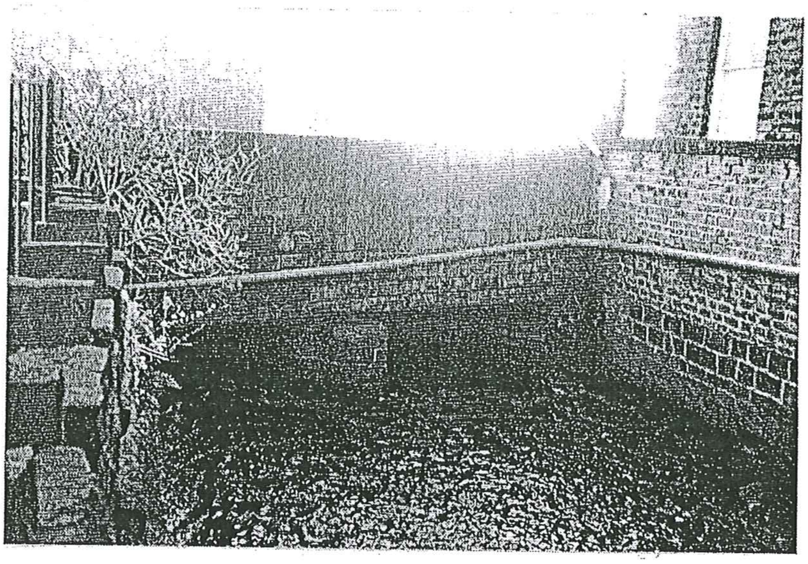


PLATE 32 RAWFOLDS BRIDGE AND ST. PEGS BRIDGE



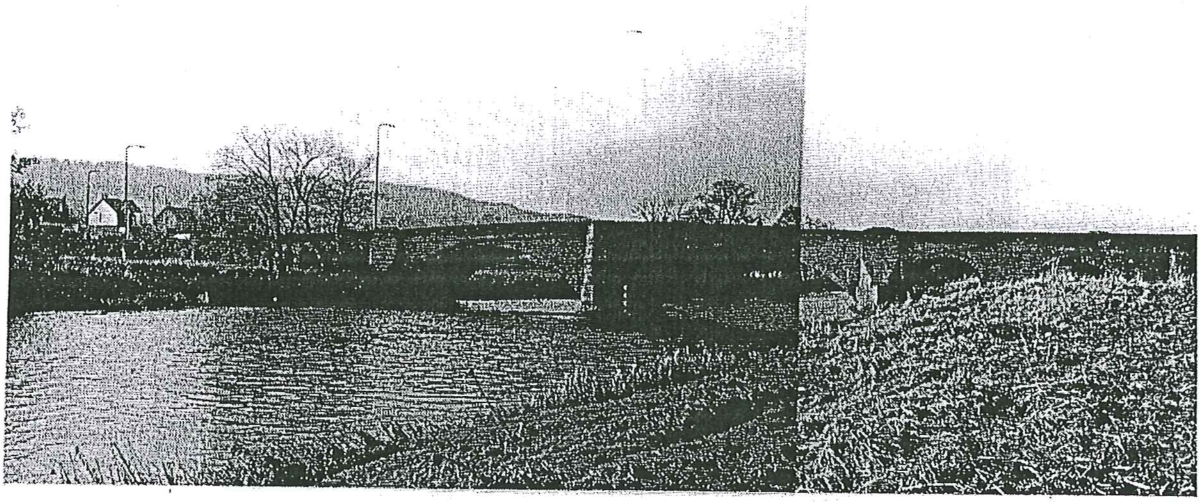
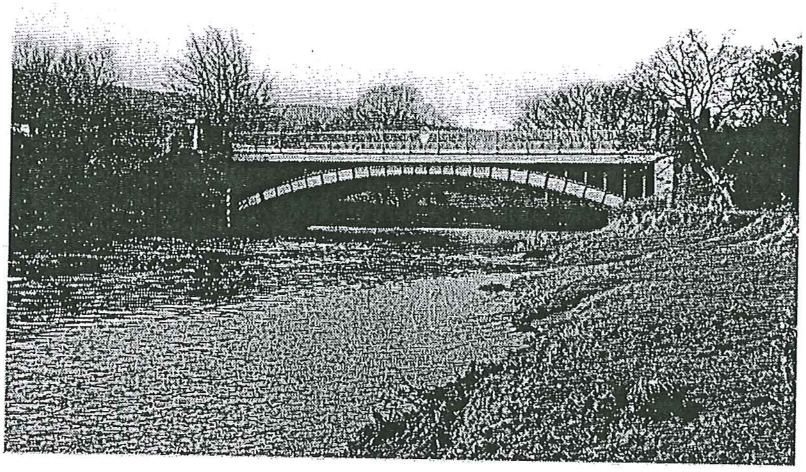


