Hydraulics Research
Wallingford

AFFLUX AT ARCH BRIDGES
SECOND INTERIM REPORT

DRAFT

Report No SR 115
March 1987

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SYMBOLS

B	Width of channel
d_1	normal depth of flow upstream
d_3	normal depth of flow downstream
C_D	coefficient of drag
ρ	mass density of water
V_1	mean velocity of flow at Section 1
V_3	mean velocity of flow at Section 3
g	acceleration due to gravity
F	Froude number = $V/\sqrt{gd}$
Q	discharge
J	Blockage area/area of flow in absence of bridge
Δh	afflux, $(d_1 - d_3)$
$\Delta h'$	afflux, defined to contain no friction loss term

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1 INTRODUCTION

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 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 afflux, the difference between upstream and downstream water levels. An interim report published in August 1985 (Ref 1) details the first part of the investigation, namely a series of laboratory tests on model single and multiple arched bridges. This report covers additional tests on multiple arched model bridges to develop further a technique for predicting afflux given in the first report. It mainly includes the collection and analysis of prototype arch bridge information from Water Authorities which was used to field test developed theories.

2 RESUMÉ OF INITIAL TESTS

A total of 118 tests were carried out on model semi-circular arched bridges in a 2.4m wide x 15m long flume. Piers were square edged for all tests but pier width, bridge length and number of arches were variables. Results from all tests and subsequent analyses are given in the interim report (Ref 1).

Results showed conclusively that predictions of afflux using existing theory based on United States Department of Transport, Bureau of Public Roads recommendations (Ref 2), over-estimated water levels above bridge soffit levels.

Figure 1 shows a graphical representation of the dimensionless parameters of Froude number F_3, blockage ratio J_1 and afflux ratio $\Delta h/d_3$ developed from the flume tests where:

F_3 = downstream Froude number = $v_3/\sqrt{g\ d_3}$

V_3 = downstream velocity

d_3 = downstream depth

g = acceleration due to gravity

J_1 = area of bridge causing blockage/area of flow in absence of bridge

Δh = afflux, difference between upstream gauged head and downstream gauged head

By using an iterative procedure the graph may be used to predict water level.

3 ADDITIONAL FLUME TESTS

One conclusion which was formulated from the laboratory tests was that behaviour of flow through a single arched bridge could not be similarly attributed to a multiple arch bridge made up of combinations of the single arch. For a given unit discharge and tailwater level, afflux was larger with the three arch bridge than with the single. This increase varied with flow and was apparent over the full tested range of water levels. However, in the early analysis all multiple bridge test results were plotted together with the single arch results and represented graphically.

A better understanding of the behaviour of flow through multiple arches was required in the light of the above conclusions. Further tests were planned and set up for these cases but owing to the amount of effort which became necessary in the collection of prototype data, only a modest programme of testing was possible.

Plate 1 shows the layout of the flume used in the experiments. The flume was 24.5m long, 0.9m wide and 0.3m deep and had an adjustable bed slope from horizontal to a maximum of 1:60. Uniform flow conditions were established for various discharges in the absence of the bridge. Earlier test were made on a three arch bridge with identical arch shape and soffit levels, so a new model bridge was constructed to test the effect of varying these parameters. Plate 2 and Figure 2 show the design.

The same discharge and bed slope conditions which reproduced uniform flow were imposed on the flume with the bridge installed. Longitudinal water surface profiles were measured and these are shown in Figure 3. Flow separators were attached to the downstream face of the bridge and to the channel bed, effectively splitting the bridge into three equal width units, so that the discharge passing through each arch could be measured, see Plate 3.

Data was processed and analysed using the same procedure as for previous model tests. The difference between static water level at upstream and downstream points furthest from the bridge was considered as gauged head afflux. The dimensionless parameter of h/d_3, F_3 and J_1 were calculated for the bridge as one total unit, and also for each of the arches separately. Table 1 lists the results from these tests and Table 2 gives analytical results when considering the bridge in total and also each arch separately.

4 RESULTS OF LABORATORY TESTS

Considering firstly the results from the additional multiple bridge tests in the adjustable bed flume Tables 2 and 3, giving the hydraulic data for all three arches analysed in total and analysed separately. This shows that the behaviour of flow through a single arch is very different from that with a multi-arch structure. Calculated water level upstream of the small arch is up to 30% higher than actually measured, and in the case of the large arch upstream water level was under-predicted by almost 18%. Lateral water surface profiles taken at the measurement locations either side of the bridge were assumed horizontal but the predicted levels indicate probable conditions in the area close to the bridge.

Figure 1 shows the graphical representation of the dimensionless parameters $\Delta h/d_3$, F_3 and J_1 presented in the interim report HRL SR 60. This covers tests on single and multiple arches. In order to directly compare the additional data on multiple arches with previous, part of Figure 1 was plotted to a larger scale and all data on multiple arch bridges shown. This data is given on Figure 4. Clearly the data for the later tests, considering the total bridge, fits very well within the contours.

Table 4 compares the measured afflux at model multiple arch bridges with that obtained using the graph, Figure 4. Although there is a degree of scatter, the measured points agree closely with the predicted, with a population standard deviation of $\pm$ 0.8%. This result gives confidence in the hand fitted curves of J_1, blockage ratio obtained from previous laboratory analysis.

Whilst the data obtained from the very limited extended tests on multiple arch bridges with different soffit levels looks promising and agrees well with previously established hydraulic representations, more research is needed on this aspect of bridges to extend the range of applicability of the method of afflux analysis.

5 COLLECTION OF PROTOTYPE BRIDGE DATA

In order to field test the developed relationships from the laboratory model tests similar data was required from actual arch type bridges which by virtue of their design cause some degree of blockage to flow. Letters were sent to 55 regional Water Authorities in England, Wales and Scotland to explain the research programme and to enquire whether they had bridges in their area which caused afflux problems. Their initial response is shown in Table 5. The total number of bridges identified was 192 which emphasises the need for a better understanding of the problem. All Water Authorities expressed an interest in the research programme and some offered assistance in gathering additional data.

Ideally the prototype information required was corresponding water level measurements upstream and downstream of an arch bridge, and a discharge measurement taken at the same time either at the bridge or, as was most likely, at a nearby gauging structure, during a flood event. Plans and sectional drawings of the bridge were needed to calculate blockage ratio and assess alignment to the flow.

Unfortunately, the Water Authorities indicted in their initial replies that whilst stressing the substantial number of arch structures which caused afflux, they were only able to supply limited data for the majority of the bridge sites. Usually, unless flood level recorders had been sited either side of a bridge specifically for flood event monitoring purposes corresponding upstream and downstream water level records were absent or incomplete. 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 chosen sites.

Gathering together the data for each flood event became an immense task for various reasons. Often the Authority had undergone many re-organisations and the whereabouts of data was unknown. Many bridge site drawings were filed in Council Planning offices and because of the effort involved in sieving archive records HRL were asked to pay for the service. Whilst efforts continue in tracking down the amount of material known to be available it was decided to concentrate effort 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 for various flood events are listed in Table 6. Figures 5 to 36 show cross-sections and structural dimensions for each bridge.

Data is still coming in from Water Authorities or Councils but as each flood event is incomplete has as yet not been processed. Often a comprehensive set of water level information was supplied but there were no bridge drawings available. HRL could, at some future time, arrange a survey of these bridges. A number of Authorities have now installed maximum level gauges measuring flood events at either side of specific bridges and as yet have not recorded many events. This programme is on-going and it has been arranged that data be sent to HRL for analysis as it becomes available.

6 ACCURACY OF PROTOTYPE DATA

For a single flow event measurements of water level upstream and downstream of the bridge, river discharge nearby taken at the same time as water levels and bridge dimensions were required for analysis.

Many of the selected bridges were very old and the only known drawings were on microfilm and often distorted. A number of drawings were supplied without reference spot levels, dimensions or scale. These were followed up but often only spot heights on road crossings were the only details available from which to calculate all bridge dimensions. The calculation of blockage ratio requires a digitised measurement from the drawings of the total flow area upstream of a bridge. For accuracy a knowledge of the bed levels at the section where water level measurements were taken is necessary. This information was never available but only a river bed survey taken at the time of the bridge drawing. The bed may have changed dramatically since that time. High water levels, resulting in large afflux ratios, were occasionally above river bank level and across the floodplain. As drawings supplied did not include floodplain details and as the analysis did not cover floodplain flow i.e. total flow was assumed through the bridge arches, the river banks were extended from actual top of bank level to recorded high water level.

Regarding water level measurements, many recorded flow events were historic and spurious water level readings could not be checked as the recorders have long since been removed. In many cases no indication of the position of the water level measurement relative to the bridge was given, nor a time of day which could be related to a discharge recording.

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 value was probably a peak daily flow. In the instances where discharges were obtained separately from Water Resources Departments, peak daily flow values were extracted. Ideally a gauging station should be close to the bridge with no inflow or outflow between the two structures. Ordnance survey charts showed some instances where some inflow was evident between gauging station and bridge but there were no discharge records for the tributaries. At this stage in the analysis flood routing techniques were not applied to more accurately define the appropriate discharge of the bridge. Assistance was given by the Institute of Hydrology in some cases where discharges were suspect and they were able to provide peak daily flow values.

7 PROTOTYPE DATA PROCESSING

The prototype data was processed in the same way as the laboratory measurements (Ref) to formulate into dimensionless hydraulic parameters.

Afflux was defined as the difference between submitted upstream and downstream water levels, at either side of a bridge, regardless of position of measurement relative to the bank or bridge. Location of gaugeboards or water level measurements was invariably unknown and so there can be no comparison directly with laboratory level measurement locations. It can only be assumed that levels were taken at a sufficient distance from the bridge so as not to be influenced by drawdown or local turbulence effects.

Discharge, $Q m^3/s$, as mentioned previously, was usually a peak daily flow. In the calculation of velocity and depth in the downstream Froude number term $F_3 = \frac{V_3}{\sqrt{g d_3}}$ the upstream bed section was carried downstream and assumed representative of bed conditions in the downstream reach. This method was adopted because there was no data available for reaches downstream of the bridges. Downstream flow area, $A_3 m^2$ was digitised from these sections and known downstream water levels. Velocity was thus calculated from $v_3 = \frac{Q}{A_3}$ m/s. Blockage ratio, J = area of bridge below water level/total flow area. The relevant areas were digitised from the structural drawings, which are reproduced in Figures 5 to 36.

8 COMPARISON BETWEEN MODEL AND PROTOTYPE BRIDGE RESULTS

The hydraulic data analysed for all model bridges is listed on Table 7 and presented as a contoured graph of dimensionless parameters $\Delta h/d_3$, F_3 and J_1 on Figure 1. A similar set of data for prototype bridges is given in Table 8 and shown on Figure 37. Both sets of data were also analysed in terms of total head H(m) and results are plotted on Figures 38 and 39.

The standard deviation of ± 0.8% for the data on model multiple arches shows the contours of blockage ratio gives a close fit to the data. A similar analysis has been undertaken for the single arch model bridges, and calculated levels are within ± 3.7% of mesured values, Table 9. Contours are shown on the plot of prototype bridge data where, as expected from the accuracy of the data, there is considerable scatter. Table compares predicted afflux with measured prototype afflux and the resultant standard deviation of the points is ± 12%. Given that the raw prototype data needs to be looked at more closely to minimise errors, the prototype data agrees reasonably well with model predictions.

9 CONCLUSIONS

Limited model tests on a multiple arch bridge with different soffit levels showed behaviour of flow to be very different through each arch separately as compared with the bridge treated as one unit. Using the graphical method to predict afflux as presented in the interim report HRL SR 60 and considering the model bridge in total, predicted afflux agreed well with measured values.

Predicted afflux, considering all test model multiple arched bridges, was within ± 0.8% of the measured values, showing good agreement. A similar analysis for single arch model bridges showed calculated data to be within ± 3.7% of measured.

A massive response to information regarding afflux and associated hydraulic data at bridges throughout England, Wales and Scotland, was received from many Water Authorities. This indicated there were a large number of bridges which caused flooding problems due to substantial afflux. Much of the data associated with these bridges was either not available or yet to be collected so the actual number of bridges analysed was reduced to 66. Prototype data has yet to be refined to eliminate such errors incurred in discharge evaluation, channel cross-sectional estimation upstream and downstream of a bridge in the absence of one or both, floodplain flow, skewed bridges, water level measurement techniques and location, etc.

The predicted afflux at prototype bridges varied between ± 12% of the actual measured value, indicating the graphical method of afflux prediction to be a reasonable iterature procedure to apply to arch bridges.

There was considerable scatter in the data which, whilst indicating possible errors as mentioned above, suggests further research is needed to refine the iterative method of prediction. The effort involved in collecting prototype information severely limited testing of multiple arch model bridges which had been planned. Prototype information already gathered includes skewed bridges, long bridges, multiple arches of different soffit levels, and bridges with various shapes of piers. All these aspects have not been fully tested in the laboratory so whilst results to date have proved promising a design manual cannot be formulated until the predictive method is refined.

10 REFERENCES

1. Afflux at British Bridges, HR Report No SR 60, 1985.

2. United States Bureau of Transport, Public Roads.

TABLES

TABLE 1 : Results of tests on bridges with multiple arches with different soffit levels

Discharge m^3/s	Bed Slope	Upstream depth m	Downstream depth m	Normal depth m
0.0795	0.00031	0.2204	0.1550	0.1595
0.0605	0.0002925	0.1722	0.1369	0.1351
0.0405	0.0002625	0.1261	0.1053	0.1062
0.0210	0.000226	0.0835	0.0729	0.0743

TABLE 2: Hydraulic data - further multiple arch bridge tests

Bridge	u/s depth h_1 m	d/s depth h_3 m	Δh	ΔH	F_3	J_1	J_3	Q m^3/s
Three arches	0.2204	0.1550	0.0654	0.0574	0.455	0.608	0.485	0.0795
	0.1722	0.1369	0.0353	0.0309	0.417	0.519	0.455	0.0605
	0.1261	0.1053	0.0207	0.0180	0.413	0.438	0.404	0.0405
	0.0835	0.0729	0.0106	0.0094	0.372	0.374	0.366	0.0210
Right arch	0.2204	0.1550	0.0654	0.0596	0.387	0.454	0.353	0.0225
	0.1722	0.1369	0.0353	0.0315	0.387	0.365	0.347	0.0187
	0.1261	0.1053	0.0207	0.0186	0.369	0.345	0.344	0.0121
	0.0835	0.0729	0.0106	0.0095	0.359	0.344	0.344	0.0067
Centre arch	0.2204	0.1550	0.0654	0.0579	0.440	0.603	0.435	0.0257
	0.1722	0.1369	0.0353	0.0300	0.461	0.492	0.394	0.0223
	0.1261	0.1053	0.0207	0.0177	0.439	0.378	0.358	0.0144
	0.0835	0.0729	0.0106	0.0093	0.387	0.347	0.345	0.0073
Left arch	0.2204	0.1550	0.0654	0.0541	0.537	0.766	0.668	0.0313
	0.1722	0.1369	0.0353	0.0313	0.401	0.701	0.624	0.0194
	0.1261	0.1053	0.0207	0.0178	0.431	0.591	0.511	0.0141
	0.0835	0.0729	0.0106	0.0094	0.371	0.432	0.408	0.0069

TABLE 3: Comparison between measured and calculated afflux - further multiple arch bridge tests

Bridge	u/s depth (measured)	u/s depth (calculated)	% difference
3 arches	0.220	0.219	0.45
	0.172	0.170	1.16
	0.126	0.123	2.4
	0.083	0.081	2.4
Right arch	0.083	0.080	3.6
	0.126	0.116	7.9
	0.172	0.152	11.6
	0.220	0.181	17.7
Centre arch	0.083	0.081	2.4
	1.126	0 121	4.0
	0.172	0.170	1.2
	0.220	0.214	2.7
Left arch	0.083	0.083	0
	0.126	0.142	-12.7
	0.172	0.203	-18.0
	0.220	0.285	-29.5

TABLE 4: Comparison between calculated and measured afflux - model multiple arch bridges

Test No	u/s depth (measured)	u/s depth (calculated)	% difference
21A	0.0636	0.0620	2.4
21B	0.1073	0.1063	0.9
21C	0.1572	0.1562	0.6
21D	0.2022	0.2014	0.4
21E	0.2449	0.2449	0
22A	0.0743	0.0732	1.5
22B	0.1138	0.1133	0.4
22C	0.1527	0.1517	0.6
22D	0.1995	0.1984	0.5
22E	0.2403	0.2399	0.2
23A	0.0935	0.0929	0.6
23B	0.1402	0.1396	0.4
23C	0.1942	0.1936	0.3
23D	0.2333	0.2328	0.2
24A	0.1021	0.1026	-0.5
24B	0.1484	0.1485	0
24C	0.1863	0.1869	-0.3
24D	0.2218	0.2216	0
24E	0.2494	0.2494	0
25A	0.1117	0.1123	-0.5
25B	0.1439	0.1441	-0.1
25C	0.1768	0.1771	-0.2
25D	0.2143	0.2142	0
25E	0.2453	0.2461	-0.3
26A	0.1308	0.1307	0
26B	0.1719	0.1721	-0.1
26C	0.2115	0.2115	0
26D	0.2413	0.2412	0
27A	0.1558	0.1526	2.0
27B	0.1976	0.1963	0.7
27C	0.2391	0.2377	0.6
28B	0.2325	0.2324	0
29B	0.2270	0.2289	-0.8
1F	0.220	0.219	0.4
2F	0.172	0.170	1.2
3F	0.126	0.123	2.4
4F	0.083	0.081	2.4

Population standard deviatio = ± 0.8%

TABLE 5: SUMMARY OF AVAILABLE DATA FROM BRIDGES WITH HIGH AFFLUX

Yorkshire Water Authority

a = data used in analysis
b = insufficient structural information
c = insufficient discharge data
d = insufficient water level data
e = information available, not yet collected

River	Bridge	Data
Aire	Kildwick	a
	Carleton	c
	Inghey	a
	Silsden	c
Spen	Station Road	a
	Union Street	a
	Rawfolds	a
	St Pegs	a
	Balme Road	a
Wharfe	Pool	a
	Ilkley	a
	Ilkley Old	e
	Bolton	a
	Grassington	a
	Otley	b
	Linton	b
	Thorp 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

SUMMARY OF AVAILABLE DATA FROM BRIDGES WITH HIGH AFFLUX

Welsh Water Authority

River	Bridge	Data
Rhymney	Draethan	b,c,d
	Forge Road	c,d
	Iron Bridge	b,c,d
	Bedwas	c
	Corbets	b,c
	Ystrad Mynach	c
	Twyn Sion Ifan	e
Taff	Ynys (Taffs Well)	b,c,d
	Leiners (Treforest)	b,d
	Tinplate	b,d
	Castle Inn	b,d
	Machine	b,d
	Ynysangharad Park	b,c,d
	Quakers Yard	b,d
Rhondda	Gelli Railway	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 Road	b,d
	Ely Foot	b,d
	St Georges	b,d
	Peterson-s-Ely	b,d
	Pontyclun Railway	d
	U-Pant	b,d
	Pont Lydan	b,d
	Railway Viaduct	b,d
Cadoxton	Dinas Powis	b,c,d
Dee	Farndon	b,d
	Bangor-on-Dee	b,d
Elwy	Pont-y-Gwyddel	e
Alyn	Pont-y-Capel	b,d
Clywedog	Bowling Bank	b,d

SUMMARY OF AVAILABLE DATA FROM BRIDGES WITH HIGH AFFLUX

Severn Trent Authority

River	Bridge	Data
Avon	Dow	a
	Boughton	a
	Avon Mill	a
	Lea Crescent	a
	Bretford	a
	Wolston	a
	Ryton	a
	Bubbenhall	a
	Cloud	a
	Stare	a
	Chesford	b
	Blackdown	b
	Binton	c
Arrow	Washford	c
	Gunnings	a
	Stratford Road	b
	Oversley	a
	Castle Road	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 Road	c
Erewash	Stanton Gate	a

SUMMARY OF AVAILABLE DATA FROM BRIDGES WITH HIGH AFFLUX

Anglian Water Authority

River	Bridge	Data
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

SUMMARY OF AVAILABLE DATA FROM BRIDGES WITH HIGH AFFLUX

Wessex Water Authority

River	Bridge	Data
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 two sites	e
Biss	Cradle	c,d
Congresbury Yeo	Perry, A38	b,d
	A370 Road Bridge	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	Railway	c,d
	Dunball	c,d
Isle	Midelney	b,c,d
	Ilford	b,d
Five Head	Pot	b,c,d
Tone	Creech Road	b,d
	Athelney	b,c,d
Halsewater	Bishops Hill	b,d

SUMMARY OF AVAILABLE DATA FROM BRIDGES WITH HIGH AFFLUX

Tay River Purification Board

River	Bridge	Data
Eden	Cupar	d
Earn	Forteviot	d
Almond	Newton Almond Bank	d d
Tay	Aberfeldy Logierait Perth	d d d
Isla	Crathies	d
Dighty	Mill of Mains	d
Lunan	Inverkeilor	d
S Esk	Brechin	d
N Esk	North Water	d

Water Authority: Forth River Purification Board

River	Bridge	Data
Tyne	A1 Road Bridge Abbey Nungate	d b,d b,d
Allan	Cromlix	b,d

SUMMARY OF AVAILABLE DATA FROM BRIDGES WITH HIGH AFFLUX

North West Water Authority

River	Bridge	Data
Irk	Blackley Road Boothroyden	d b
Mersey	Barfoot Aqueduct	e
Tame	Broomstairs	b
Sankey Brook	Sankey Mill	e
Kent	Nether	d
Leven	Newby	d
Greta	Keswick	b,c,d

SUMMARY OF AVAILABLE DATA FROM BRIDGES WITH HIGH AFFLUX

Southern Water Authority

River	Bridge	Data
Eastern 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
	East Farleigh	b,d
Dudwell	Budwash	b,d
Rother	Withereaden	b,c,d
	Etchingham	b,d
	Udiam	b,d
	Blackwall	b,c
Teise	Stonebridge	b,d
Beult	Stile Bridge	b,d
Great Stour	Wye	b,d
	A28 Road Bridge	b,c
Hexden Channel	Hope Mill	b,c,d

SUMMARY OF AVAILABLE DATA FROM BRIDGES WITH HIGH AFFLUX

Thames Water Authority

River	Bridge	Data
Salmons Brook	Enfield Road Clarendon Arch	b,c,d b,c,d
Hounsden Gutter	Hounsden Road	b,c,d
Rib	Bengeo	b,c,d
Nimney Bourne	Wareside	b,c,d
Roding	Abridge Shonk's Mill Roding Lane	e b b,c,d
Ingrebourne	A13 Road Bridge	c,d
Ching Brook	Beech Hall Road	b,c,d
Nazing Brook	Nazing	b,c,d

E 6: Selected prototype bridge data

Water Authority	River	Bridge	Date	Upstream water level mAD	Downstream water level mAD	Discharge m^3/s	Channel width m	Arch details M = Multiple S = Single
Severn Trent	Avon	Dow bridge	14.03.47	92.660	92.560	19	48.05	M
	Avon	Boughton Road bridge	11.07.68	87.020	86.500	25	30.20	M
	Avon		11.07.68	87.020	86.500	25	27.60	M
	Avon		09.03.75	86.080	85.970	19	28.20	M
	Avon	Lea Crescent bridge	09.03.75	80.910	80.450	56.6	29.10	M
	Avon		30.12.81	80.100	79.990	53	25.30	M
	Avon	Bretford bridge	09.03.75	72.530	72.420	55.9	46.40	M
	Avon		09.03.75	72.530	72.420	55.9	41.90	M
	Avon		30.12.81	72.330	72.200	56.3	44.60	M
	Avon		30.12.81	72.330	72.200	56.3	41.90	M
	Avon	Wolston bridge	11.07.68	70.662	70.586	71.4	30.15	M
	Avon		30.12.81	70.330	70.230	56.3	28.00	M
	Avon	Avon Mill bridge	30.12.81	83.630	83.500	53	18.70	M
	Avon	Ryton bridge	30.12.81	64.230	64.170	56.3	44.50	M
	Avon	Bubenhall bridge	09.03.75	59.100	58.780	55.9	27.50	M
	Avon		30.12.81	59.140	59.030	56.3	27.25	M
	Avon	Cloud bridge	09.03.75	58.490	58.190	55.9	46.00	M
	Avon		30.12.81	58.190	58.150	56.3	44.40	M
	Avon	Stare bridge	30.12.81	56.490	56.420	56.3	66.60	M
	Erewash	Stanton Gate bridge	26.02.77	38.730	38.180	41	17.60	M
	Arrow	Wixford bridge	25.01.60	33.205	32.991	69	38.72	S
	Arrow	Broom bridge	25.01.60	31.288	31.187	69	49.21	M
	Arrow	Salford bridge	25.01.60	28.971	28.502	69	14.85	S
	Arrow	Gunnings bridge	25.01.60	40.718	40.444	69	28.81	M
	Arrow	Oversley bridge	25.01.60	39.368	39.097	69	87.90	M
Wessex	Stour	Blandford bridge	28.12.79	34.150	33.840	204	81.88	M
	Stour		11.03.81	32.398	32.320	95	81.38	M
	Stour		15.12.81	32.460	32.380	98	81.38	M
	Stour		16.03.82	32.690	32.600	114	81.38	M
	Stour	Julians bridge	11.03.81	17.590	17.550	95	90.40	M
	Stour		15.12.81	17.720	17.680	98	90.15	M
	Stour		16.03.82	17.800	17.770	114	90.45	M
	Stour	Canford bridge	11.03.81	16.110	16.050	95	80.90	M
	Stour		15.12.81	16.090	16.050	98	90.90	M
	Stour		16.03.82	16.330	16.300	114	82.85	M
	Stour	Crawford bridge	16.03.82	26.940	26.860	114	80.00	M
Yorkshire	Aire	Kildwick bridge	22.01.75	89.820	89.670	65	48.20	M
	Aire		28.10.80	90.790	90.610	99	69.50	M
	Aire		03.01.82	89.900	89.740	67	56.50	M
	Aire	Inghey bridge	. .46	96.410	95.970	118	165.30	M
	Aire		22.01.75	96.230	95.890	99	164.70	M
	Aire		02.01.76	96.120	95.740	87	164.40	M
	Aire		15.01.74	95.850	95.700	57	21.80	S
	Spen	Station Road bridge	26.04.83	53.430	53.190	17.4	6.50	S
	Spen		01.06.83	53.460	53.200	17.7	6.50	S
	Spen		09.12.83	53.530	53.230	18.2	6.50	S
	Spen	Union Street bridge	26.04.83	55.380	55.220	17.1	6.00	S
	Spen		09.12.83	55.310	55.230	17.5	6.00	S
	Spen	Rawfolds bridge	26.04.83	68.500	67.850	14.7	7.50	S
	Spen		01.06.83	68.270	67.750	13.1	7.50	S
	Spen		09.12.83	68.310	67.850	12.9	7.50	S
	Spen	St Pegs bridge	26.04.83	70.870	70.650	13.4	8.80	S
	Spen		01.06.83	70.590	70.430	10.8	8.03	M
	Spen		09.12.83	70.530	70.430	10.4	7.90	M
	Spen	Balme Road bridge	26.04.83	77.890	77.410	10.7	8.80	M
	Spen		01.06.83	77.520	77.180	8.2	8.80	M
	Spen		09.12.83	77.530	77.140	7.8	8.80	M
	Wharfe	Pool bridge	20.09.46	45.310	44.900	416.4	90.75	M
	Wharfe		16.02.50	45.610	45.300	437.4	93.00	M
	Wharfe		09.12.65	45.660	45.460	405.0	93.00	M
	Wharfe	Ilkley bridge	20.09.46	73.880	73.630	436.4	36.59	S
	Wharfe		16.02.50	74.130	73.820	457.4	36.59	S
	Nidd	Cattal bridge	09.12.65	18.510	18.030	242.5	58.02	M
	Wharfe	Bolton bridge	16.02.50	95.690	95.190	462.4	44.20	M
	Wharfe		09.12.65	95.480	94.930	427.1	43.75	M
	Wharfe	Grassington bridge	09.12.65	166.520	165.810	437.1	66.00	M

TABLE 7

Data from Model Tests

TEST	Q (m^3/s)	d_1 (m)	d_3 (m)	J_1	J_3	F_3	Depth at G9 (m)	MODEL DESCRIPTION
2A	.01	.0747	.0698	.1556	.1506	.5092	.0747	SINGLE ARCH BRIDGE
2B	.01	.0907	.0876	.1748	.1707	.3622	.0890	WIDTH 0.34m
2C	.01	.1227	.1207	.2295	.2254	.2239	.1220	"
2D	.01	.1487	.1468	.3016	.3000	.1669	.1485	"
2E	.01	.1875	.1849	.4456	.4378	.1181	.1885	"
2F	.01	.2136	.2105	.5133	.5062	.0972	.2139	"
3A	.025	.1189	.0845	.2217	.1668	.9557	.1161	"
3B	.025	.1354	.1182	.2598	.2203	.5777	.1334	"
3C	.025	.1571	.1427	.3383	.2809	.4355	.1557	"
3D	.025	.1989	.1807	.4774	.4247	.3056	.1949	"
3E	.025	.2379	.2175	.5630	.5221	.2314	.2381	"
4A	.035	.1625	.1012	.3603	.1901	1.0209	.1599	"
4B	.035	.1713	.1360	.3932	.2614	.6553	.1679	"
4C	.035	.2043	.1698	.4912	.3878	.4697	.2027	"
4D	.035	.2363	.1957	.5601	.4688	.3796	.2351	"
5A	.044	.2311	.0919	.5502	.1765	1.4831	.2293	"
5B	.044	.2348	.1556	.5573	.3319	.6732	.2334	"
6A	.0098	.0767	.0713	.1578	.1521	.4834	.0759	SINGLE ARCH BRIDGE
6B	.0098	.1134	.1107	.2110	.2060	.2498	.1131	LENGTH 0.06m
6C	.0098	.1446	.1424	.2869	.2799	.1712	.1443	"
6D	.0102	.1679	.1656	.3809	.3723	.1421	.1679	"
6E	.0102	.1993	.1961	.4784	.4699	.1103	.1992	"
6F	.0102	.2365	.2328	.5605	.5535	.0853	.2360	"
7A	.0248	.1196	.0867	.2231	.1696	.9122	.1171	"
7B	.0245	.1429	.1311	.2815	.2488	.4847	.1415	"
7C	.0245	.1728	.1613	.3984	.3555	.3551	.1719	"
7D	.0248	.2037	.1884	.4897	.4482	.2847	.2028	"
7E	.025	.2417	.2201	.5699	.5277	.2273	.2411	"
8A	.035	.1643	.1003	.3673	.1887	1.0347	.1608	"
8B	.035	.1683	.1300	.3823	.2462	.7012	.1657	"
8C	.035	.1878	.1586	.4465	.3446	.5203	.1858	"
8D	.035	.2359	.1993	.5593	.4784	.3694	.2349	"
9A	.044	.2288	.0888	.5457	.1723	1.5614	.2269	"
9B	.044	.2352	.1734	.5580	.4005	.5722	.2335	"
10A	.0105	.0795	.0715	.2492	.2415	.4614	.0787	SINGLE ARCH BRIDGE
10B	.0104	.1123	.1083	.2922	.2858	.2452	.1122	WIDTH 0.38m
10C	.0106	.1416	.1380	.3535	.3441	.1737	.1414	"
10D	.0103	.1692	.1655	.4503	.4380	.1285	.1691	"
10E	.01	.1996	.1954	.5340	.5240	.0973	.1995	"
10F	.01	.2318	.2272	.5987	.5906	.0775	.2318	"
11A	.0249	.1282	.0843	.3217	.2542	.8547	.1266	"
11B	.0248	.1375	.1124	.3429	.2924	.5529	.1362	"
11C	.025	.1589	.1398	.4147	.3487	.4018	.1579	"
11D	.0248	.1901	.1688	.5107	.4490	.3004	.1894	"
11E	.0247	.2388	.2115	.6105	.5602	.2134	.2380	"
12A	.035	.1787	.0892	.4795	.2599	1.1038	.1774	"
12B	.035	.1868	.1407	.5021	.3511	.5572	.1852	"
12C	.035	.2165	.1725	.5704	.4608	.4104	.2147	"
12D	.0349	.2481	.1984	.6251	.5312	.3318	.2474	"
13A	.0429	.2376	.0735	.6085	.2434	1.8089	.2363	"

TABLE 7 (Cont'd)

Data from Model Tests

TEST	Q (m^3/s)	d_1 (m)	d_3 (m)	J_1	J_3	F_3	Depth at G9 (m)	MODEL DESCRIPTION
14A	.0110	.0838	.0717	.3835	.3736	.3977	.0837	SINGLE ARCH BRIDGE
14B	.0105	.1039	.0972	.4046	.3969	.2405	.1040	WIDTH 0.46m
14C	.0104	.1304	.1254	.4435	.4349	.1625	.1305	"
14D	.0102	.1576	.1529	.5125	.4975	.1184	.1567	"
14E	.0104	.1847	.1796	.5840	.5722	.0948	.1849	"
14F	.0104	.2192	.2134	.6495	.6399	.0732	.2195	"
14G	.0103	.2447	.2386	.6860	.6780	.0613	.2449	"
15A	.0258	.1402	.0832	.4628	.3830	.7462	.1399	"
15B	.0262	.1439	.1033	.4713	.4039	.5477	.1436	"
15C	.0260	.1621	.1300	.5260	.4428	.3850	.1619	"
15D	.0261	.1889	.1586	.5933	.5155	.2868	.1890	"
15E	.0265	.2115	.1773	.6367	.5666	.2464	.2116	"
15F	.0264	.2362	.1988	.6747	.6135	.2067	.2363	"
15G	.0262	.2483	.2105	.6906	.6350	.1883	.2483	"
16A	.0290	.1529	.0803	.4975	.3805	.8845	.1526	"
16B	.0285	.1537	.1086	.5001	.4104	.5527	.1532	"
16C	.0288	.1713	.1319	.5515	.4463	.4173	.1712	"
16D	.0285	.1936	.1558	.6031	.5068	.3217	.1934	"
16E	.0290	.2203	.1794	.6512	.5717	.2649	.2201	"
16F	.0285	.2482	.2050	.6904	.6252	.2131	.2483	"
17A	.0360	.1936	.0844	.6031	.3841	1.0190	.1960	"
17B	.0355	.1943	.1308	.6046	.4443	.5209	.1939	"
17C	.0352	.2120	.1505	.6376	.4895	.4184	.2118	"
17D	.0350	.2276	.1674	.6624	.5335	.3547	.2275	"
17E	.0347	.2465	.1876	.6883	.5904	.2964	.2465	"
18A	.0385	.2141	.0865	.6411	.3860	1.0504	.2136	"
18C	.0378	.2101	.1334	.6343	.4491	.5385	.2098	"
18D	.0373	.2275	.1550	.6623	.5043	.4242	.2275	"
18E	.0380	.2385	.1656	.6778	.5360	.3914	.2378	"
19A	.0398	.2236	.0903	.6564	.3897	1.0180	.2262	"
19B	.0394	.2229	.1395	.6550	.4613	.5248	.2230	"
19C	.0400	.2467	.1611	.6885	.5231	.4294	.2463	"
20A	.0412	.2392	.0934	.6788	.3928	1.0018	.2385	"
21A	.0038	.0636	.0619	.1448	.1434	.0768	.0622	THREE ARCH BRIDGE
21B	.0029	.1073	.1062	.2001	.1982	.0262	.1060	WIDTH 1.02m
21C	.0028	.1572	.1561	.3387	.3341	.0145	.1558	"
21D	.0029	.2022	.2011	.4859	.4831	.0101	.2009	"
21E	.0029	.2449	.2444	.5755	.5747	.0075	.2421	"
22A	.0099	.0743	.0726	.1552	.1534	.1584	.0722	"
22B	.0099	.1138	.1129	.2117	.2101	.0817	.1126	"
22C	.0100	.1527	.1513	.3192	.3129	.0532	.1515	"
22D	.0102	.1995	.1977	.4789	.4742	.0365	.1976	"
22E	.0100	.2403	.2387	.5674	.5645	.0268	.2388	"
23A	.0254	.0935	.0892	.1787	.1728	.2984	.0915	"
23B	.0256	.1402	.1373	.2733	.2650	.1575	.1388	"
23C	.0253	.1942	.1906	.4647	.4546	.0952	.1929	"
23D	.0257	.2333	.2289	.5544	.5459	.0734	.2313	"
24A	.0347	.1021	.0966	.1915	.1831	.3618	.1005	"
24B	.0343	.1484	.1445	.3004	.2866	.1954	.1468	"

TABLE 7 (Cont'd)

Data from Model Tests

TEST	Q (m^3/s)	d_1 (m)	d_3 (m)	J_1	J_3	F_3	Depth at G9 (m)	MODEL DESCRIPTION
24C	.0350	.1863	.1813	.4420	.4266	.1419	.1848	"
24D	.0340	.2218	.2152	.5313	.5170	.1066	.2199	"
24E	.0358	.2494	.2417	.5832	.5699	.0943	.2866	"
25A	.0445	.1117	.1036	.2079	.1939	.4177	.1097	"
25B	.0442	.1439	.1378	.2847	.2664	.2705	.1422	"
25C	.0443	.1768	.1695	.4120	.3867	.1987	.1753	"
25D	.0441	.2143	.2048	.5149	.4924	.1489	.2127	"
25E	.0441	.2453	.2344	.5762	.5565	.1216	.2438	"
26A	.0611	.1308	.1167	.2481	.2173	.4797	.1279	"
26B	.0612	.1719	.1586	.3953	.3446	.3033	.1695	"
26C	.0617	.2115	.1933	.5085	.4622	.2272	.2094	"
26D	.0608	.2413	.2211	.5692	.5298	.1830	.2394	"
27A	.0800	.1558	.1288	.3328	.2433	.5417	.1530	"
27B	.0795	.1976	.1704	.4739	.3900	.3538	.1953	"
27C	.0792	.2391	.2053	.5652	.4937	.2665	.2368	"
28A	.0930	.1741	.1360	.4029	.2614	.5804	.1714	"
28B	.0900	.2325	.1932	.5529	.4619	.3317	.2301	"
29A	.1100	.2199	.1407	.5273	.2747	.6524	.2169	"
29B	.1100	.2270	.1721	.5421	.3960	.4823	.2248	"

TABLE 8: Hydraulic Data from Prototype Bridges

No	h_1 mAD u/s	h_3 mAD d/s	dh m AF	dH	Q m^3/s	J_1	F_3	dh/d2	dH/d2
1	92.660	92.560	0.100	0.104	19	0.440	0.080	0.074	0.076
2	87.020	86.500	0.520	0.524	25	0.547	0.073	0.221	0.223
3	87.020	86.500	0.520	0.524	25	0.532	0.072	0.206	0.208
4	86.080	85.970	0.110	0.116	19	0.309	0.082	0.058	0.061
5	80.910	80.450	0.460	0.503	56.6	0.291	0.290	0.277	0.303
6	80.100	79.990	0.110	0.201	53	0.190	0.379	0.075	0.137
7	72.530	72.420	0.110	0.130	55.9	0.563	0.156	0.060	0.071
8	72.530	72.420	0.110	0.131	55.9	0.550	0.153	0.056	0.066
9	72.330	72.200	0.030	0.059	56.3	0.504	0.194	0.018	0.037
10	72.330	72.200	0.030	0.060	56.3	0.496	0.192	0.018	0.035
11	70.662	70.586	0.076	0.134	71.4	0.391	0.240	0.035	0.062
12	70.330	70.230	0.100	0.149	56.3	0.345	0.237	0.052	0.077
13	83.630	83.500	0.130	0.211	53	0.367	0.294	0.061	0.100
14	64.230	64.170	0.060	0.073	56.3	0.326	0.109	0.025	0.031
15	59.110	58.780	0.330	0.378	55.9	0.247	0.276	0.187	0.214
16	59.140	59.030	0.110	0.161	56.3	0.243	0.240	0.056	0.082
17	58.490	58.190	0.300	0.309	55.9	0.435	0.097	0.119	0.123
18	58.190	58.150	0.040	0.052	56.3	0.360	0.098	0.015	0.020
19	56.490	56.420	0.070	0.081	56.3	0.539	0.116	0.040	0.046
20	38.730	38.180	0.550	0.624	41	0.524	0.460	0.399	0.453
21	33.205	32.991	0.214	0.233	69	0.288	0.129	0.079	0.086
22	31.288	31.187	0.101	0.133	69	0.055	0.210	0.061	0.080
23	28.971	28.502	0.469	0.556	69	0.082	0.274	0.152	0.180
24	40.718	40.444	0.274	0.315	69	0.471	0.209	0.115	0.133
25	39.368	39.097	0.271	0.276	69	0.645	0.072	0.118	0.120
26	34.150	33.840	0.310	0.320	204	0.670	0.067	0.060	0.062
27	32.398	32.320	0.098	0.112	95	0.528	0.120	0.046	0.052
28	32.460	32.380	0.080	0.093	98	0.514	0.110	0.035	0.040
29	32.690	32.600	0.090	0.104	114	0.532	0.106	0.034	0.040
30	17.590	17.550	0.040	0.076	95	0.355	0.250	0.033	0.062
31	17.720	17.680	0.040	0.069	98	0.371	0.212	0.029	0.050
32	17.800	17.770	0.030	0.065	114	0.381	0.220	0.020	0.043
33	16.110	16.050	0.060	0.079	95	0.264	0.145	0.032	0.042
34	16.090	16.050	0.040	0.060	98	0.264	0.157	0.024	0.035
35	16.330	16.300	0.030	0.049	114	0.283	0.131	0.013	0.022
36	26.940	26.860	0.080	0.136	114	0.372	0.317	0.063	0.107
37	89.820	89.670	0.150	0.185	65	0.326	0.239	0.101	0.125
38	90.790	90.610	0.180	0.206	99	0.488	0.188	0.100	0.115
39	89.900	89.740	0.160	0.193	67	0.337	0.252	0.122	0.147
40	98.410	95.970	0.440	0.457	118	0.552	0.317	0.548	0.569
41	96.230	95.890	0.340	0.355	99	0.522	0.288	0.446	0.466
42	96.120	95.740	0.380	0.395	87	0.490	0.358	0.627	0.651
43	95.850	95.700	0.150	0.241	57	0.185	0.345	0.083	0.134
44	53.430	53.190	0.240	0.369	17.4	0.426	0.492	0.166	0.255
45	53.460	53.200	0.260	0.383	17.7	0.448	0.477	0.174	0.257
46	53.530	53.230	0.300	0.418	18.2	0.474	0.468	0.195	0.271
47	55.380	55.220	0.160	0.325	17.1	0.099	0.536	0.112	0.228
48	55.310	55.230	0.080	0.265	17.5	0.067	0.534	0.055	0.183
49	68.500	67.850	0.650	0.706	14.7	0.355	0.467	0.534	0.581

TABLE 8 (CONT'D)

No	h_1 mAD	h_3 mAD	dh m	dH	Q m^3/s	J_1	F_3	dh/d2	dH/d2
50	68.270	67.750	0.520	0.582	13.1	0.242	0.505	0.487	0.545
51	68.310	67.850	0.460	0.514	12.9	0.277	0.415	0.382	0.427
52	70.870	70.650	0.220	0.265	13.4	0.384	0.293	0.157	0.189
53	70.590	70.430	0.160	0.201	10.8	0.320	0.279	0.120	0.151
54	70.530	70.430	0.100	0.141	10.4	0.311	0.263	0.732	0.103
55	77.890	77.410	0.480	0.503	10.7	0.515	0.258	0.365	0.383
56	77.520	77.180	0.340	0.361	8.2	0.406	0.249	0.302	0.320
57	77.530	77.140	0.390	0.409	7.8	0.406	0 254	0.362	0.380
58	45.310	44.900	0.410	0.520	416.4	0.268	0.327	0.151	0.191
59	45.610	45.300	0.310	0.410	437.4	0.294	0.284	0.102	0.135
60	45.660	45.460	0.200	0.286	405.0	0.294	0.249	0.064	0.091
61	73.880	73.630	0.250	0.479	436.4	0.158	0.306	0.047	0.089
62	74.130	73.820	0.310	0.555	457.4	0.165	0.319	0.058	0.103
63	18.510	18.030	0.480	0.548	242.5	0.389	0.240	0.153	0.174
64	95.690	95.190	0.500	1.109	462.4	0.157	0.832	0.198	0.439
65	95.480	94.930	0.550	1.171	427.1	0.141	0.925	0.245	0.521
66	166.520	165.810	0.710	1.199	437.1	0.350	1.241	0.498	0.841

TABLE 9: Comparison between measured and calculated afflux - single arch model bridges

Test No	u/s depth (measured)	u/s depth (calculated)	% difference
2A	0.0747	0.0768	-2.8
2B	0.0907	0.911	-0.4
2C	0.1227	0.1231	-0.3
2D	0.1487	0.1490	-0.2
2E	0.1875	0.1886	-0.6
2F	0.2136	0.2141	-0.2
3A	0.1189	0.1174	1.2
3B	0.1354	0.1377	-1.7
3C	0.1571	0.1605	-2.2
3D	0.1989	0.2015	-1.3
3E	0.2379	0.2442	-2.6
4A	0.1625	0.1629	-0.2
4B	0.1713	0.1795	-4.8
4C	0.2043	0.2097	-2.6
4D	0.2363	0.2446	-3.5
5A	0.2311	0.2688	-16.3
5B	0.2348	0.2451	-4.4
6A	0.0767	0.0777	-1.3
6B	0.1134	0.1135	0
6C	0.1446	0.1445	0
6D	0.0102	0.1680	0
6E	0.1993	0.2000	-0.3
6F	0.0102	0.2379	-2.2
7A	0.0248	0.1174	1.7
7B	0.1429	0.1468	-2.2
7C	0.1728	0.1863	-7.8
7D	0.2037	0.2091	-2.6
7E	0.2417	0.2483	-2.7
8A	0.1643	0.1654	-0.7
8B	0.1683	0.1748	-3.9
8C	0.1878	0.1990	-5.9
8D	0.2359	0.2471	-4.7
9A	0.2288	0.1072	53.1
9B	0.2352	0.2566	-9.0
10A	0.795	0.0790	0.6
10B	0.1123	0.1120	0.3
10C	0.1416	0.1120	0.3
10D	0.1692	0.1696	-0.2
10E	0.1996	0.2002	-0.3
10F	0.2318	0.2317	0

TABLE 9 (CONT'D)

Test No	u/s depth (measured)	u/s depth (calculated)	% difference
11A	0.1282	0.1180	7.9
11B	0.1375	0.1343	2.3
11C	0.1589	0.1600	-0.7
11D	0.1901	0.1924	-1.2
11E	0.2388	0.1435	+4.0
12A	0.1787	0.1780	0.4
12B	0.1868	0.1868	0
12C	0.2165	0.2216	-2.3
12D	0.2481	0.2510	-1.2
13A	0.2376	0.2609	-9.8
14A	0.0838	0.0806	3.3
14B	0.1039	0.1025	1.3
14C	0.1304	0.1297	0.5
14D	0.1576	0.1636	-3.8
14E	0.1847	0.1844	0.2
14F	0.2192	0.2208	-3.5
14G	0.2447	0.2471	-0.9
15A	0.1402	0.1243	11.3
15B	0.1439	0.1338	7.0
15C	0.1621	0.1570	3.1
15D	0.1889	0.1863	1.4
15E	0.2115	0.2120	-0.2
15F	0.2362	0.2345	0.7
15G	0.2483	0.2462	0.8
16A	0.1529	0.1389	9.1
16B	0.1537	0.1433	6.8
16C	0.1713	0.1688	1.4
16D	0.1936	0.1939	-0.1
16E	0.2203	0.2179	1.1
16F	0.2482	0.2439	1.7
17A	0.1936	0.1932	0.2
17B	0.1943	0.1944	0
17C	0.2120	0.2122	0
17D	0.2276	0.2251	1.1
17E	0.2465	0.2466	0
18A	0.2141	0.2162	10.9
18C	0.2101	0.2101	0
18D	0.2275	0.2228	2.1
18E	0.2385	0.2359	1.1
19A	0.2236	0.2221	0.7
19B	0.2229	0.2197	1.4
19C	0.2467	0.2440	1.1
20A	0.2392	0.2391	0