PLATE 33 BALME ROAD BRIDGE AND POOL BRIDGE



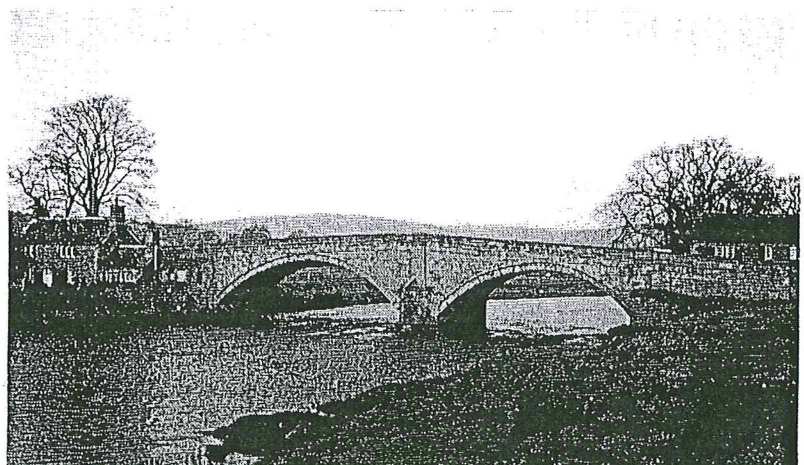


PLATE 34 ILKLEY BRIDGE AND BOLTON BRIDGE

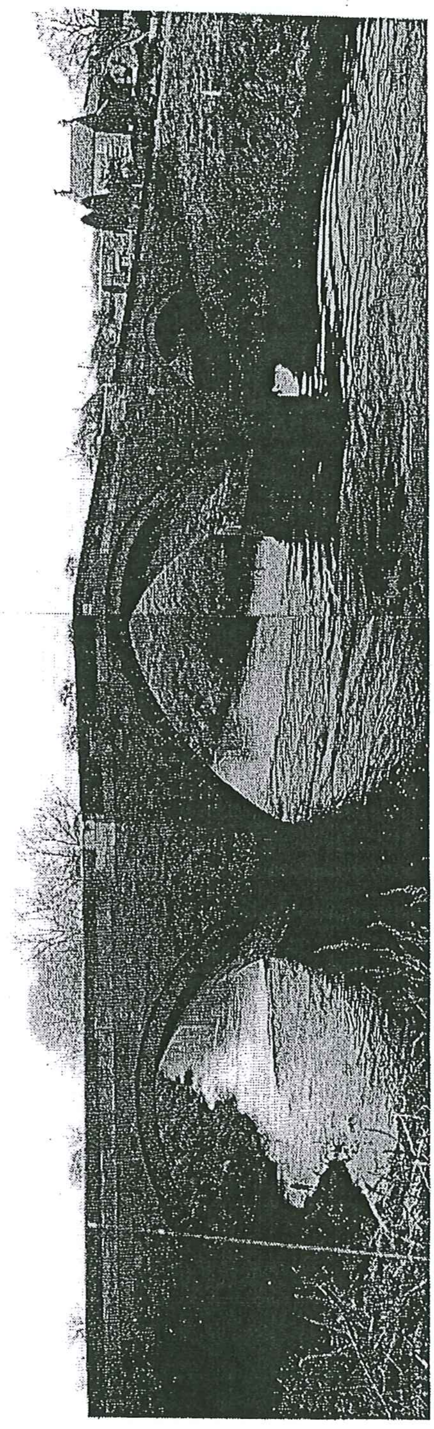


PLATE 35 CATTAL BRIDGE

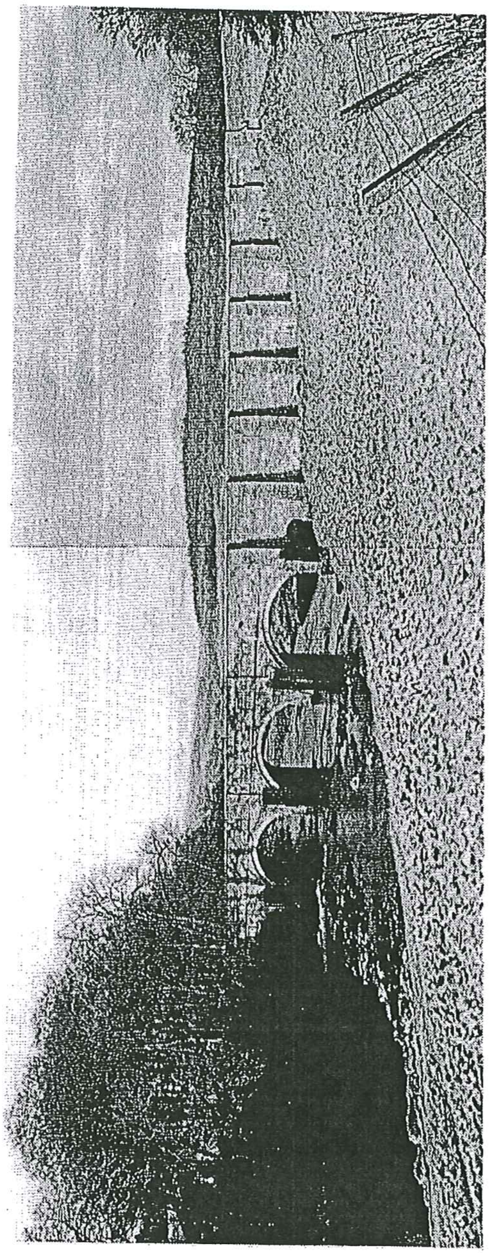


PLATE 36 GRASSINGTON BRIDGE

APPENDICES.

APPENDIX 1

Worked example of calculating an estimate of afflux using an iterative method

Consider a semi-circular arched bridge of similar design to that shown on Fig 3. Pier width is 0.4m and arch radius is 3m. Total height of the bridge is 5m. Assume a backwater calculation yields a downstream water level of 32.36 mAD above a mean bed level of 30.0 mAD for a flood discharge of 44.72 cumecs. A best estimate of the upstream water level may be obtained from Fig 38 using the following iterative procedure.

(i) Calculate downstream Froude number F3 from downstream velocity and depth.

F3 = V3 / SQR (gxD3)
= (Q/(BxD3)) / SQR (gxD3)
= (44.72/6.80x2.36) / 4.81
= 0.577

(ii) Assume an initial upstream water level and calculate the corresponding blockage ratio. It is convenient to let initial upstream depth D1 equal D3.

First estimate of D1 = 2.36 m
Initial blockage ratio J1 = area of blockage below waterlevel/total flow area

= (160.75–125.32)/160.75
= 0.220

Using Fig 38 this initial estimate of J1 and the calculated value of F3 give an afflux ratio dh/D3 of 0.143.

dh/D3 = (D1-D3)/D3 = 0.143

New estimate of D1 = (0.143xD3) + D3
= 2.702 m

(iii) If the difference between the initial estimate of D1 and the new value is greater than an acceptable tolerance of, say 0.001m then the procedure is repeated using the new value of D1.

New estimate of D1 = 2.702 m
New blockage ratio J1 = (183.76-136.15)/183.76
= 0.259

From Fig 38 dh/D3 = 0.164
new D1 = 2.752 m
Since (new D1- previous D1) > 0.001 m the procedure is repeated.

New estimate of D1 = 2.752 m
New blockage ratio J1 = (187.21-137.41)/187.21