Population standard deviation = ± 3.7%

TABLE 10: Comparison between calculated and measured afflux Prototype Bridges

No	u/s water level m AD	d/s water level m AD	$\Delta h/d_3$ (proto)	$\Delta h/d_3$ (graph)	u/s depth (graph) m	u/s depth (proto)	c/o difference
1	92.660	92.560	0.100	0.019	1.3852	1.4594	5.0
2	87.020	86.500	0.520	0.047	2.4609	2.8705	14.3
3	87.020	86.500	0.520	0.050	2.6485	3.0424	12.9
4	86.080	85.970	0.110	0.023	1.9488	2.0150	3.3
5	80.910	80.450	0.460	0.088	1.8075	2.1213	14.8
6	80.100	79.990	0.110	0.079	1.5754	1.5701	-0.3
7	72.530	72.420	0.110	0.124	2.0519	1.9355	-6.0
8	72.530	72.420	0.110	0.130	2.2314	2.0847	-7.0
9	72.330	72.200	0.030	0.117	1.8200	1.6594	-9.7
10	72.330	72.200	0.030	0.116	1.9065	1.7383	-9.7
11	70.662	70.586	0.076	0.124	2.4122	2.2221	-8.5
12	70.330	70.230	0.100	0.093	2.1216	2.0411	-3.9
13	83.630	83.500	0.130	0.153	2.4423	2.2483	-8.6
14	64.230	64.170	0.060	0.034	2.4783	2.4568	-0.8
15	59.110	58.780	0.330	0.071	1.8942	2.0986	9.7
16	59.140	59.030	0.110	0.063	2.085	2.0716	-0.6
17	58.490	58.190	0.300	0.045	2.6393	2.8258	6.6
18	58.190	58.150	0.040	0.036	2.6760	2.6231	-2.0
19	56.490	56.420	0.070	0.070	1.8796	1.8266	-2.9
20	38.730	38.180	0.550	0.394	1.9212	1.9282	0.4
21	33.205	32.991	0.214	0.043	2.8118	2.9099	3.4
22	31.288	31.187	0.101	0.010	1.6755	1.7599	4.8
23	28.971	28.502	0.469	0.074	3.3099	3.5509	6.8
24	40.718	40.444	0.274	0.276	3.0344	2.6521	-14.4
25	39.368	39.097	0.271	0.088	2.5055	2.5739	2.6
26	34.150	33.840	0.310	0.219	6.3485	5.5180	-15.0
27	32.398	32.320	0.098	0.090	2.3256	2.2316	-4.2
28	32.460	32.380	0.080	0.083	2.4940	2.3829	-4.7
29	32.690	32.600	0.090	0.090	2.8513	2.7059	-5.4
30	17.590	17.550	0.040	0.066	1.2962	1.2560	-3.2
31	17.720	17.680	0.040	0.097	1.5239	1.4292	-6.6
32	17.800	17.770	0.030	0.117	1.6691	1.5243	-9.5
33	16.110	16.050	0.060	0.030	1.9389	1.9424	0.2
34	16.090	16.050	0.040	0.034	1.7461	1.7287	-1.0
35	16.330	16.300	0.030	0.036	2.3170	2.2665	-2.2
36	26.940	26.860	0.080	0.107	1.4086	1.3525	-4.1
37	89.820	89.670	0.150	0.068	1.5809	1.6303	3.0
38	90.790	90.610	0.180	0.115	2.0063	1.9794	-1.3
39	89.900	89.740	0.160	0.042	1.3659	1.4709	7.1
40	98.410	95.970	0.440	0.151	0.9233	1.2422	25.7
41	96.230	95.890	0.340	0.108	0.8443	1.1020	23.4
42	96.120	95.740	0.380	0.101	0.6673	0.9861	32.3
43	95.850	95.700	0.150	0.076	1.9408	1.9537	0.6
44	53.430	53.190	0.240	0.315	1.8999	1.6848	-12.8
45	53.460	53.200	0.260	0.331	1.9869	1.7528	-13.3
46	53.530	53.230	0.300	0.360	2.0951	1.8405	-13.8
47	55.380	55.220	0.160	0.088	1.5484	1.5832	-0.5
48	55.310	55.230	0.080	0.061	1.4471	1.8861	23.3
49	68.500	67.850	0.650	0.190	1.2122	1.5880	23.7

TABLE 10 (CONT'D)

No	u/s water level m AD	d/s water level m AD	$\Delta h/d_3$ (proto)	$\Delta h/d_3$ (graph)	u/s depth (graph) m	u/s depth (proto)	c/o difference
50	68.270	67.750	0.520	0.135	1.2122	1.5880	23.7
51	68.310	67.850	0.460	0.113	1.3414	1.6652	19.4
52	70.870	70.650	0.220	0.109	1.5553	1.6224	4.1
53	70.590	70.430	0.160	0.075	1.4321	1.4923	4.0
54	70.530	70.430	0.100	0.068	1.4581	1.4653	0.5
55	77.890	77.410	0.480	0.155	1.5172	1.7936	15.4
56	77.520	77.180	0.340	0.074	1.2093	1.4660	17.5
57	77.530	77.140	0.390	0.073	1.1545	1.4660	21.2
58	45.310	44.900	0.410	0.163	3.1621	3.1289	-1.0
59	45.610	45.300	0.310	0.237	3.7579	3.3479	-12.2
60	45.660	45.460	0.200	0.132	3.5634	3.3479	-6.4
61	73.880	73.630	0.250	0.161	6.2390	5.6239	-10.9
62	74.130	73.820	0.310	0.172	6.3151	5.6984	-10.8
63	18.510	18.030	0.480	0.182	3.7115	3.6208	-2.5
64	95.690	95.190	0.500	0.581	3.9941	3.0263	-32.0
65	95.480	94.930	0.550	0.557	3.4996	2.7977	-25.1
66	166.520	165.810	0.710	-	-	-	-

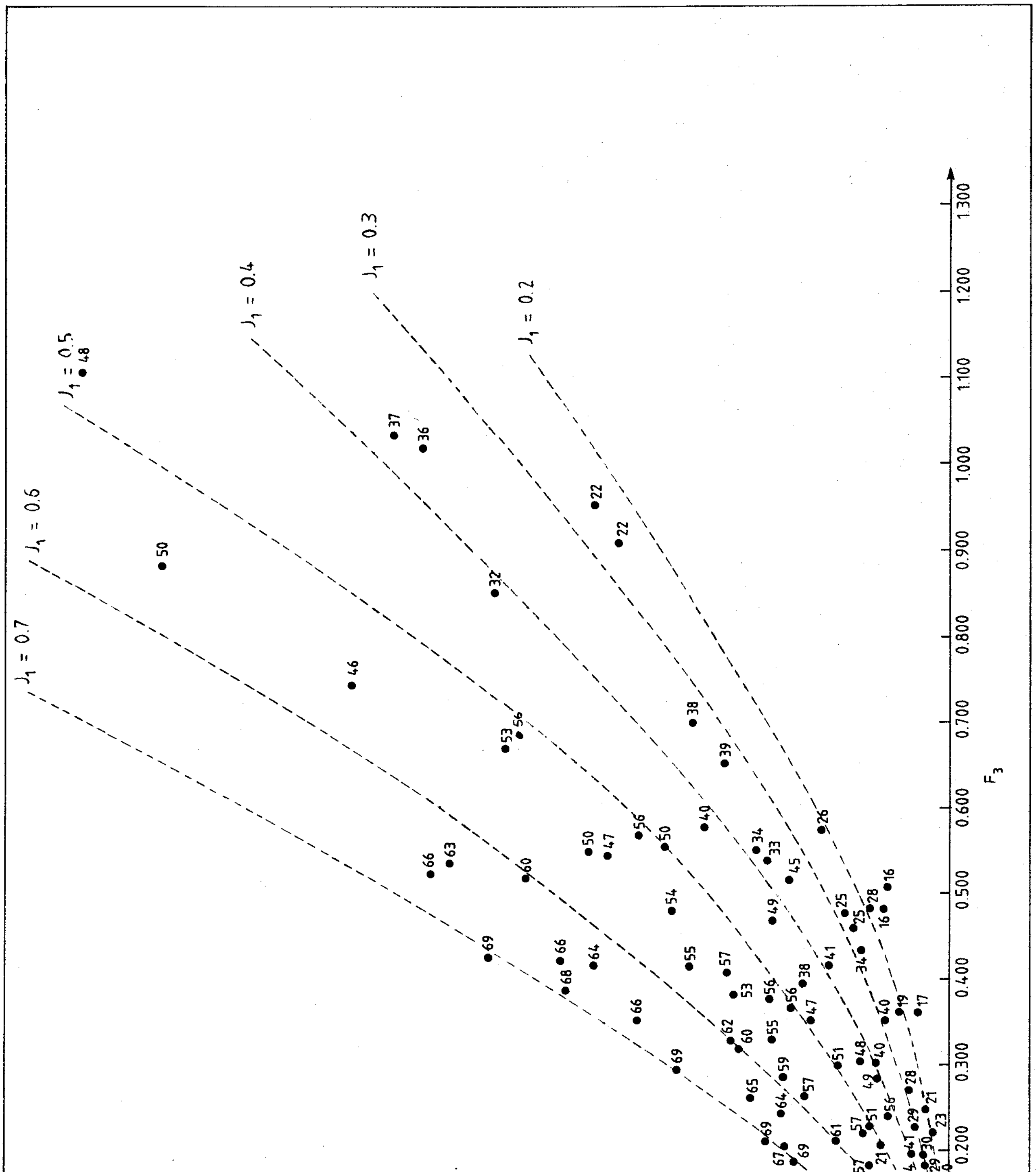


Fig 1 Plot of $\Delta h/d_3$ v F_3 and J_1, laboratory tests

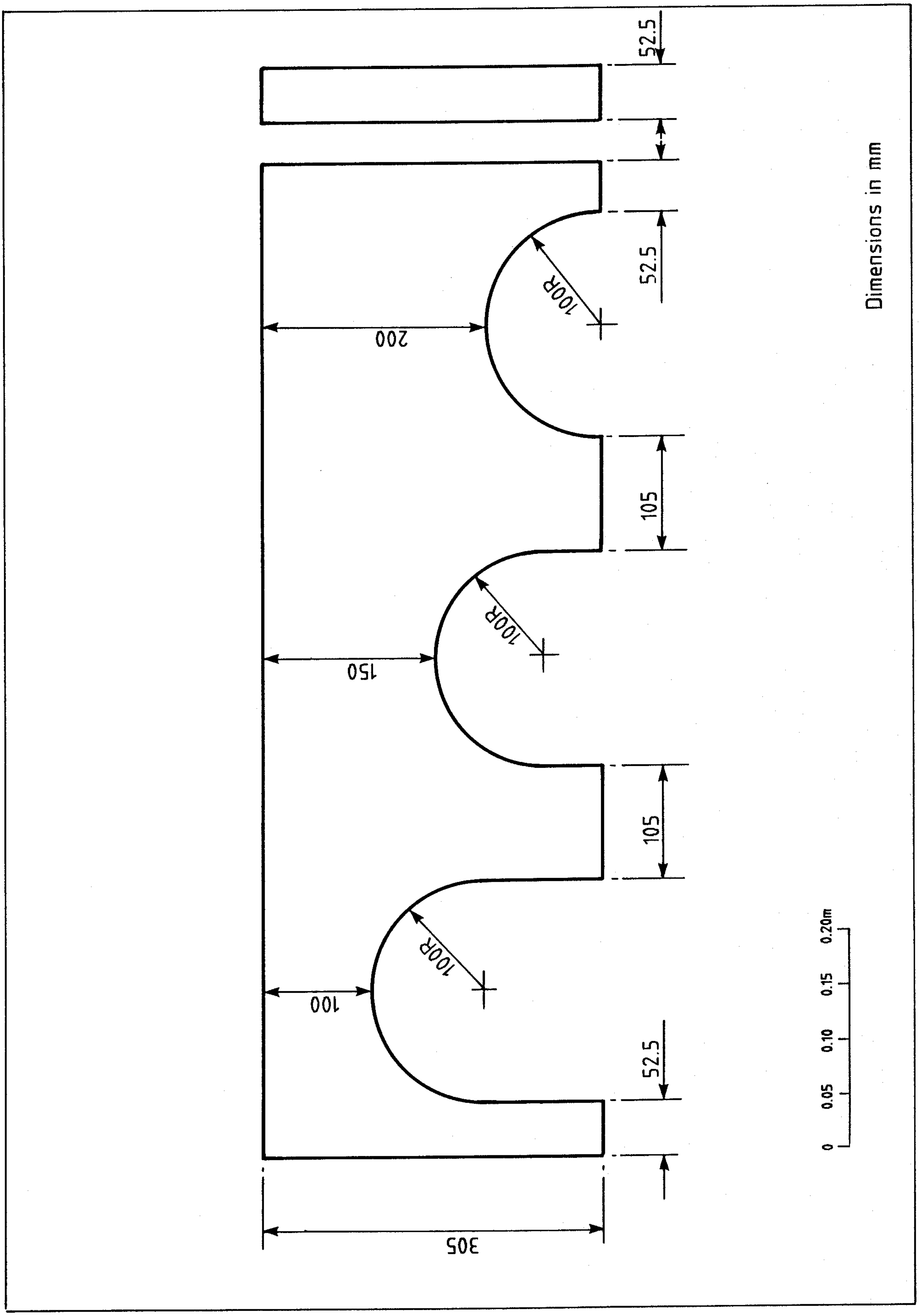


Fig 2 Section of multiple arch bridge tested in laboratory

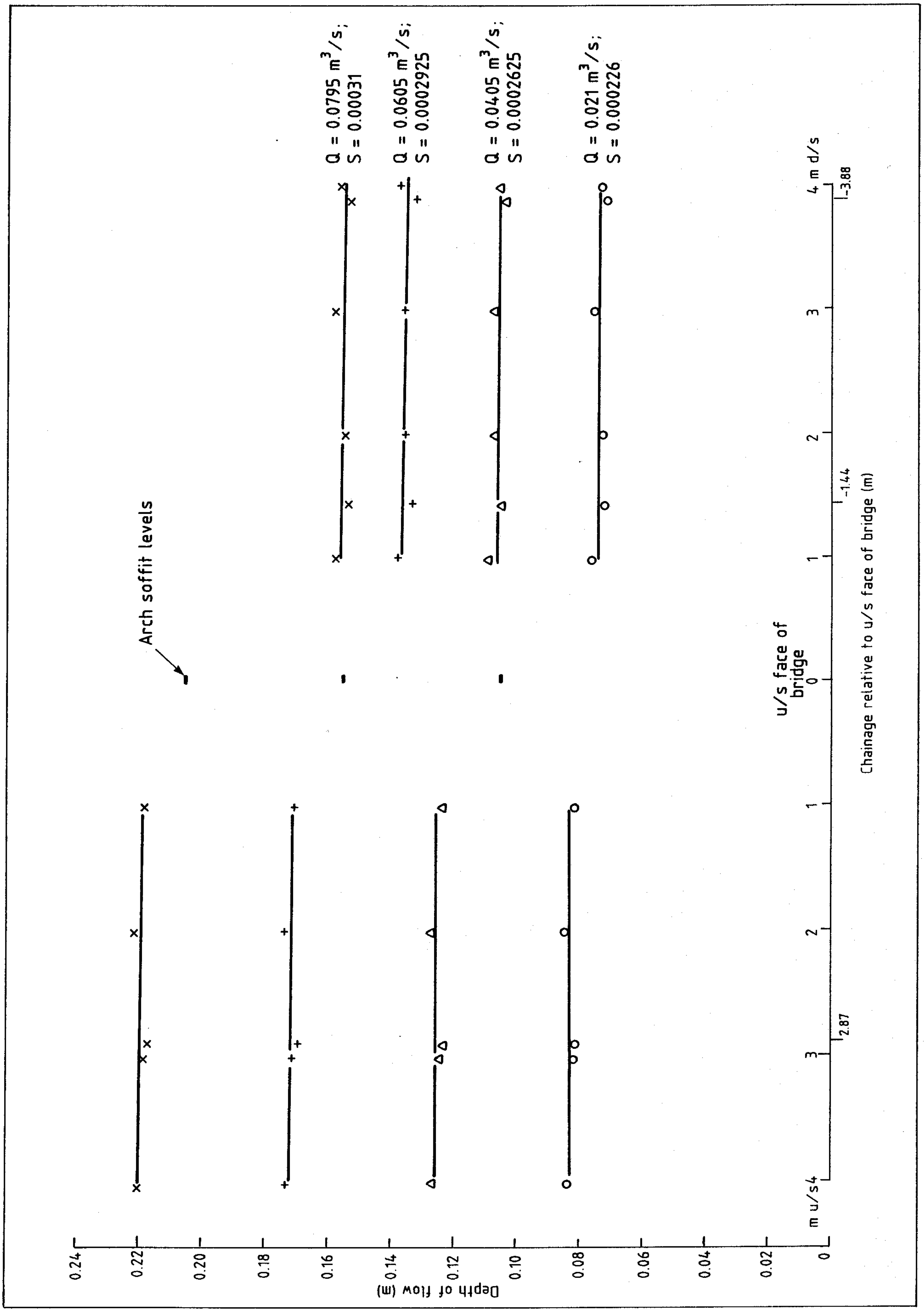


Fig 3 Water surface profiles, multiple arch bridge with different soffit levels

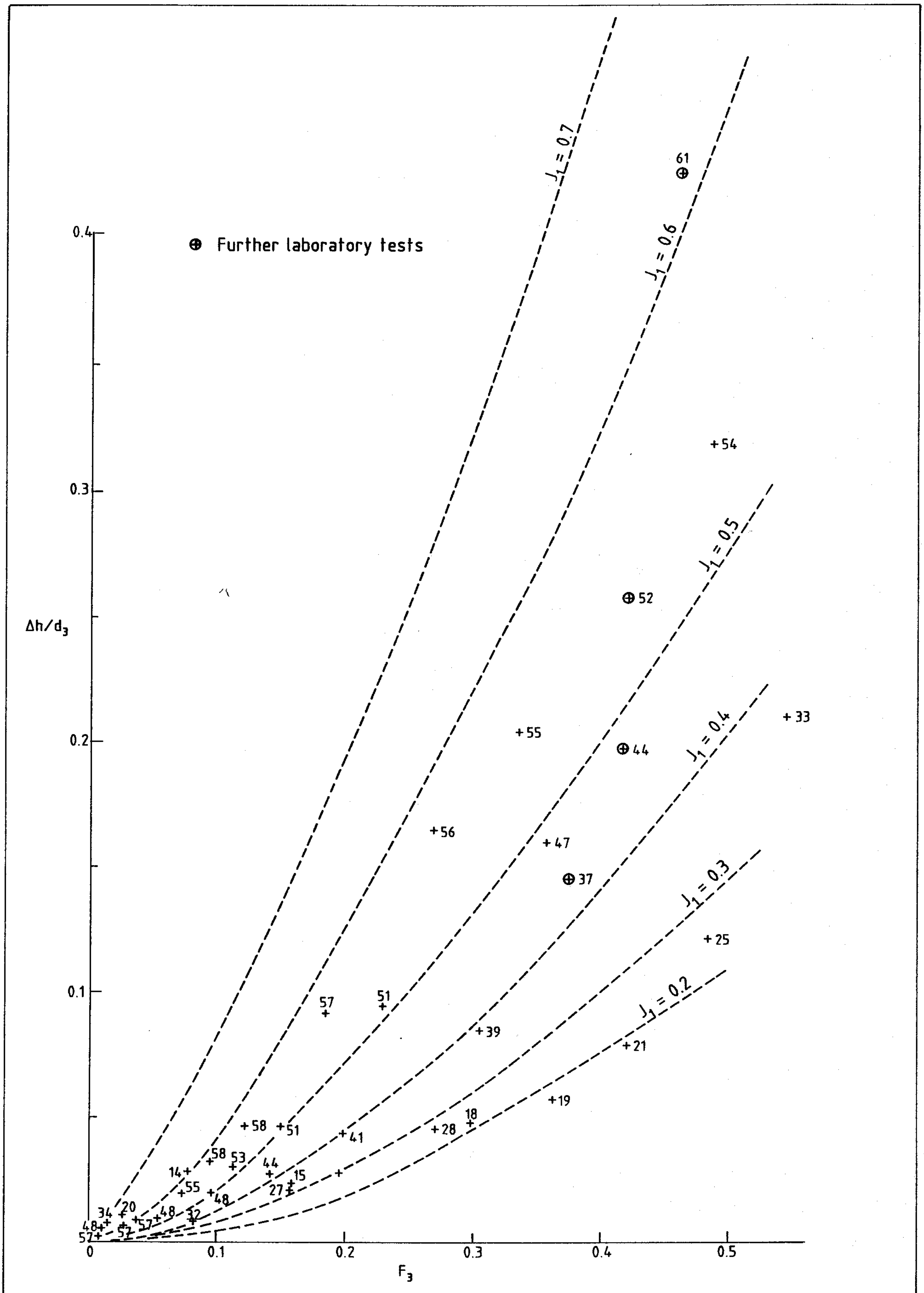


Fig 4 Mulitiple arch bridges - combined laboratory tests

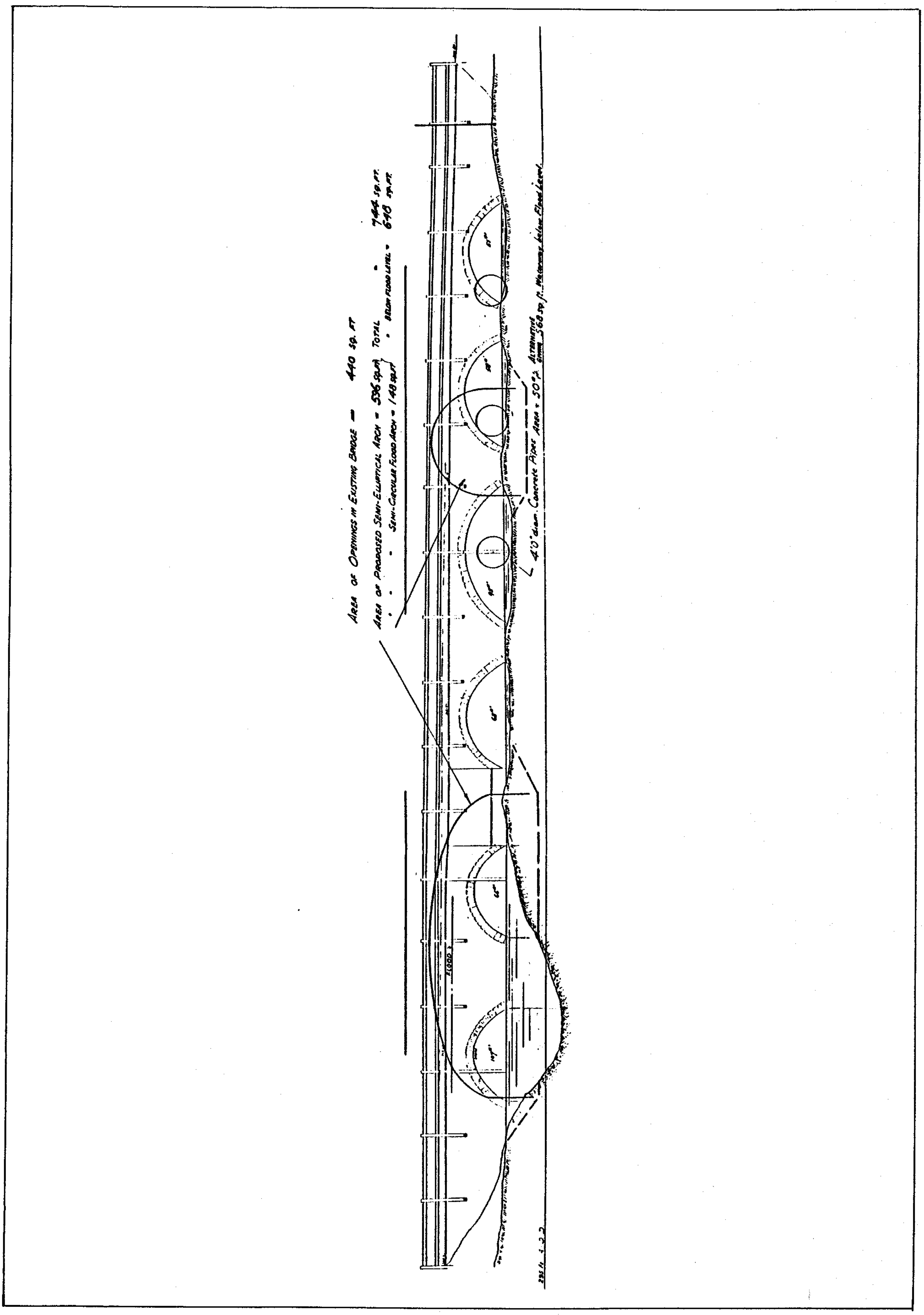


Fig 5 Dow Bridge, River Avon, Severn-Trent Water Authority

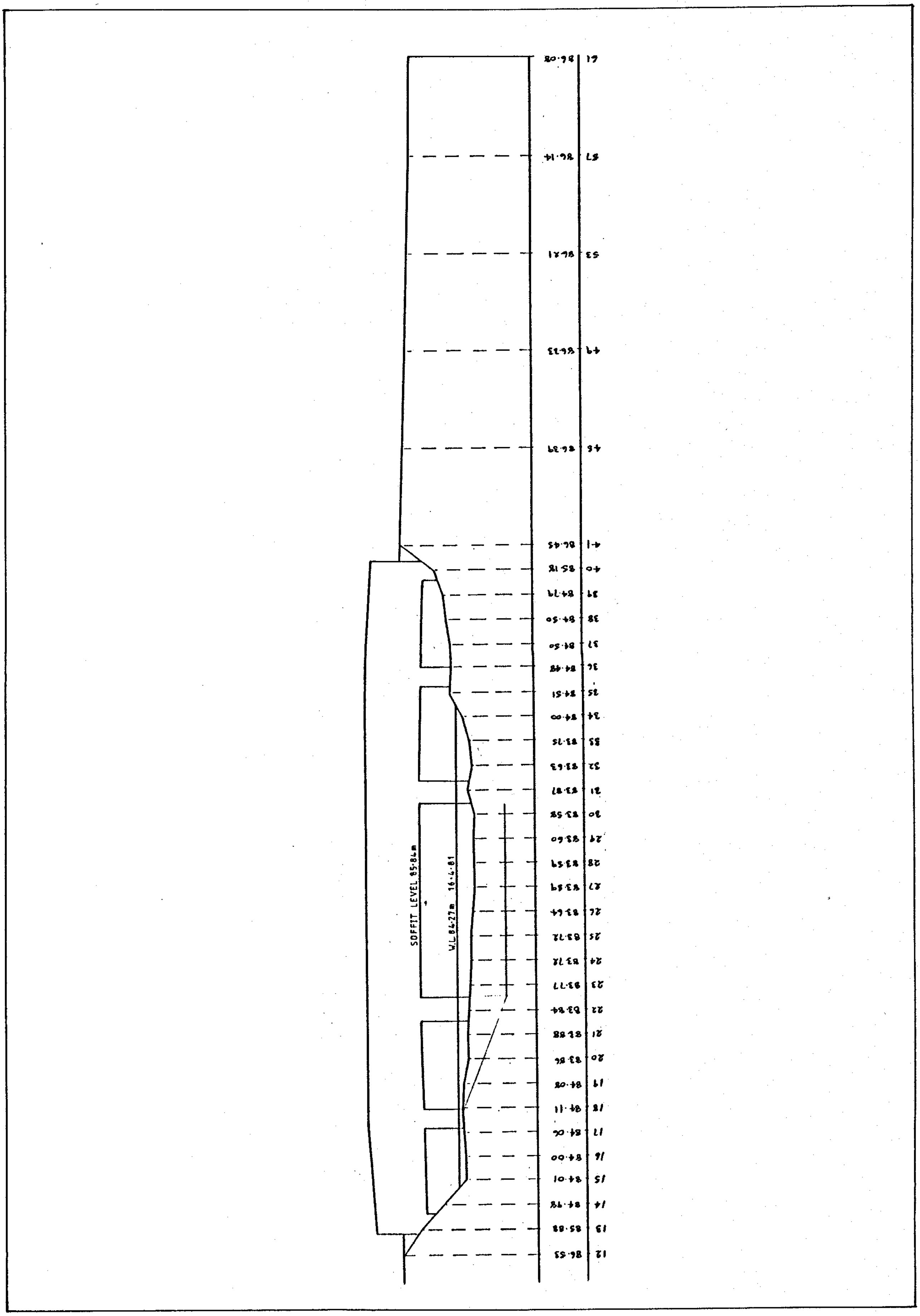


Fig 6 Boughton Road Bridge, River Avon,
Severn-Trent Water Authority

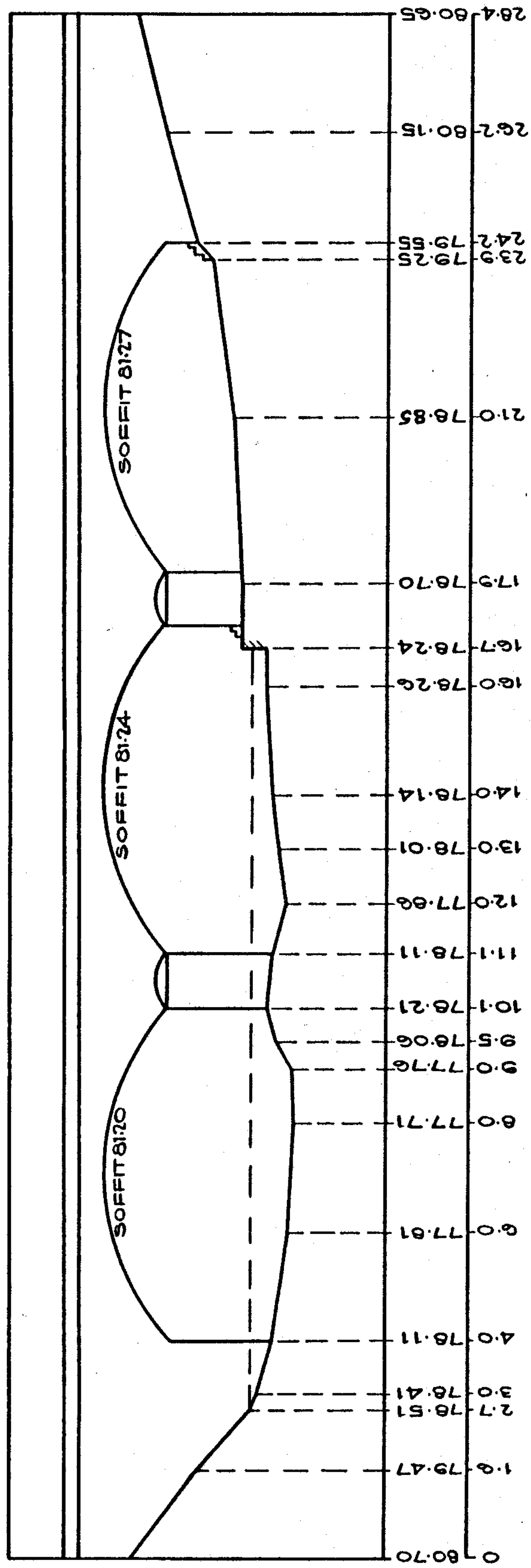


Fig 7 Lea Crescent Bridge, River Avon, Severn-Trent Water Authority

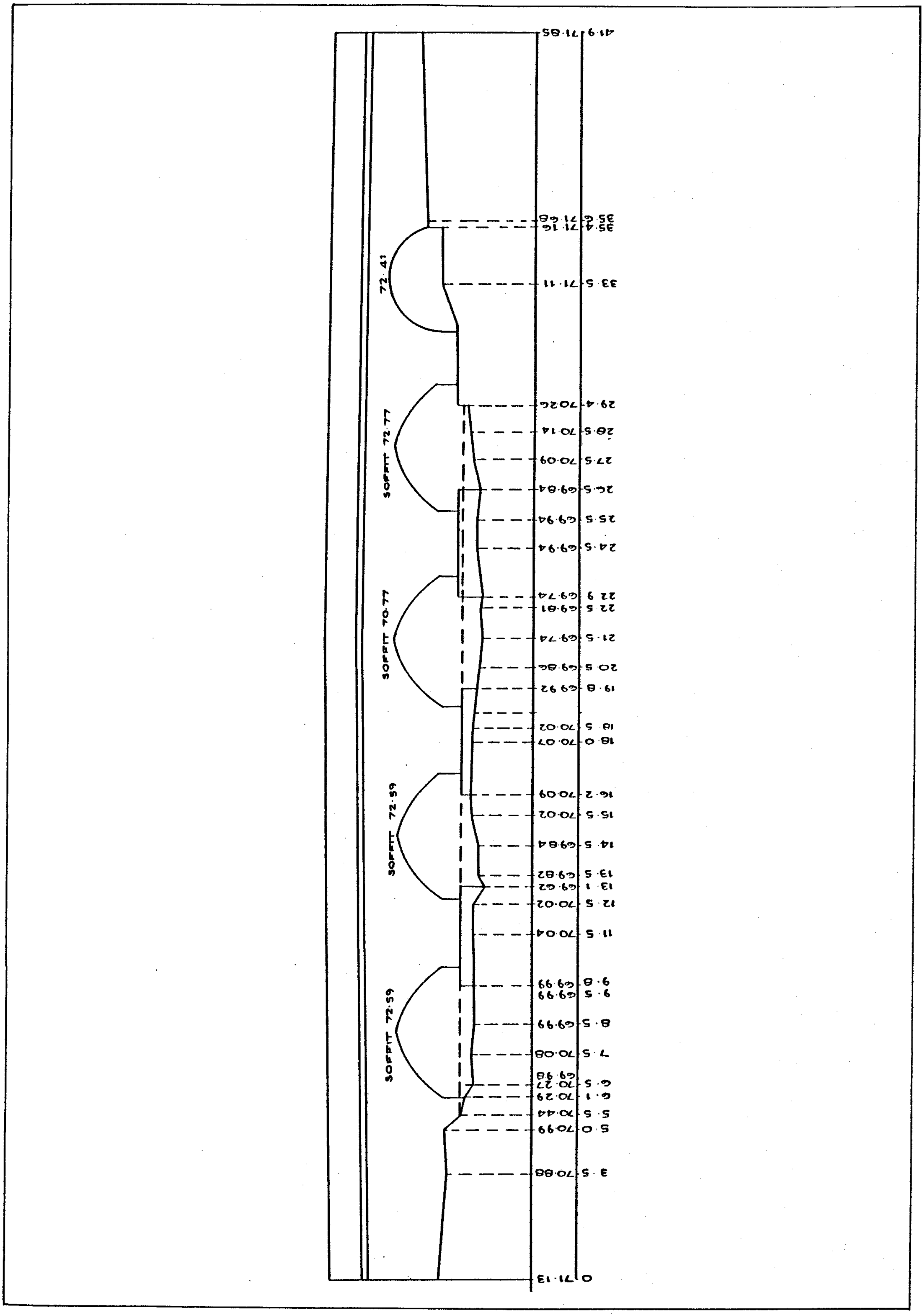


Fig 8 Bretford Bridge, River Avon, Severn-Trent Water Authority

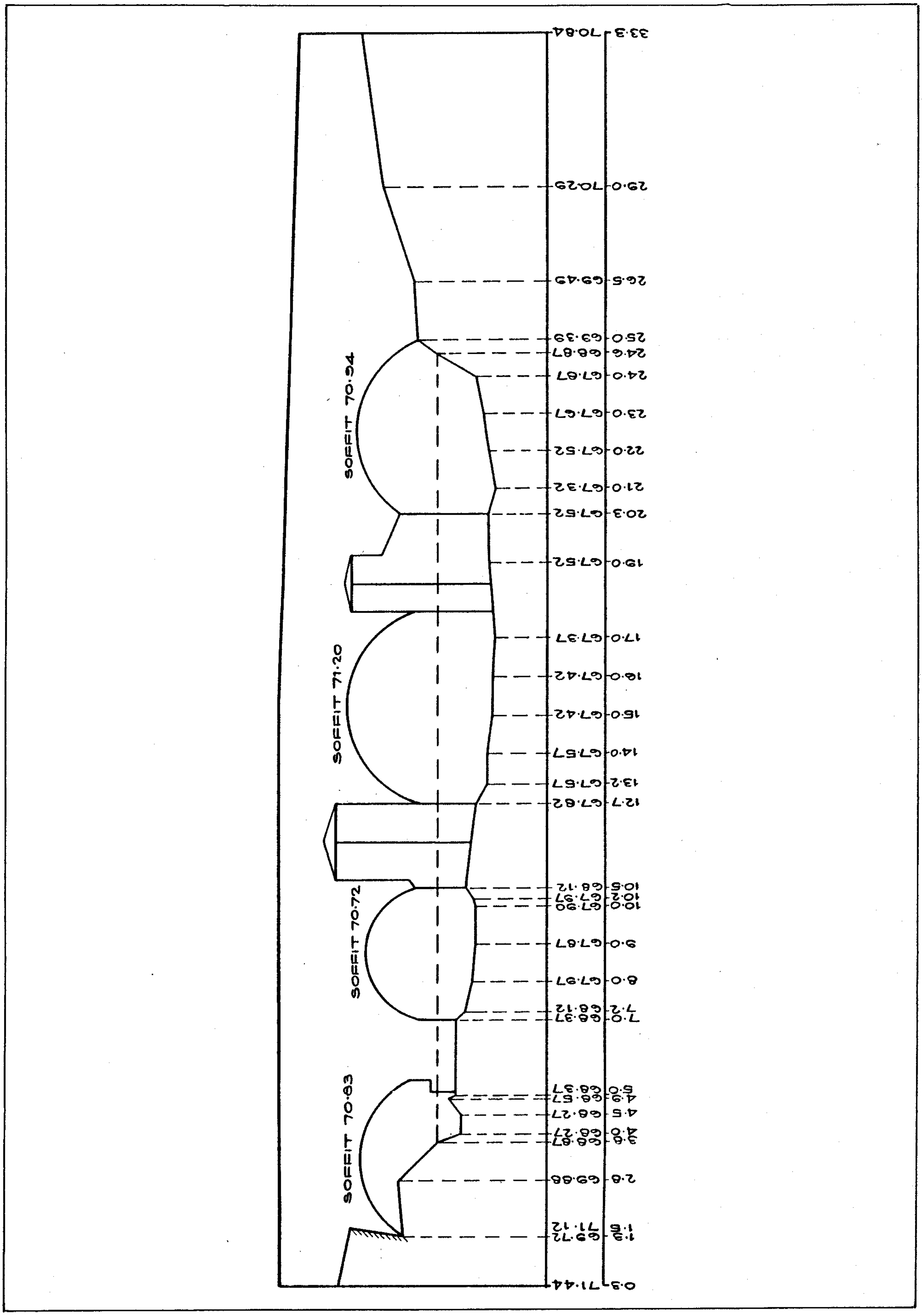