= 0.266
dh/D3 = 0.168
new D1 = 2.762 m
(new D1 - previous D1) > 0.001 m

New estimate of D1 = 2.762 m

New blockage ratio J1 = (187.82-137.63)/187.82
= 0.267
dh/D3 = 0.169
new D1 = 2.762 m

This new depth is within 0.001m of the previously calculated value so this is acceptable. The best estimate of upstream water level is therefore 32.762 m AD.

APPENDIX 2

Worked example of calculating an estimate of afflux using a direct method

Consider Avon Mill bridge crossing the River Avon as an example. The bridge cross section is shown in Fig 11 and relevant hydraulic data listed in Tables 2 and 7. The bridge reference No is 13. Plate 18 shows the bridge in a normal flow condition.

Assume that a backwater calculation from downstream has given a water level downstream of the bridge of 83.50 m AD at a discharge of 53 cumecs. To obtain an estimate of the corresponding upstream water level,

(i) calculate the downstream blockage ratio J3 from a downstream elevation of the bridge, bed level section and water level. This involves calculating the area of bridge structure below the water level and expressing the value as a fraction of the total available water area.

area of flow through arch 1 = 5.93 sq m
area of flow through arch 2 = 12.85 sq m
area of flow through arch 3 = 7.89 sq m
total flow area through arches = 26.67 sq m

total river flow area = 39.09 sq m

Blockage ratio J3 = (39.09 - 26.67)/39.09 = 0.318

(ii) calculate the downstream Froude number F3
mean bed level = 81.37 mAD
mean depth of flow D3 = 83.50 - 81.37 = 2.13 m
mean velocity V3 = Q/(BxD3) = 53 / (18.7 x 2.13)
= 1.33 m/s

F3 = V3/(SQR (gxD3))
= 1.33 / 4.57
= 0.29

(iii) obtain a value of dh/D3 from Fig 39 corresponding to the calculated values of J3 and F3.

dh/D3 = 0.061 = (D1-D3) / D3
Upstream depth D1 = 2.26 m

Best estimate of the upstream water level is therefore

81.37 + 2.26 = 83.63 m AD