Fig 9 Wolston Bridge, River Avon,
Severn-Trent Water Authority

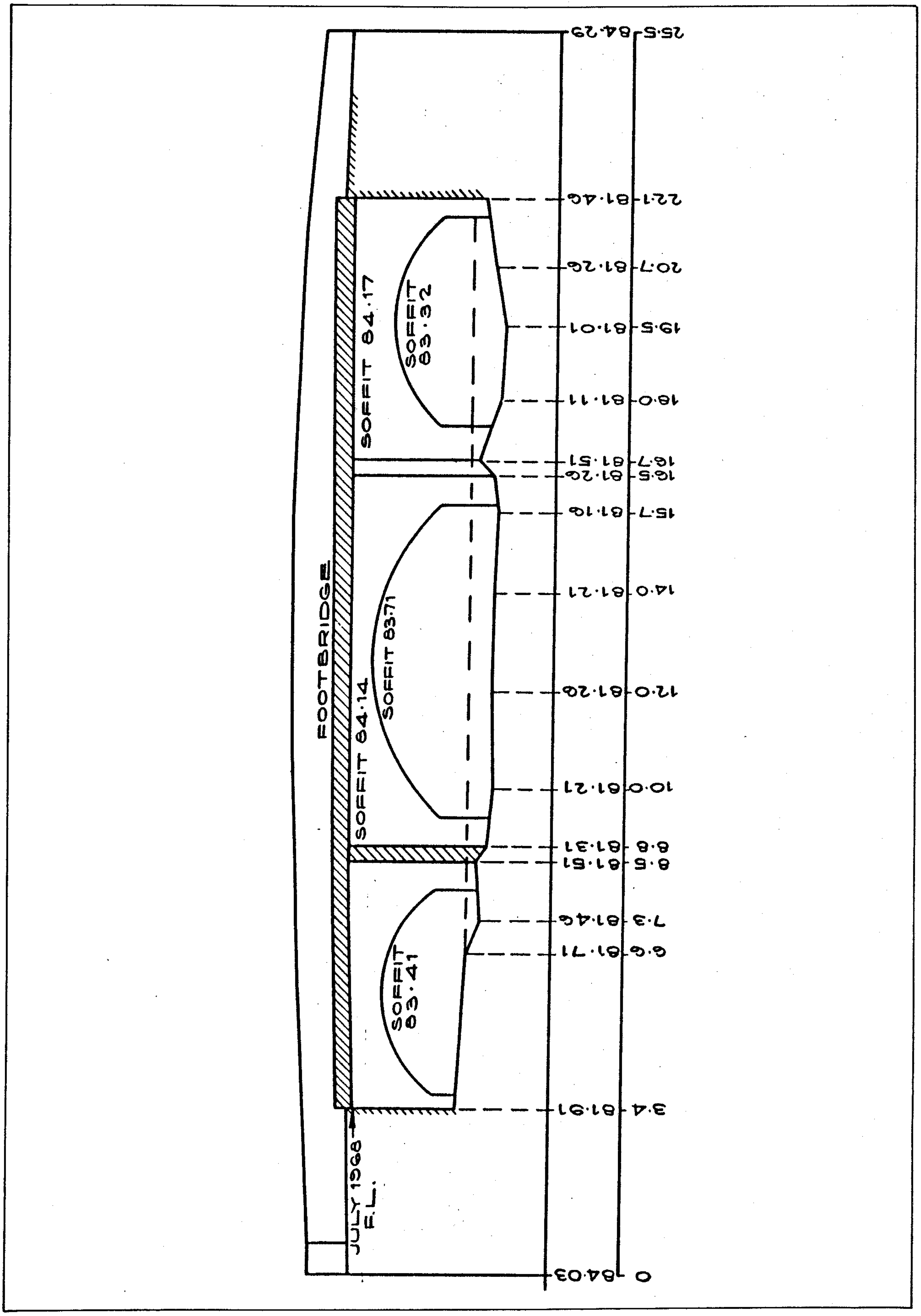


Fig 10 Avon Mill Bridge, River Avon,
Severn-Trent Water Authority

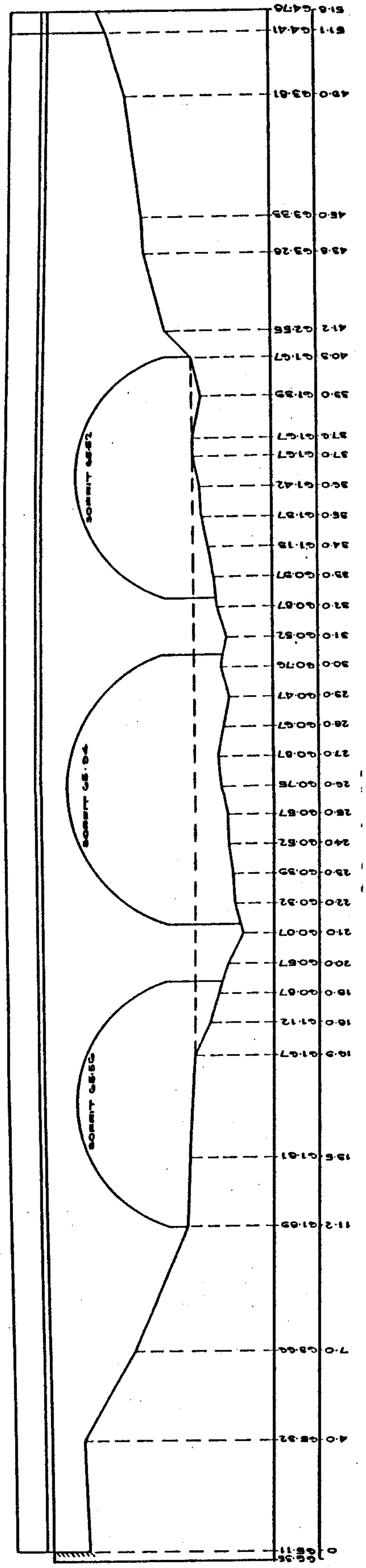


Fig 11   Ryton Bridge, River Avon,
Severn-Trent Water Authority

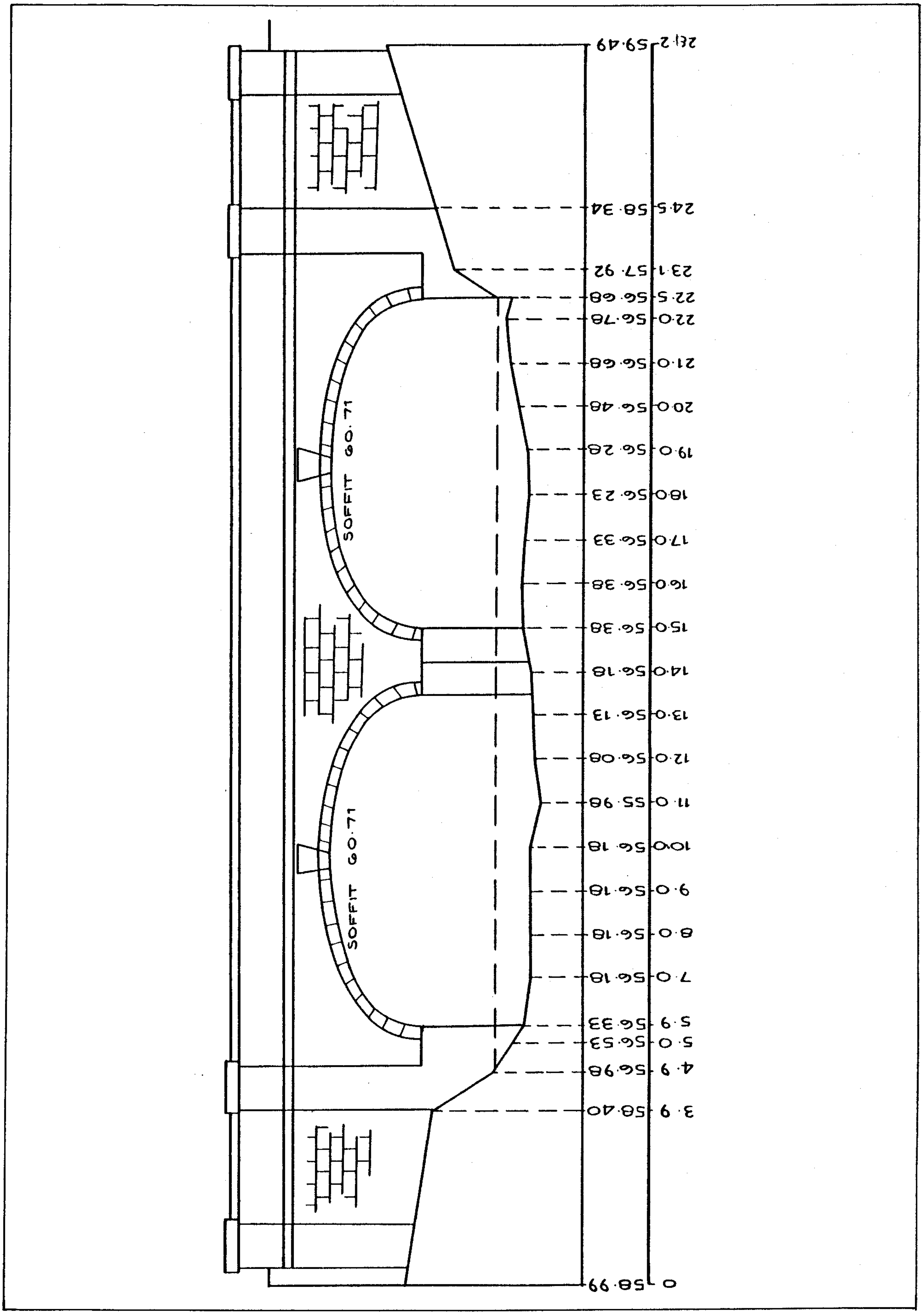


Fig 12 Bubbenhall Bridge, River Avon, Severn-Trent Water Authority

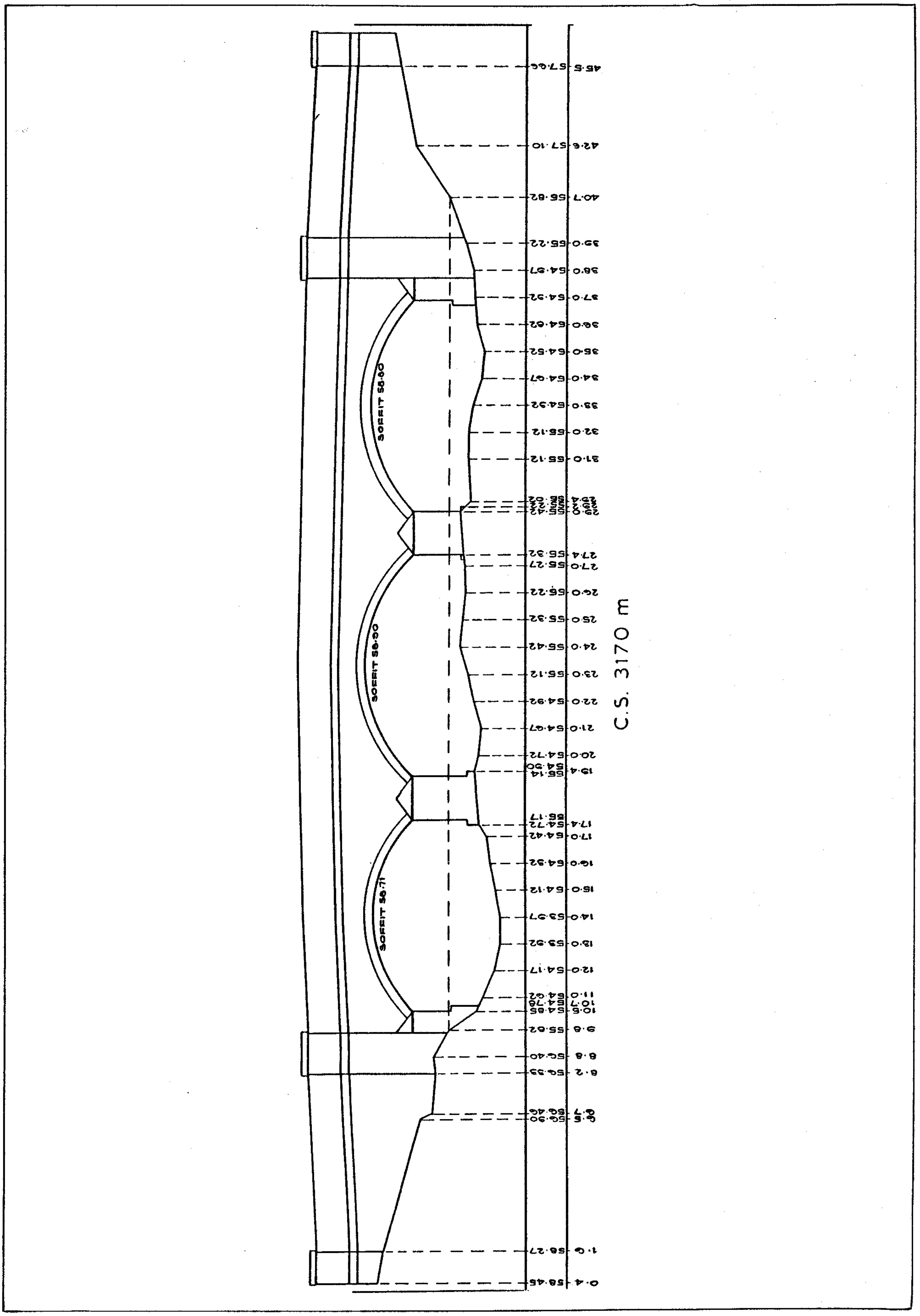


Fig 13 Cloud Bridge, River Avon, Severn-Trent Water Authority

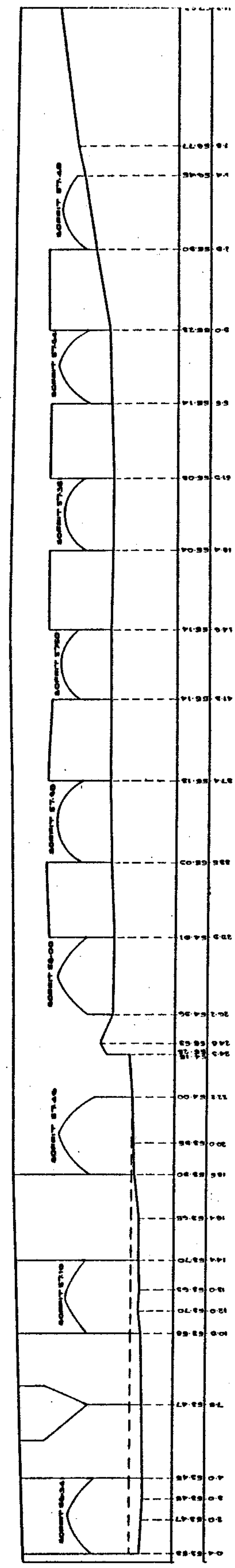


Fig 14 Stare Bridge, River Avon,
Severn-Trent Water Authority

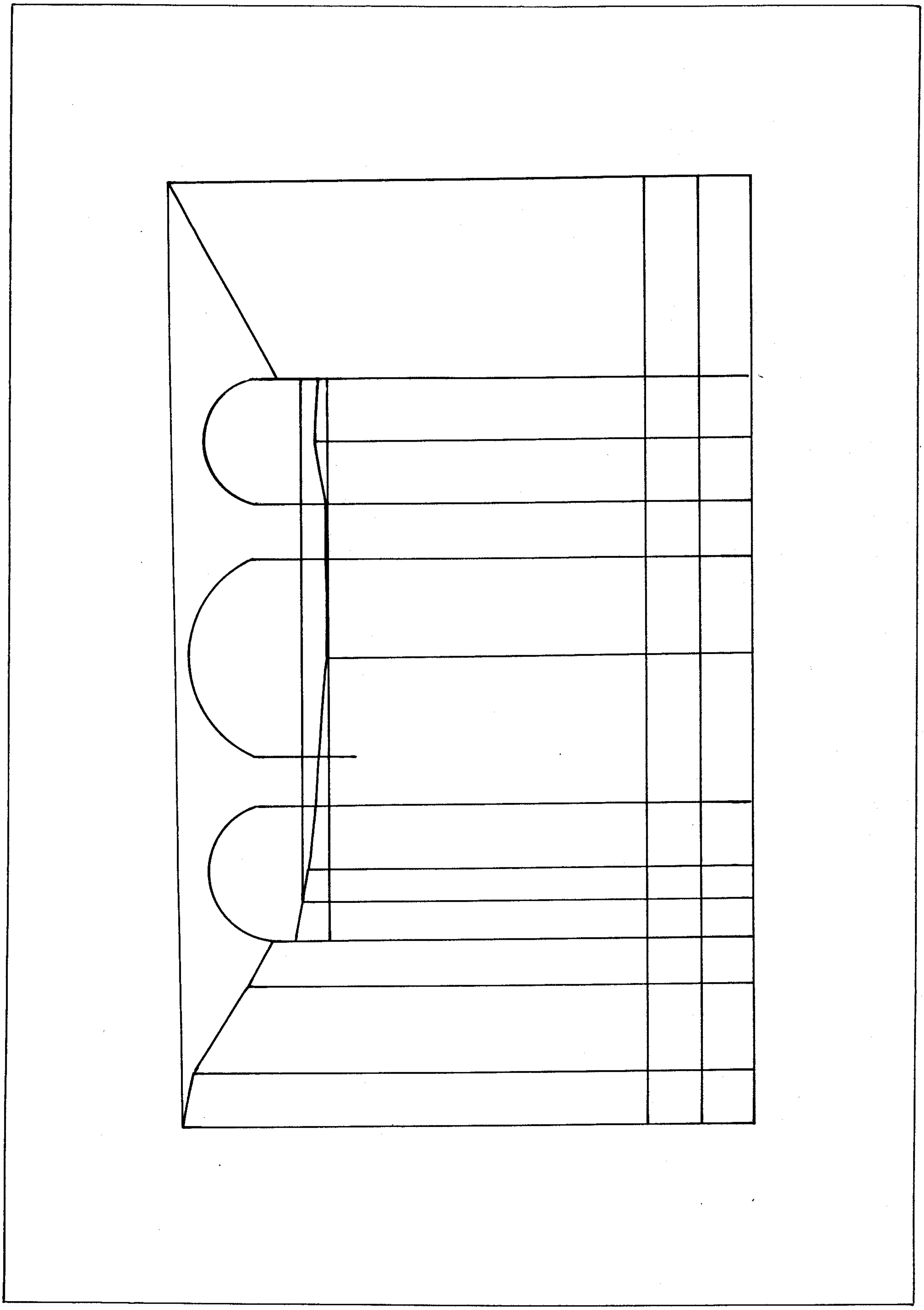


Fig 15 Stanton Gate Bridge, River Erewash,
Severn-Trent Water Authority

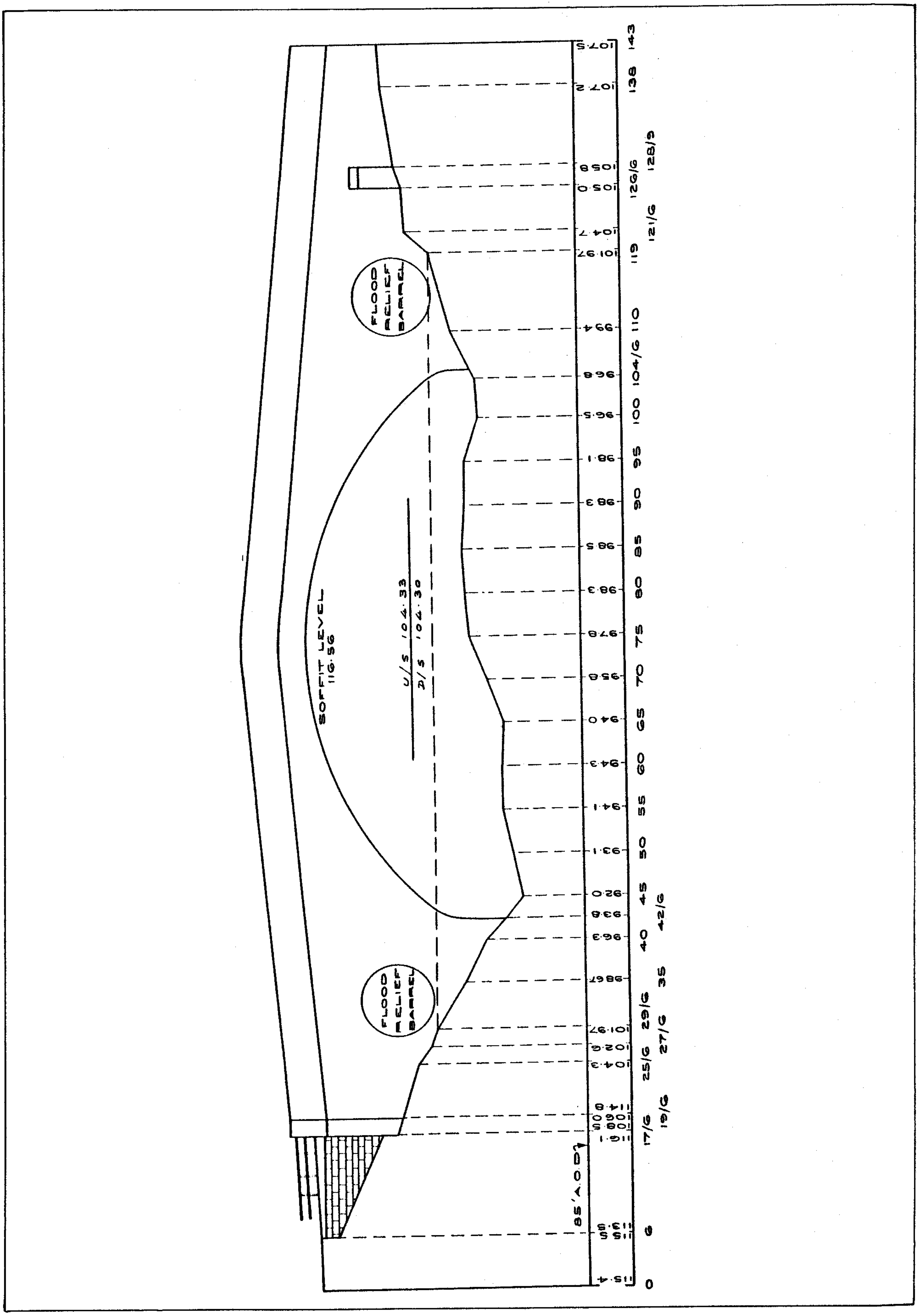


Fig 16 Wixford Bridge, River Arrow, Severn-Trent Water Authority

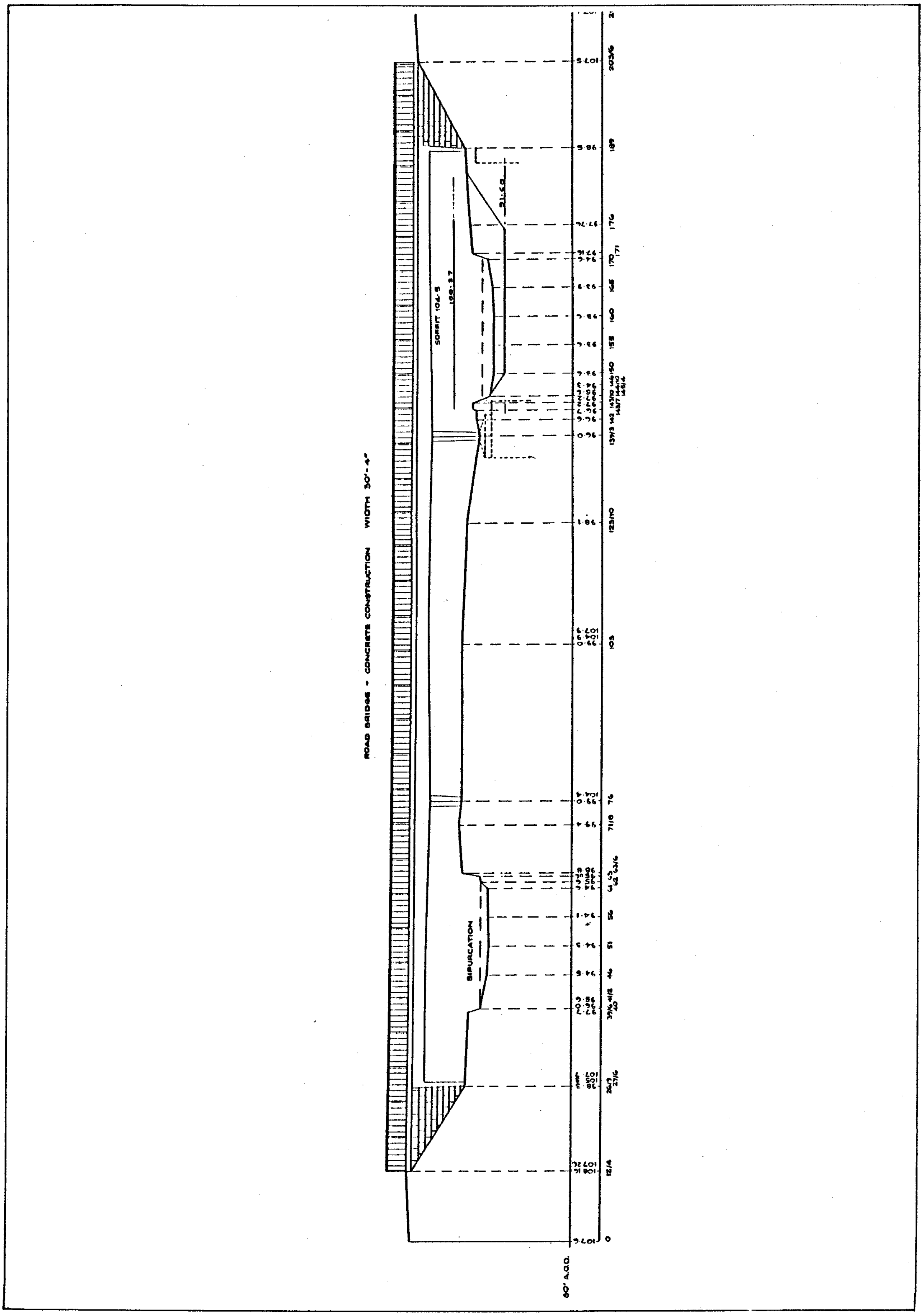


Fig 17 Broom Bridge, River Arrow,
Severn-Trent Water Authority

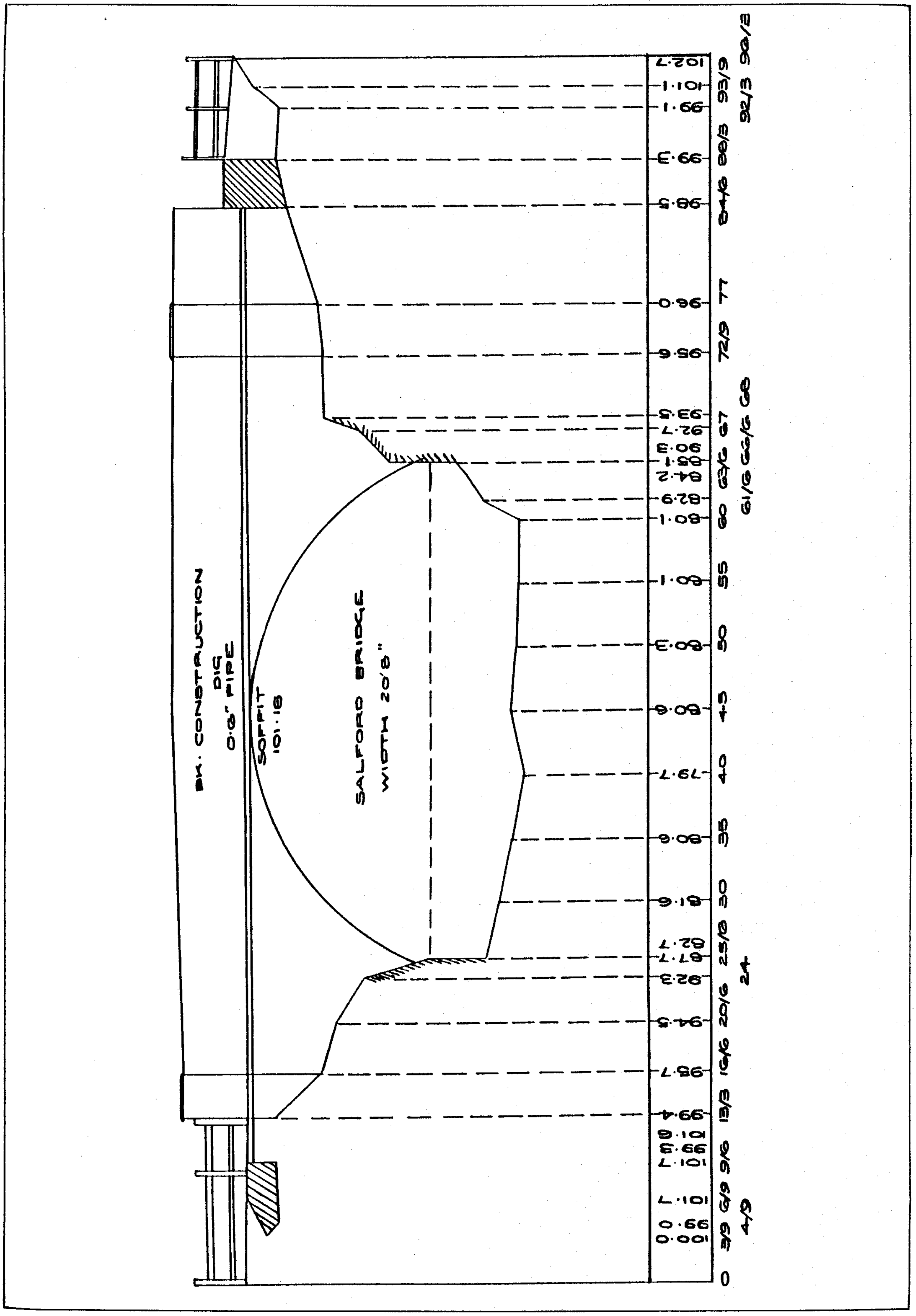


Fig 18 Salford Bridge, River Arrow,
Severn-Trent Water Authority

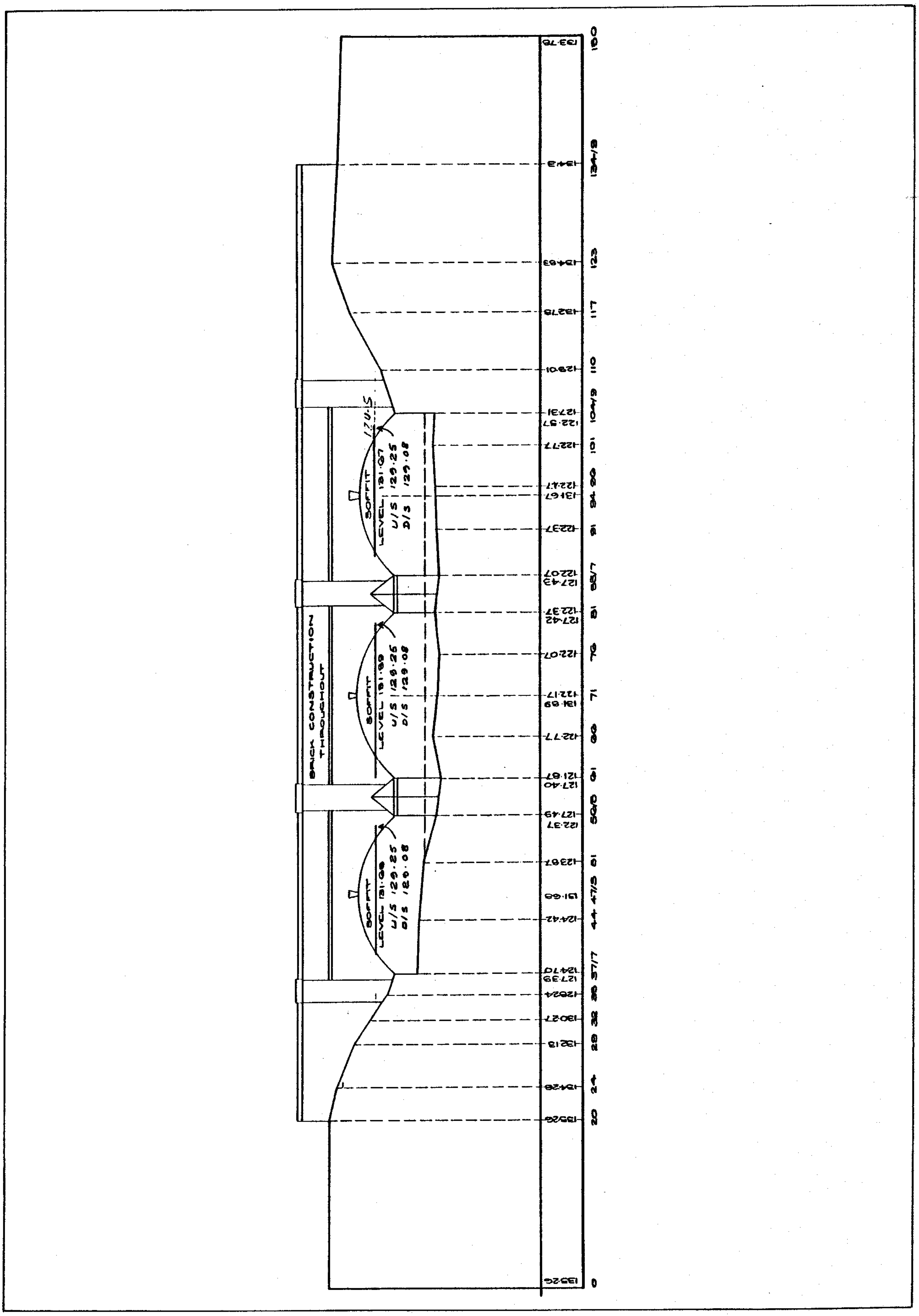


Fig 19 Gunnings Bridge, River Arrow, Severn-Trent Water Authority

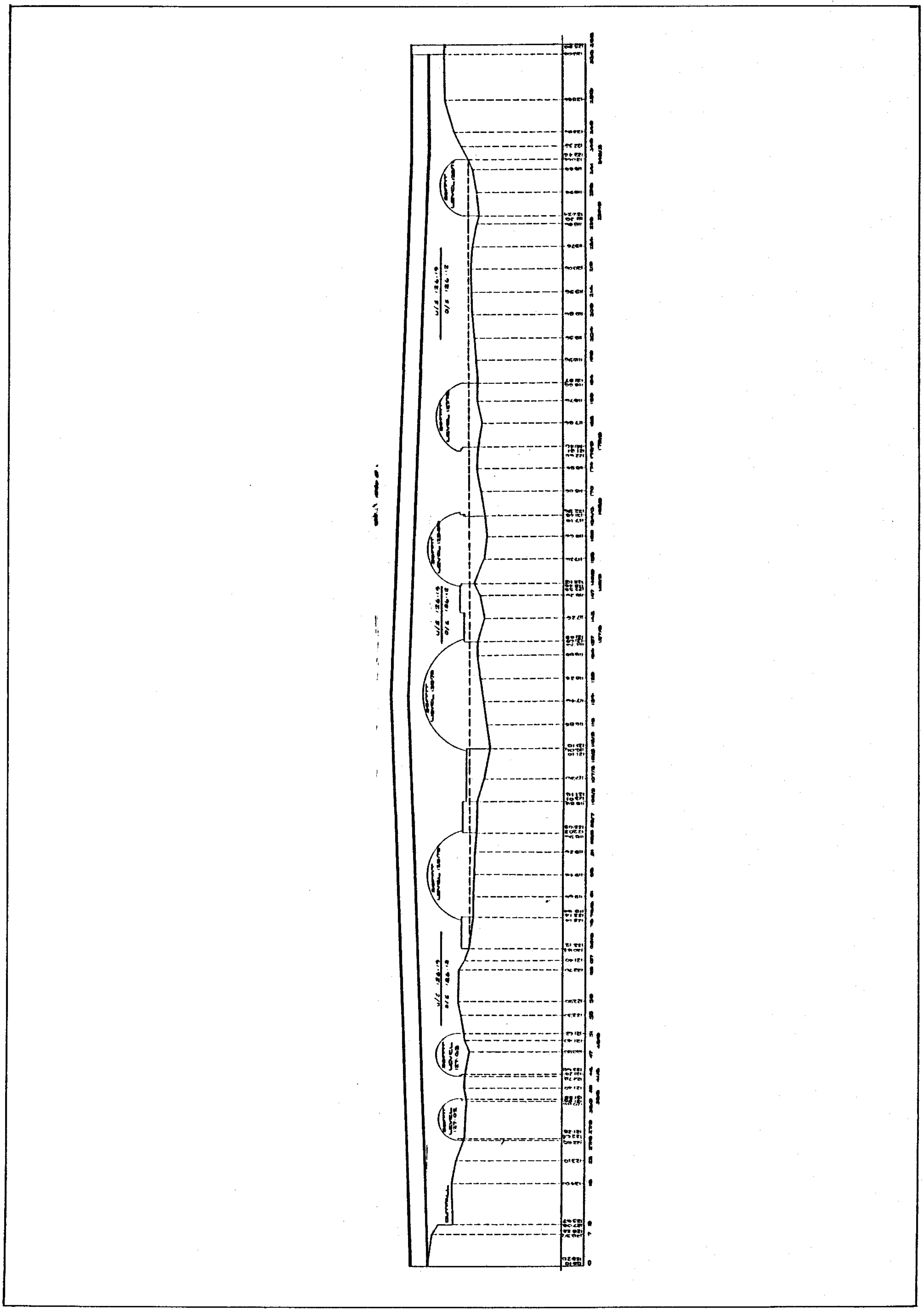


Fig 20 Oversley Bridge, River Arrow, Severn-Trent Water Authority

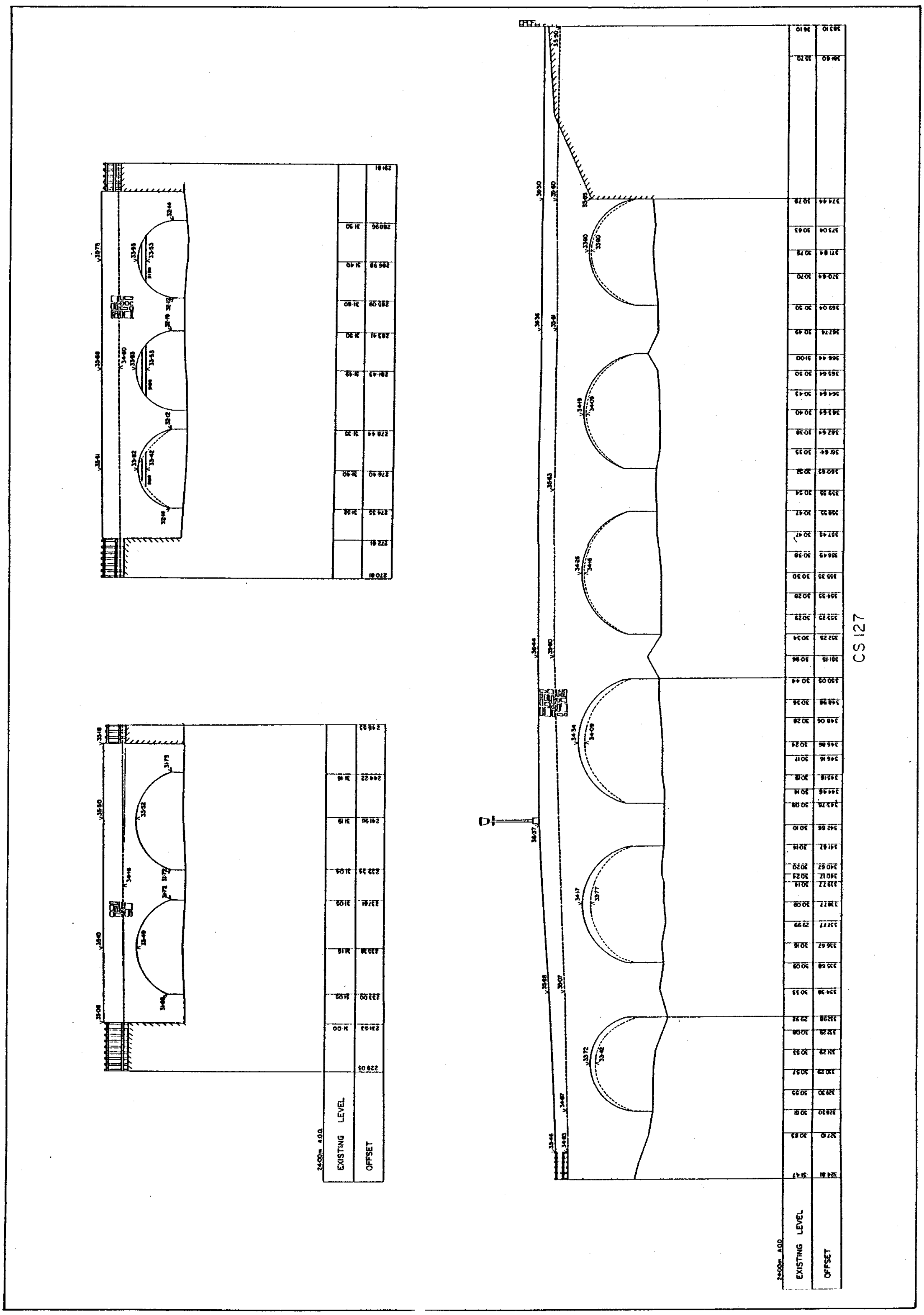


Fig 21 Blandford Bridge, River Stour,
Wessex Water Authority

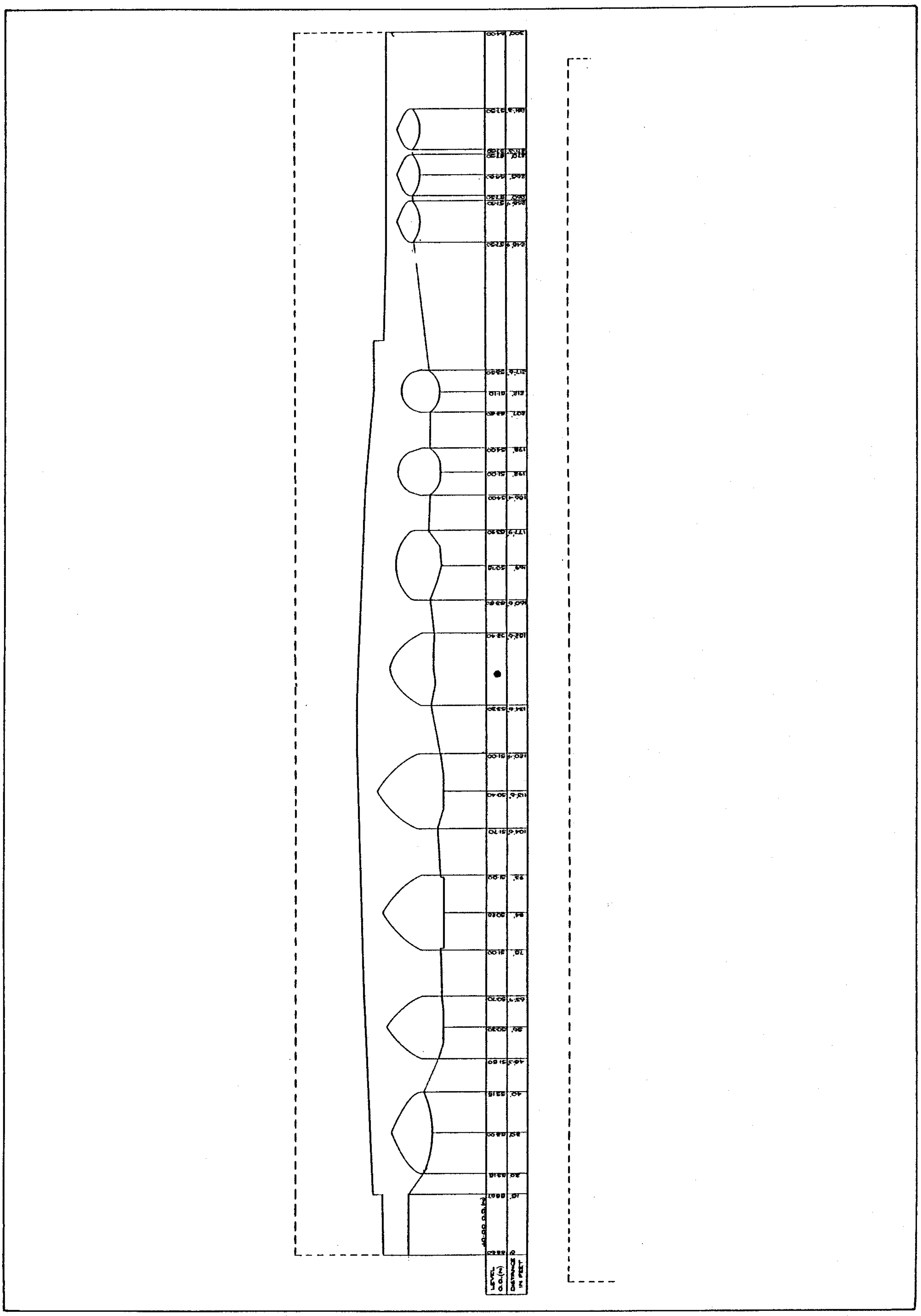


Fig 22 Julian's Bridge, River Stour, Wessex Water Authority

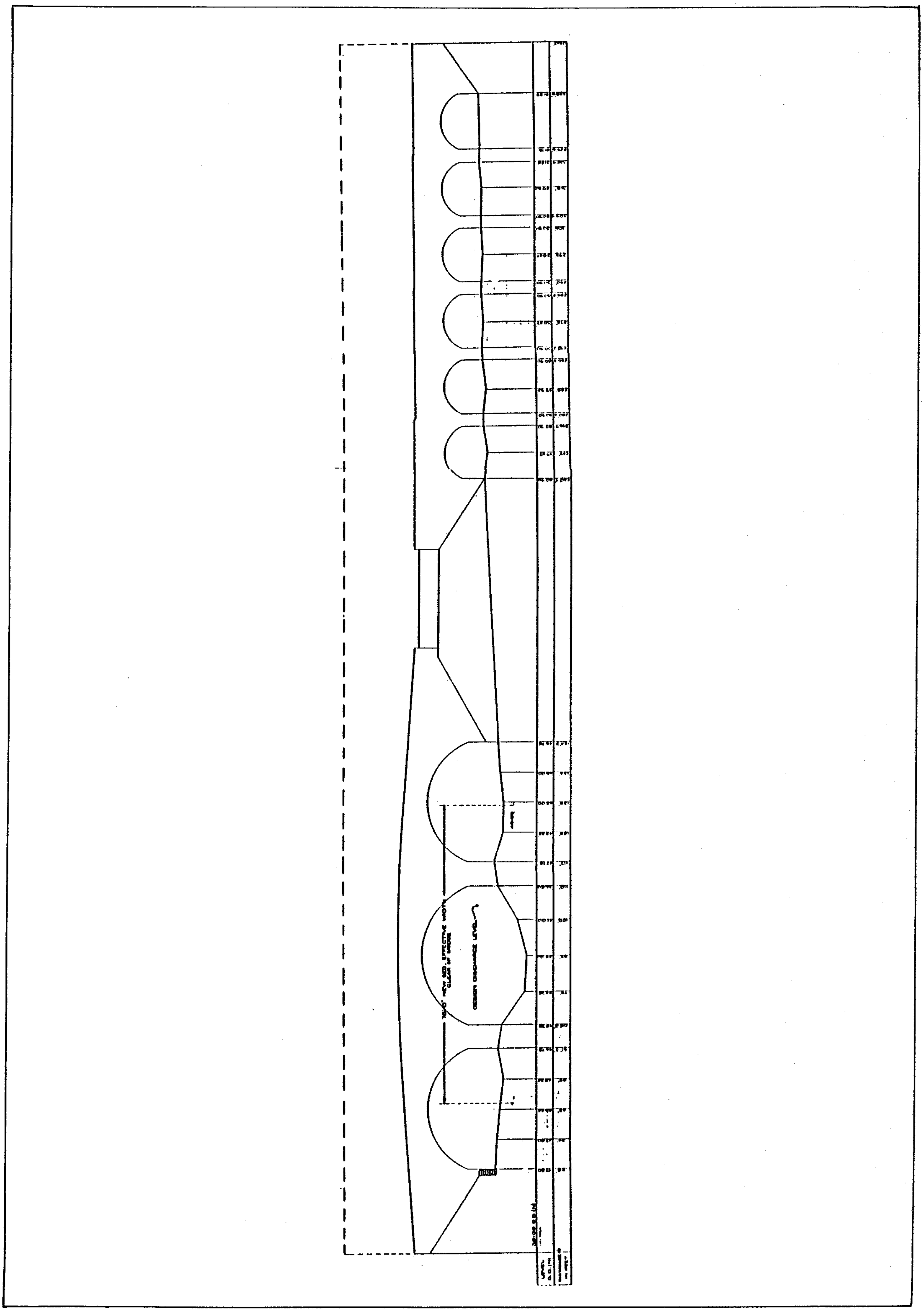


Fig 23 Canford Bridge, River Stour, Wessex Water Authority

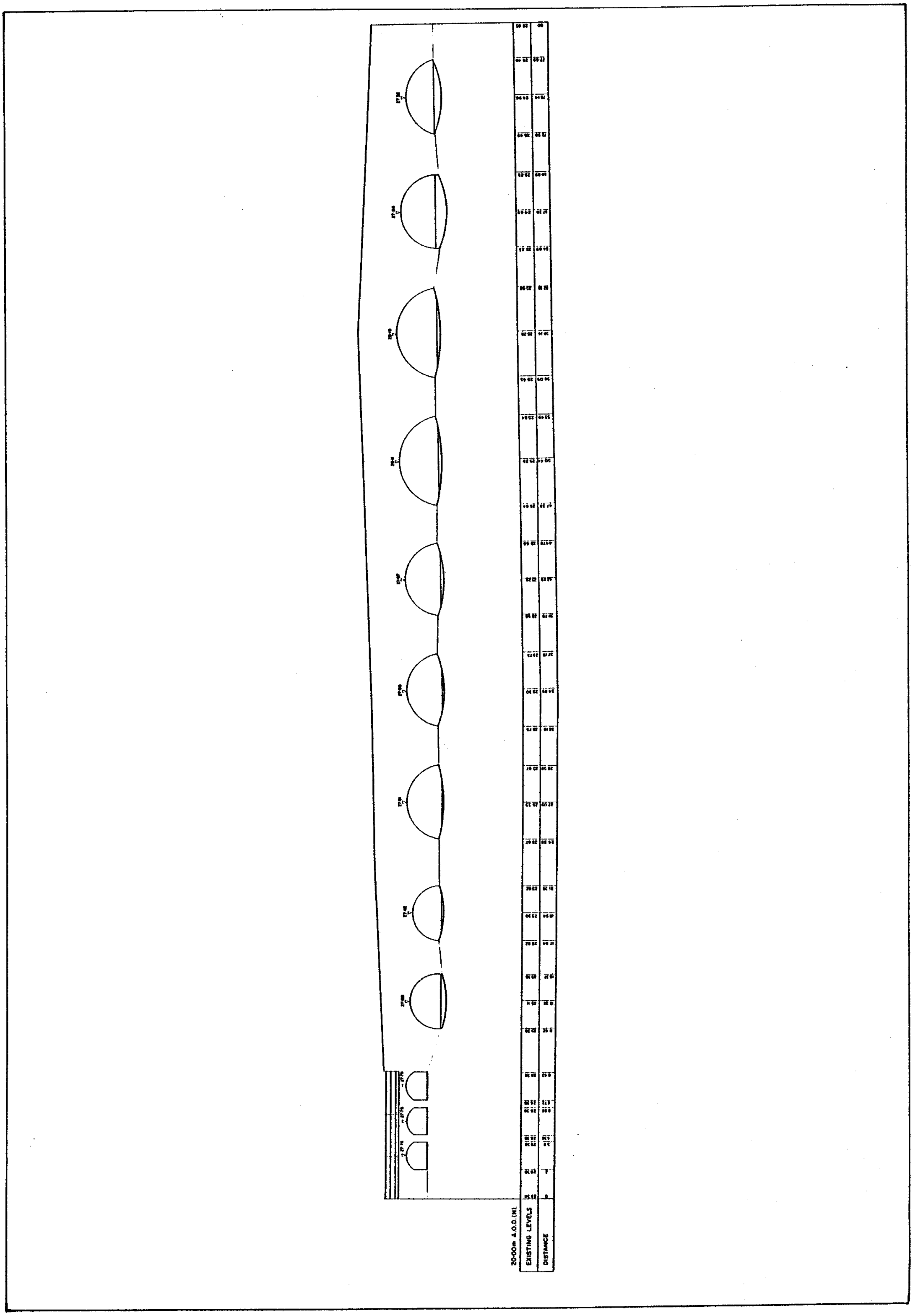


Fig 24 Crawford Bridge, River Stour, Wessex Water Authority

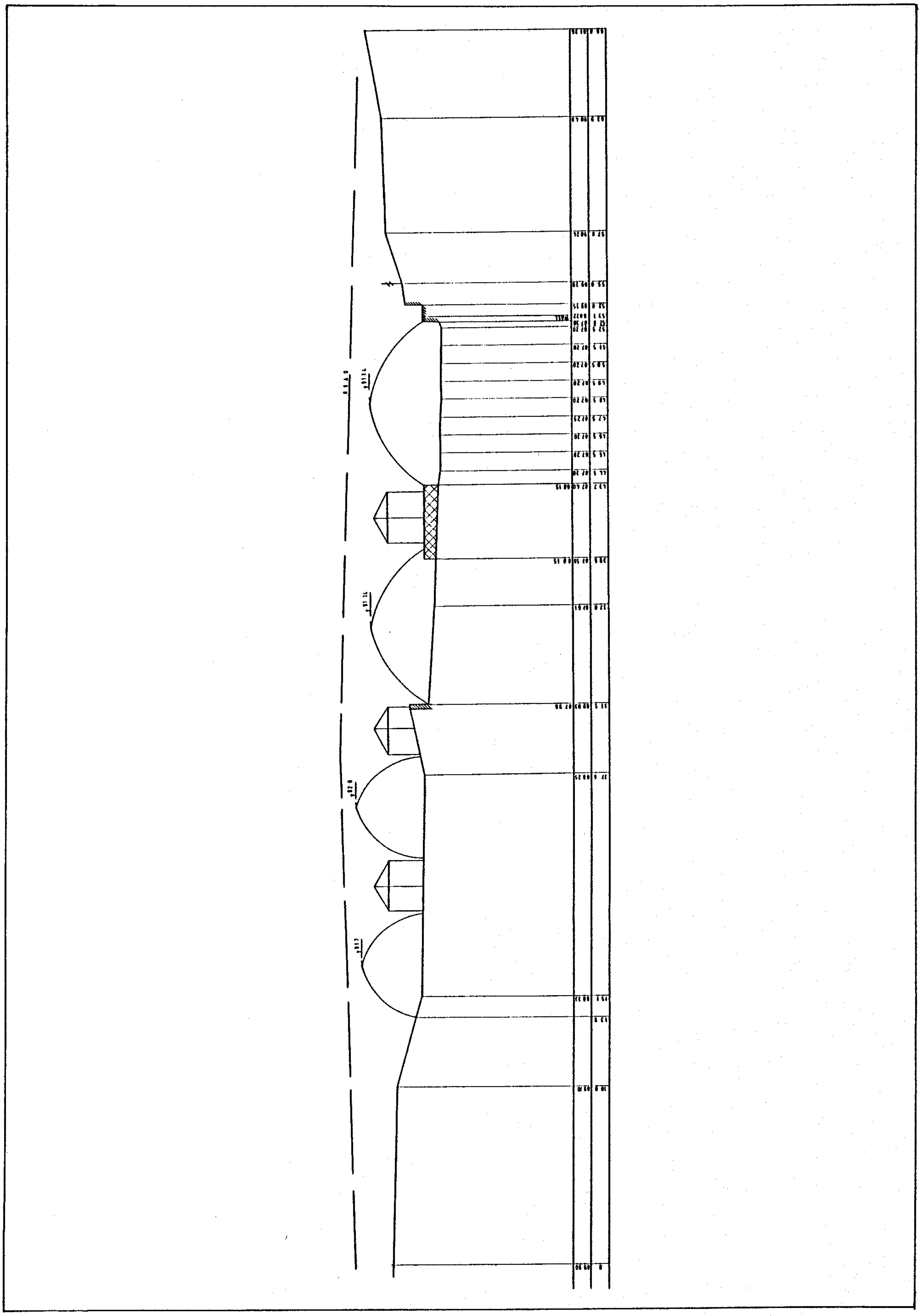


Fig 25 Kildwick Bridge, River Aire,
Yorkshire Water Authority

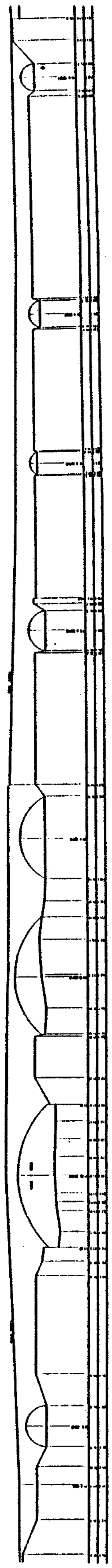
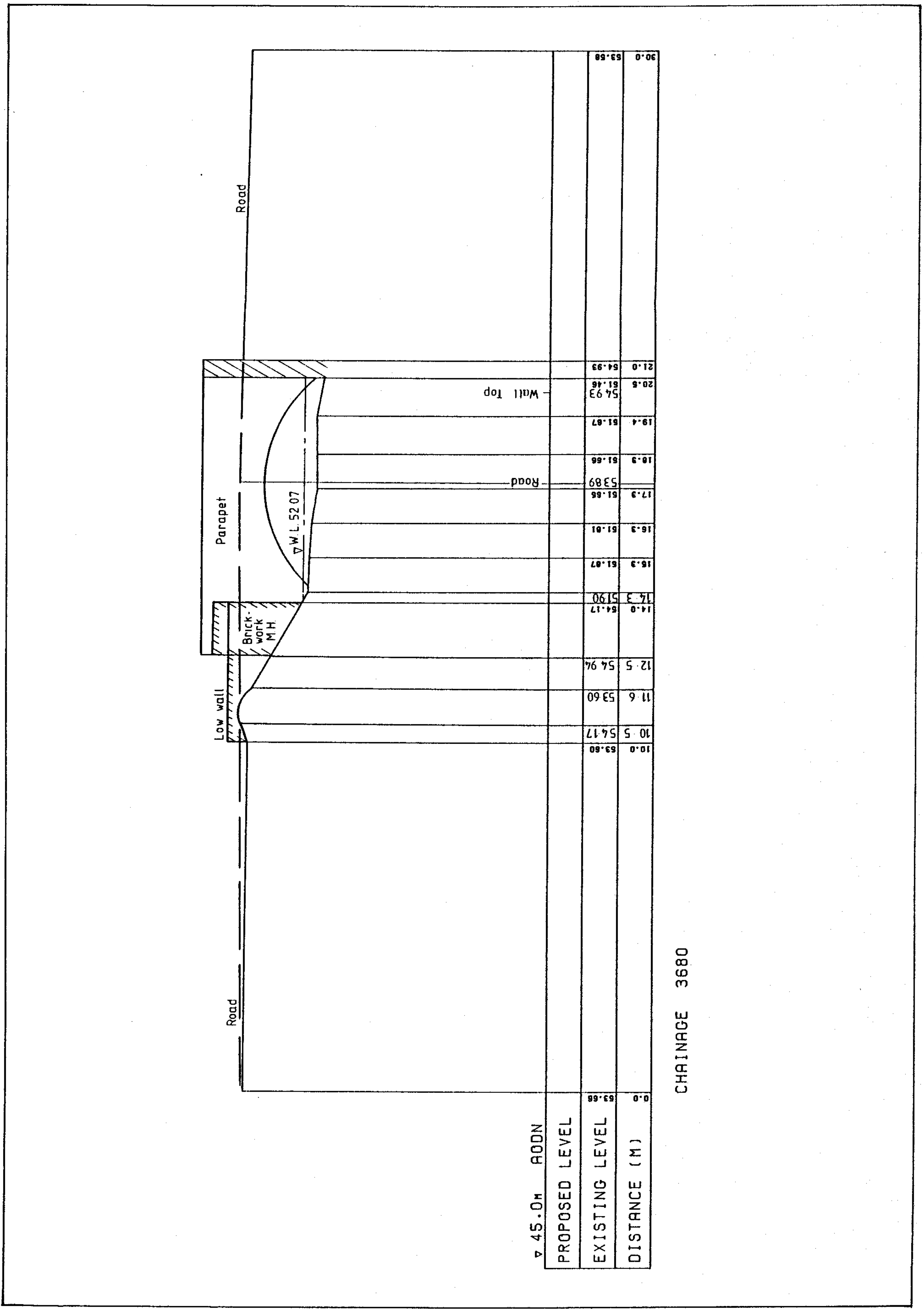


Fig 26 Inghey Bridge, River Aire,
Yorkshire Water Authority



Fs 27 Station Road Bridge, River Spen,
Yorkshire Water Authority

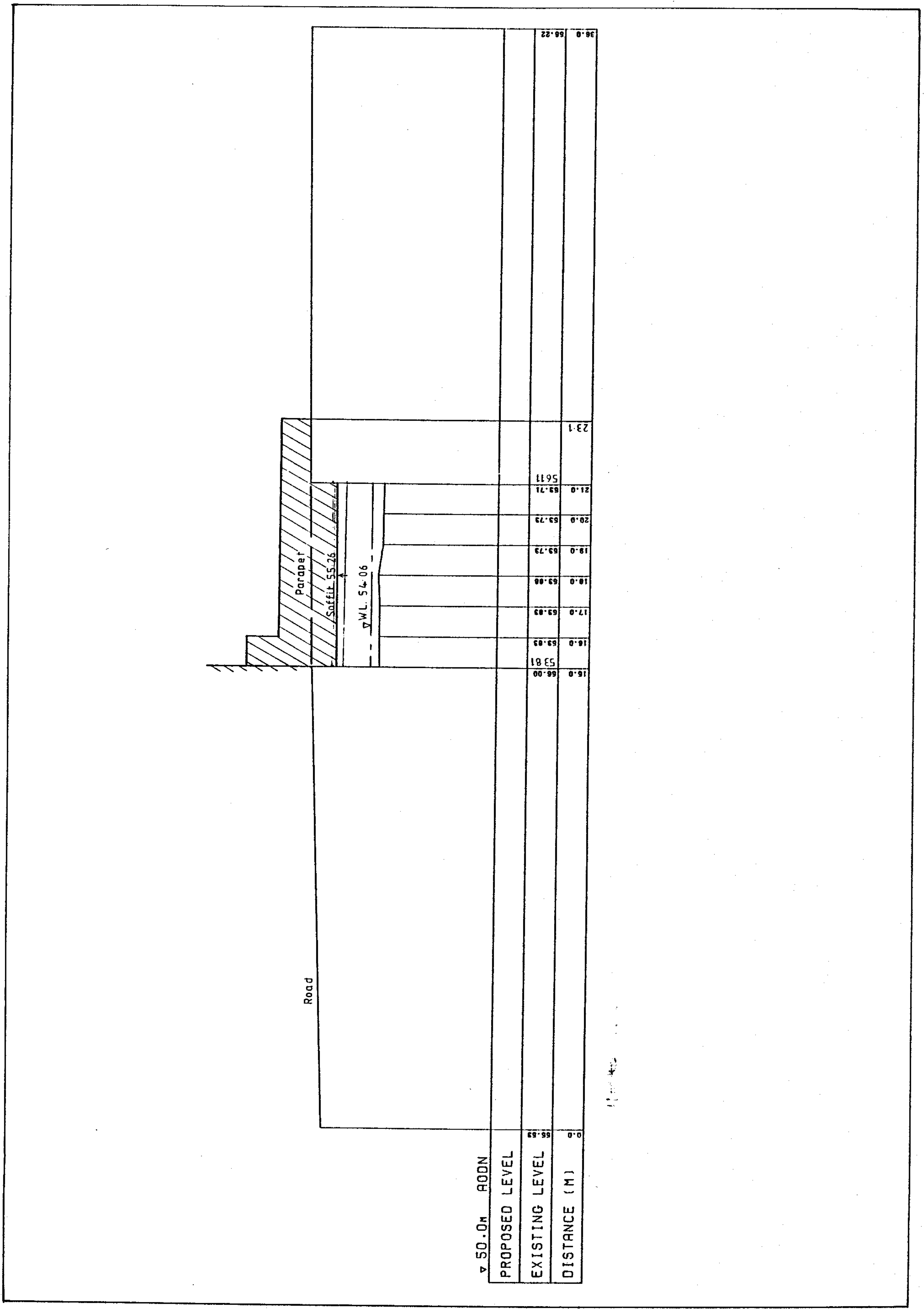


Fig 28 Union Street Bridge, River Spen,
Yorkshire Water Authority

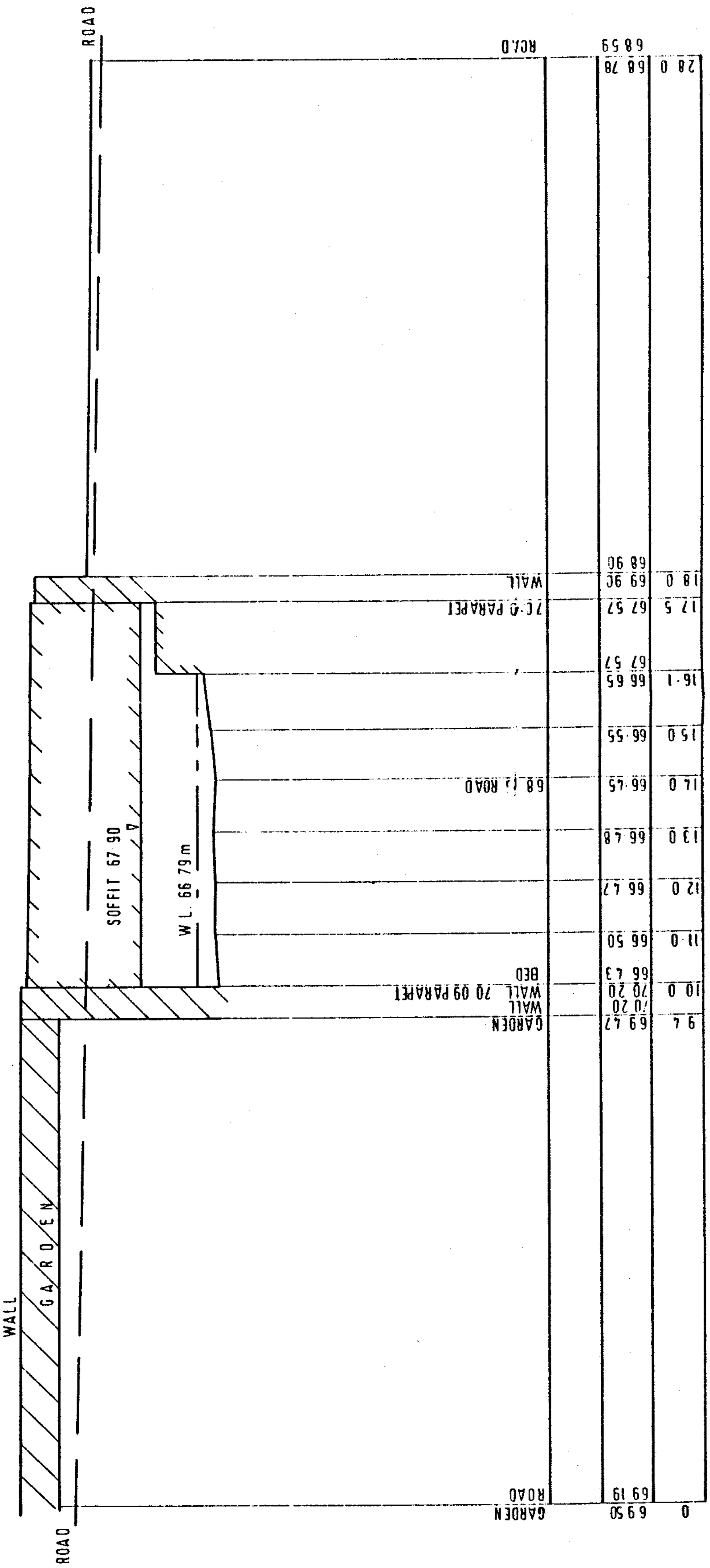


Fig 29 Rawfolds Bridge, River Spen, Yorkshire Water Authority

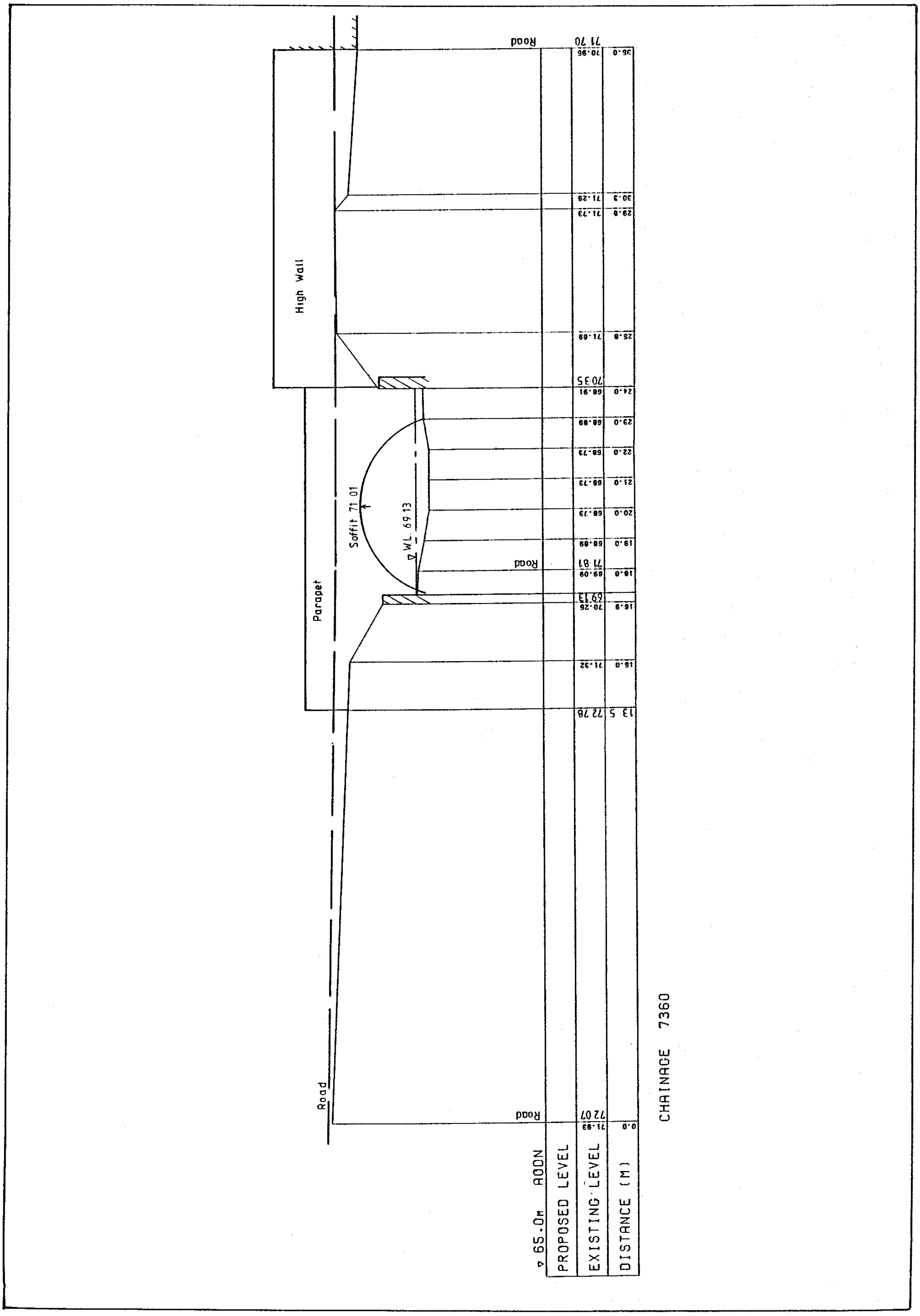


Fig 30 St. Pegs Bridge, River Spen,
Yorkshire Water Authority

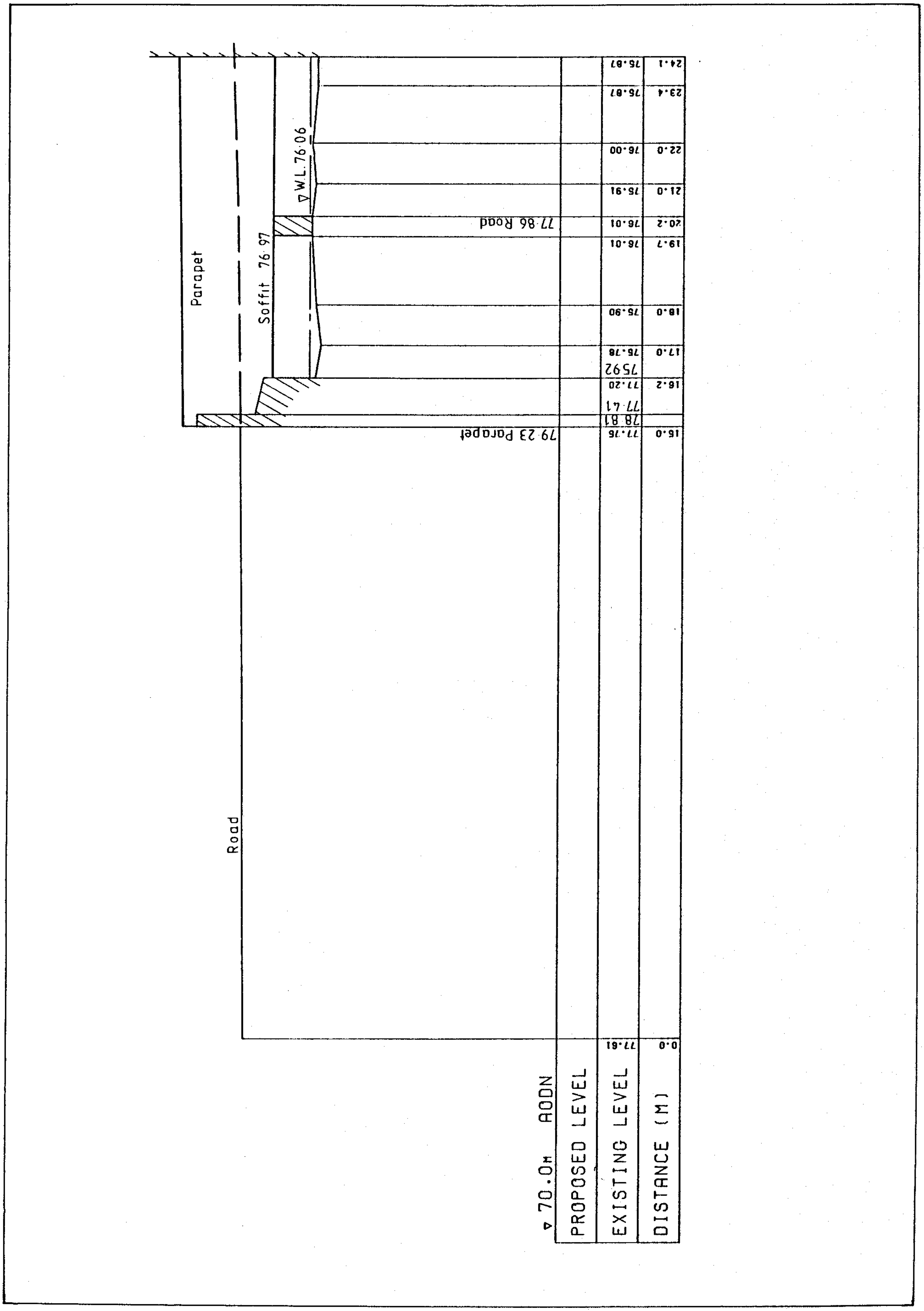


Fig 31 Balme Road Bridge, River Spen, Yorkshire Water Authority

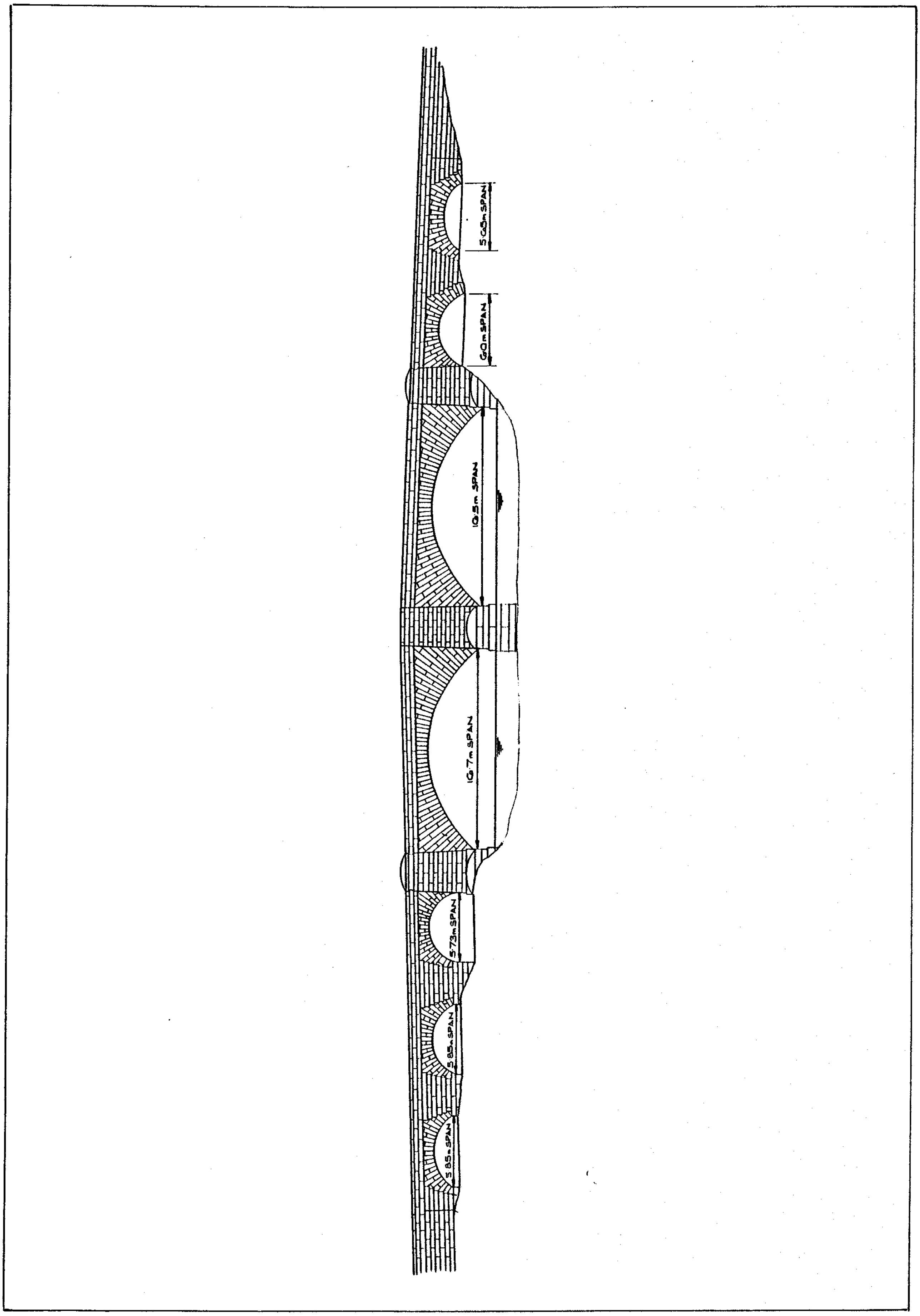


Fig 32 Pool Bridge, River Wharfe, Yorkshire Water Authority

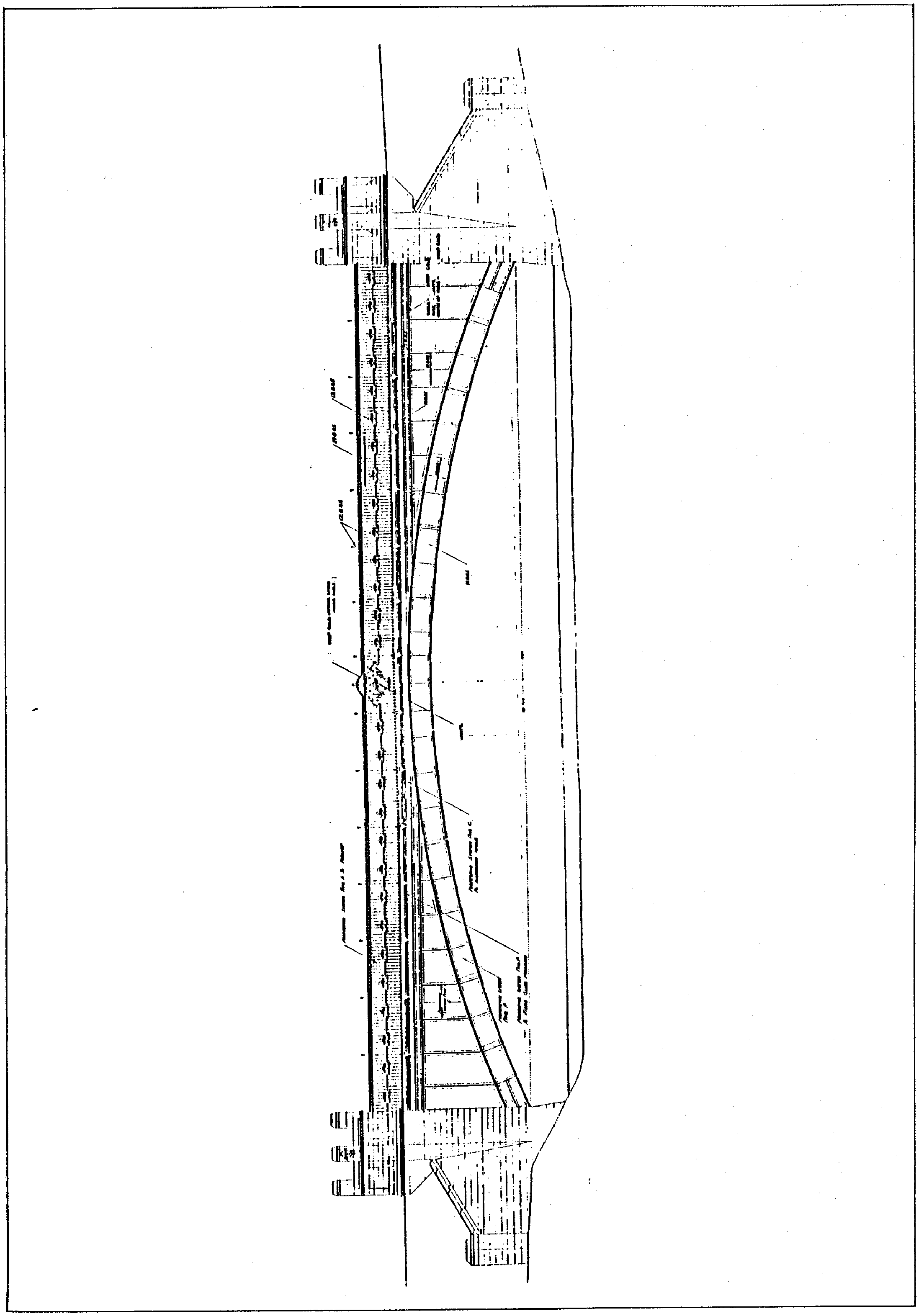


Fig 33 Ilkley Bridge, River Wharfe, Yorkshire Water Authority

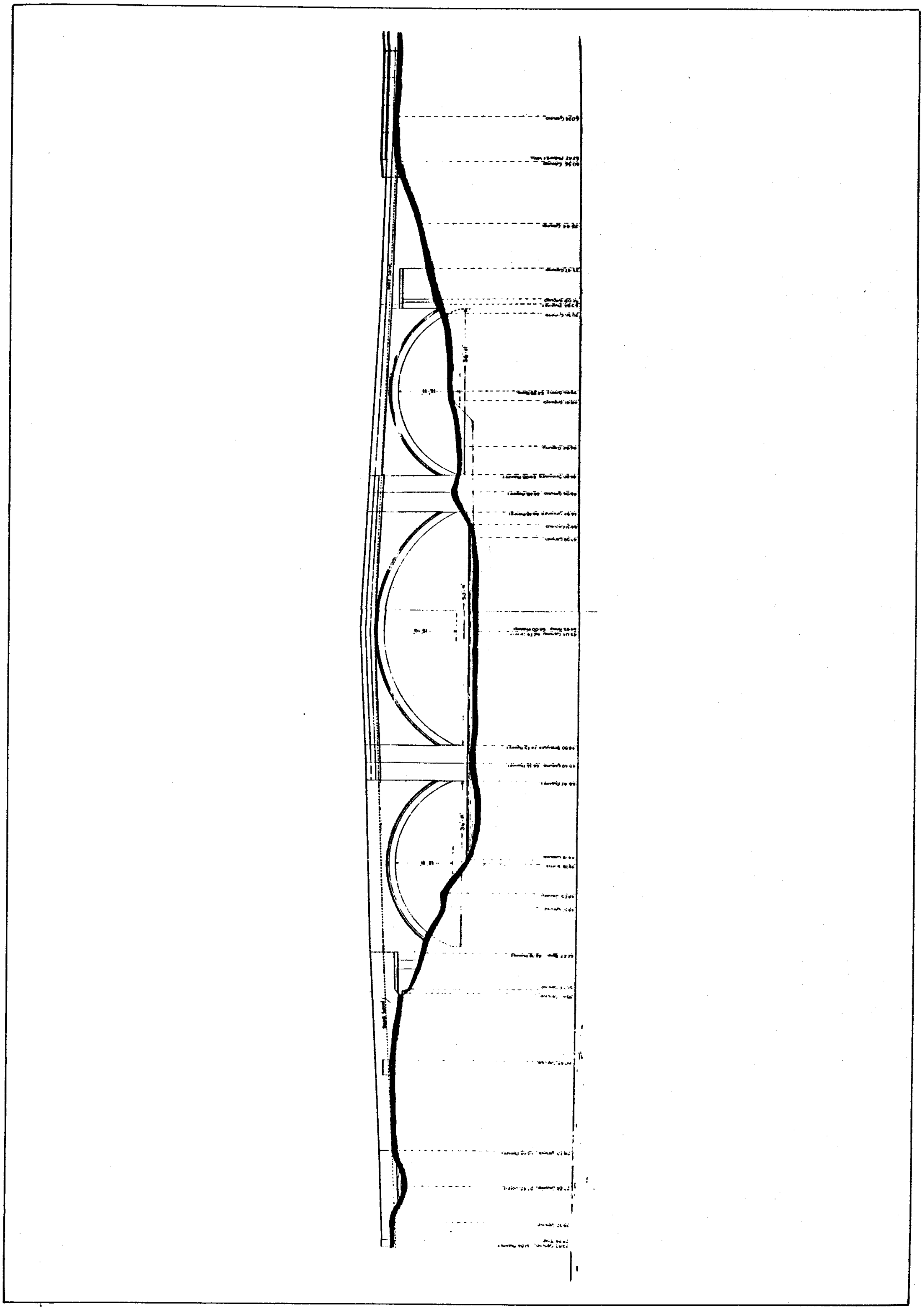


Fig 34 Cattall Bridge, River Nidd, Yorkshire Water Authority

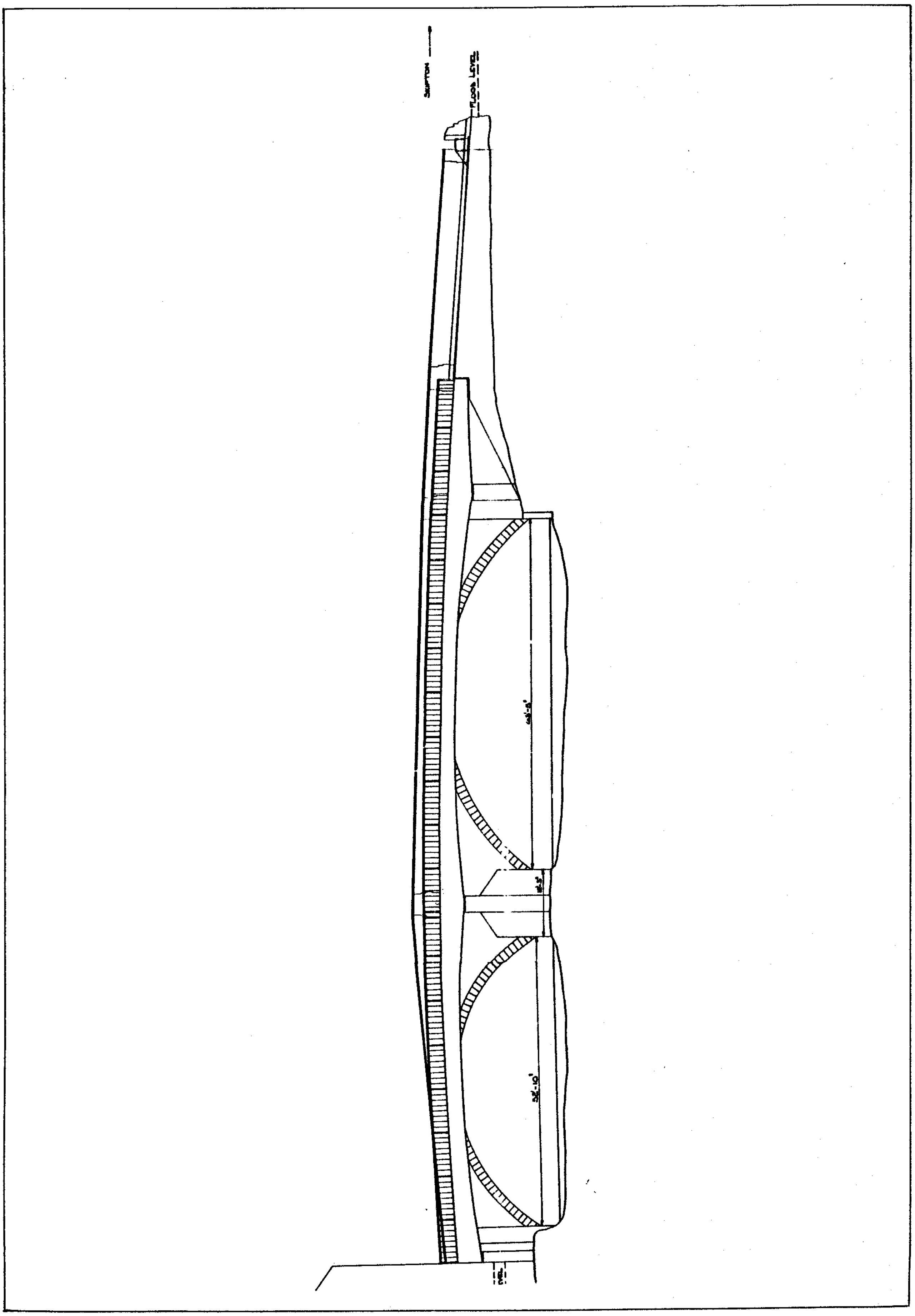


Fig 35 Bolton Bridge, River Wharfe, Yorkshire Water Authority

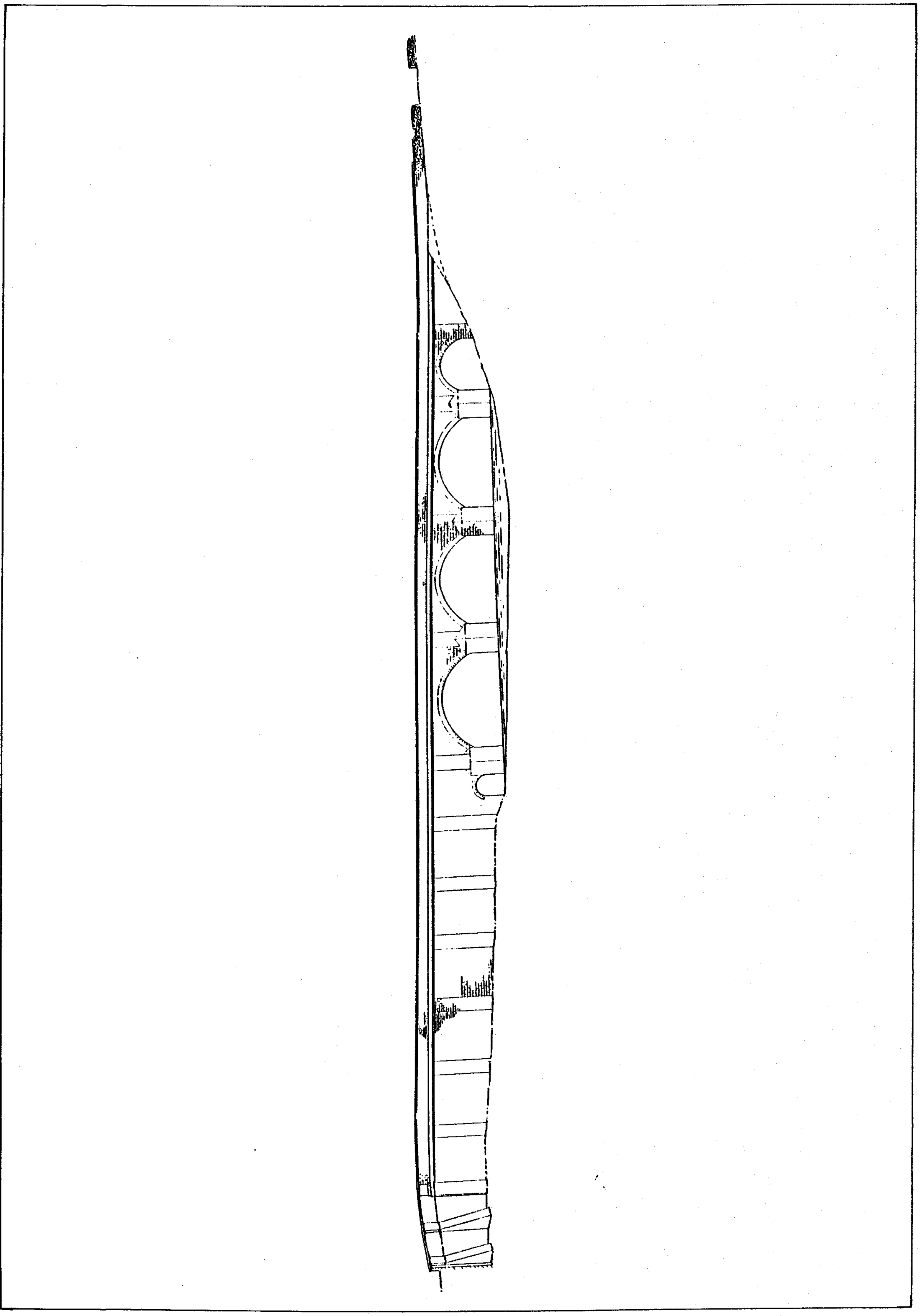


Fig 36 Grassington Bridge, River Wharfe,
Yorkshire Water Authority

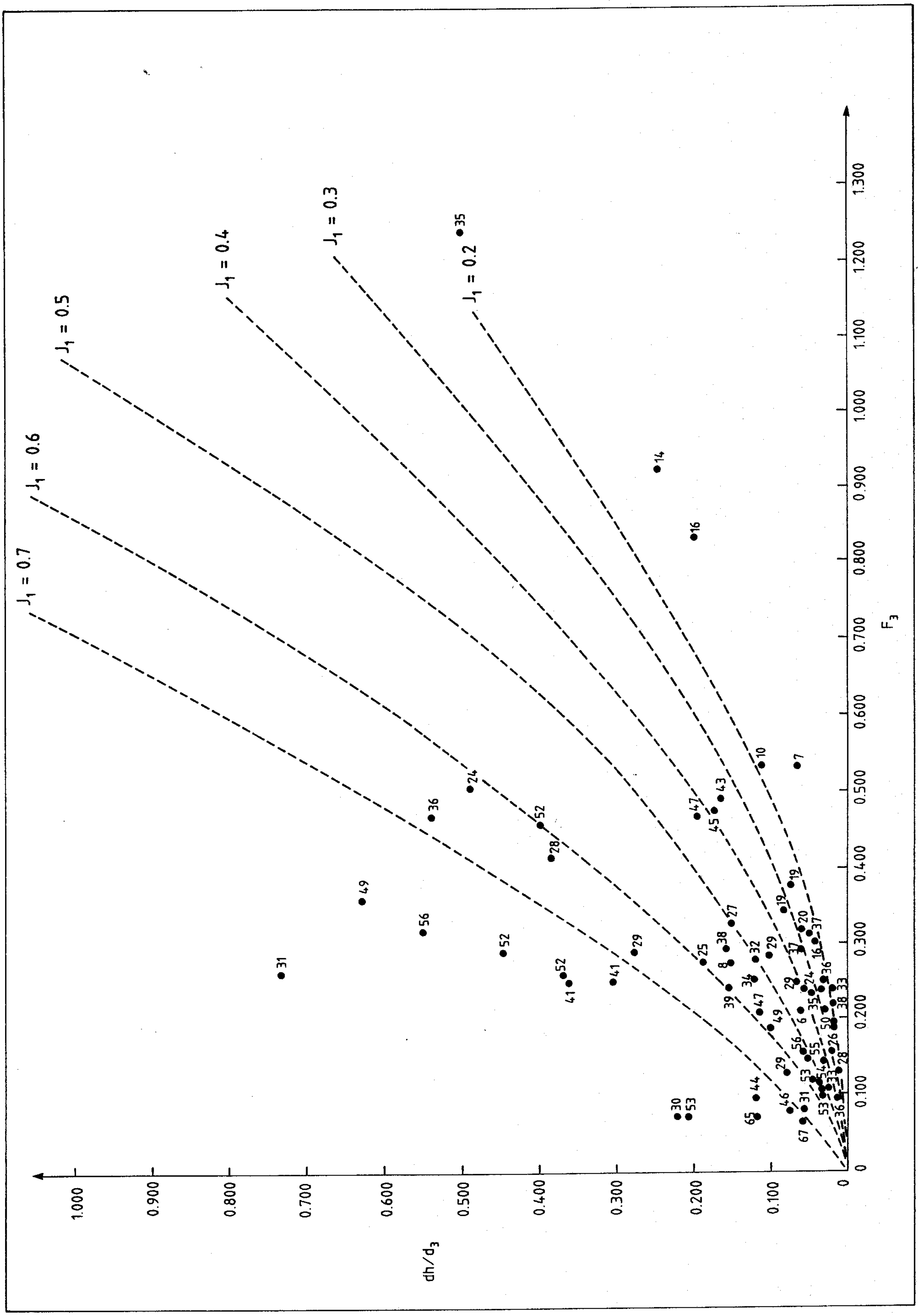


Fig 37 Plot of $\Delta h/d_3$ v F_3 and J_1, prototype data

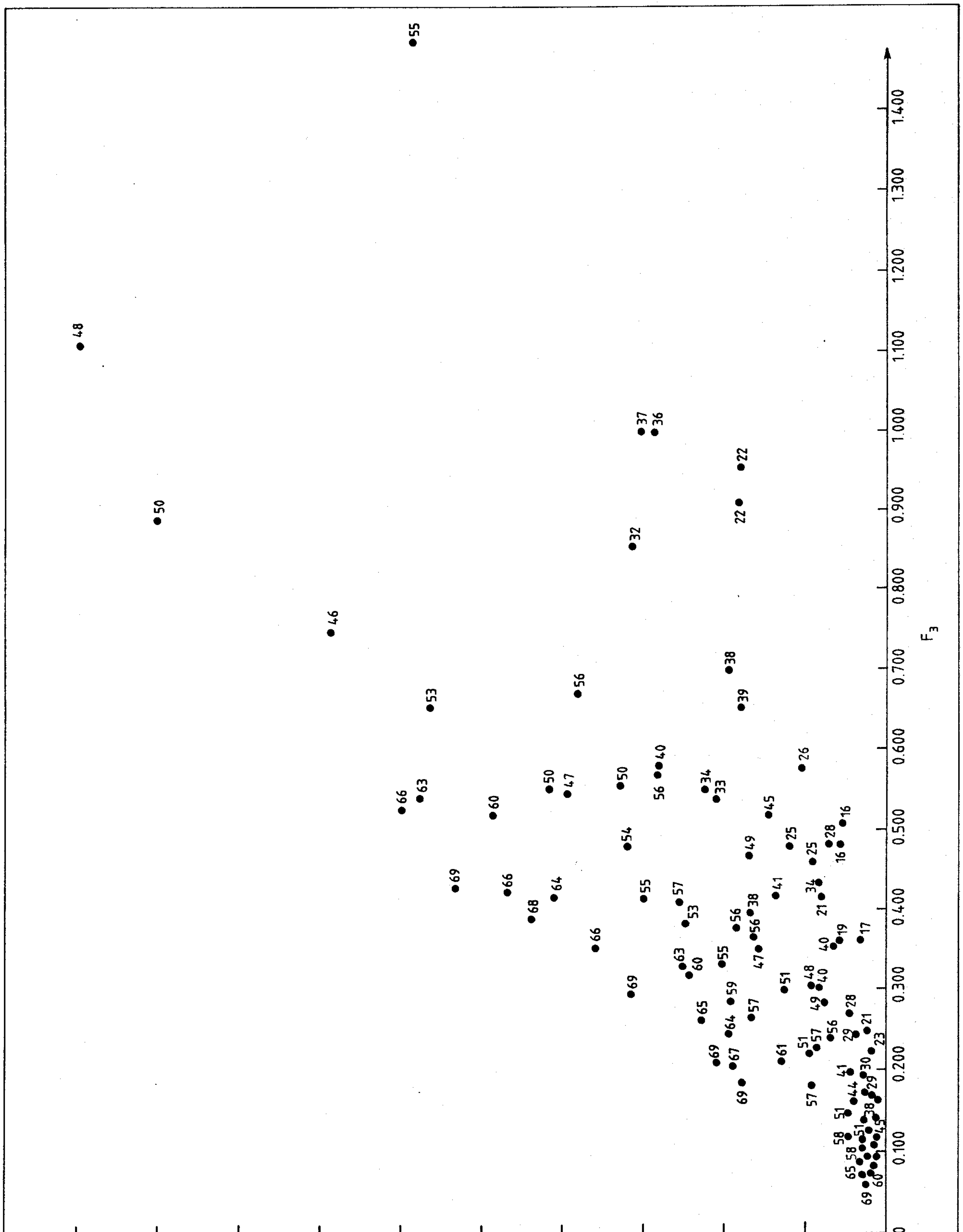


Fig 38 Plot of $\Delta H/d_3$ v F_3 and J_1, laboratory tests

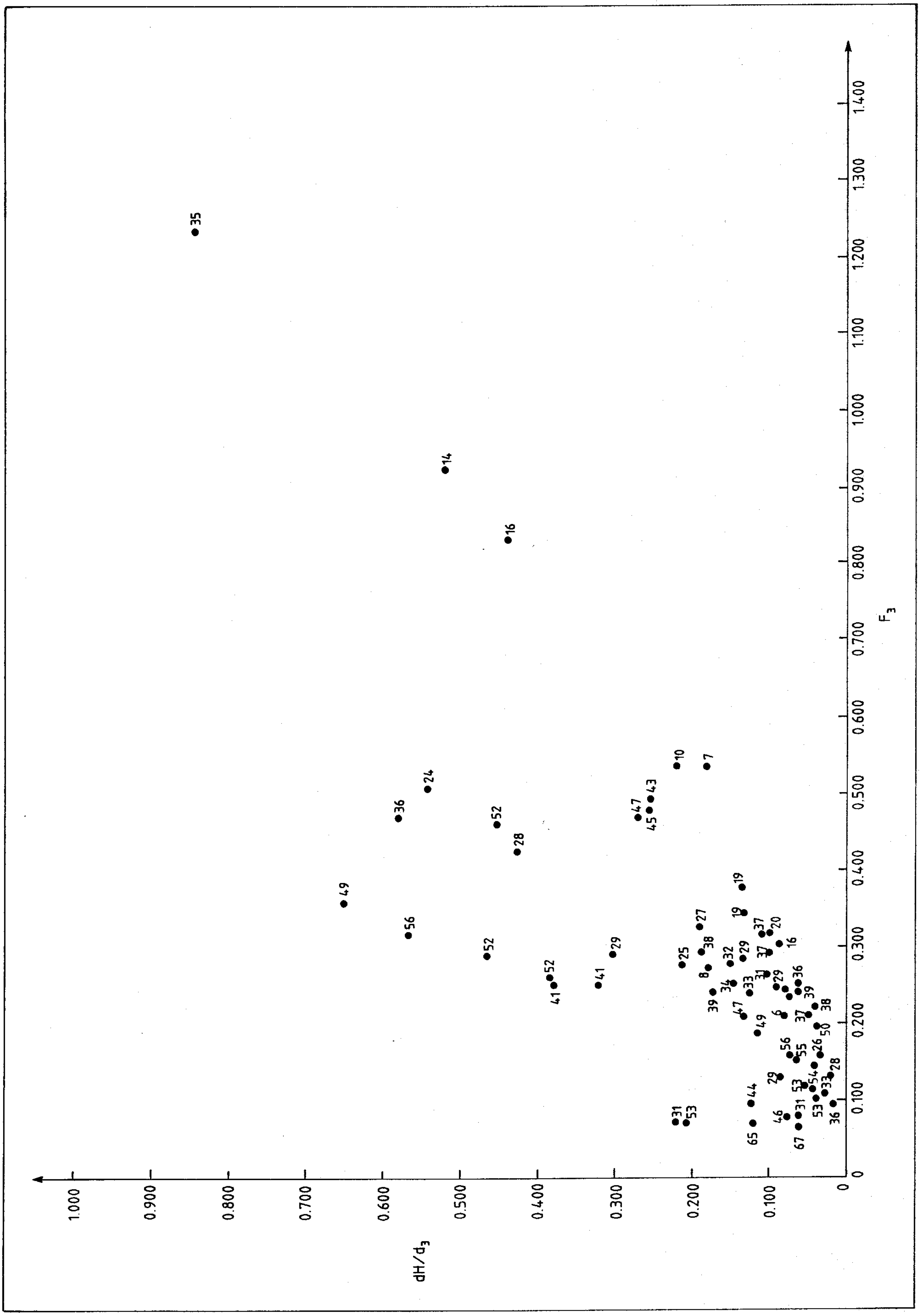


Fig 39 Plot of $\Delta H/d_3$ v F_3 and J_1, prototype data

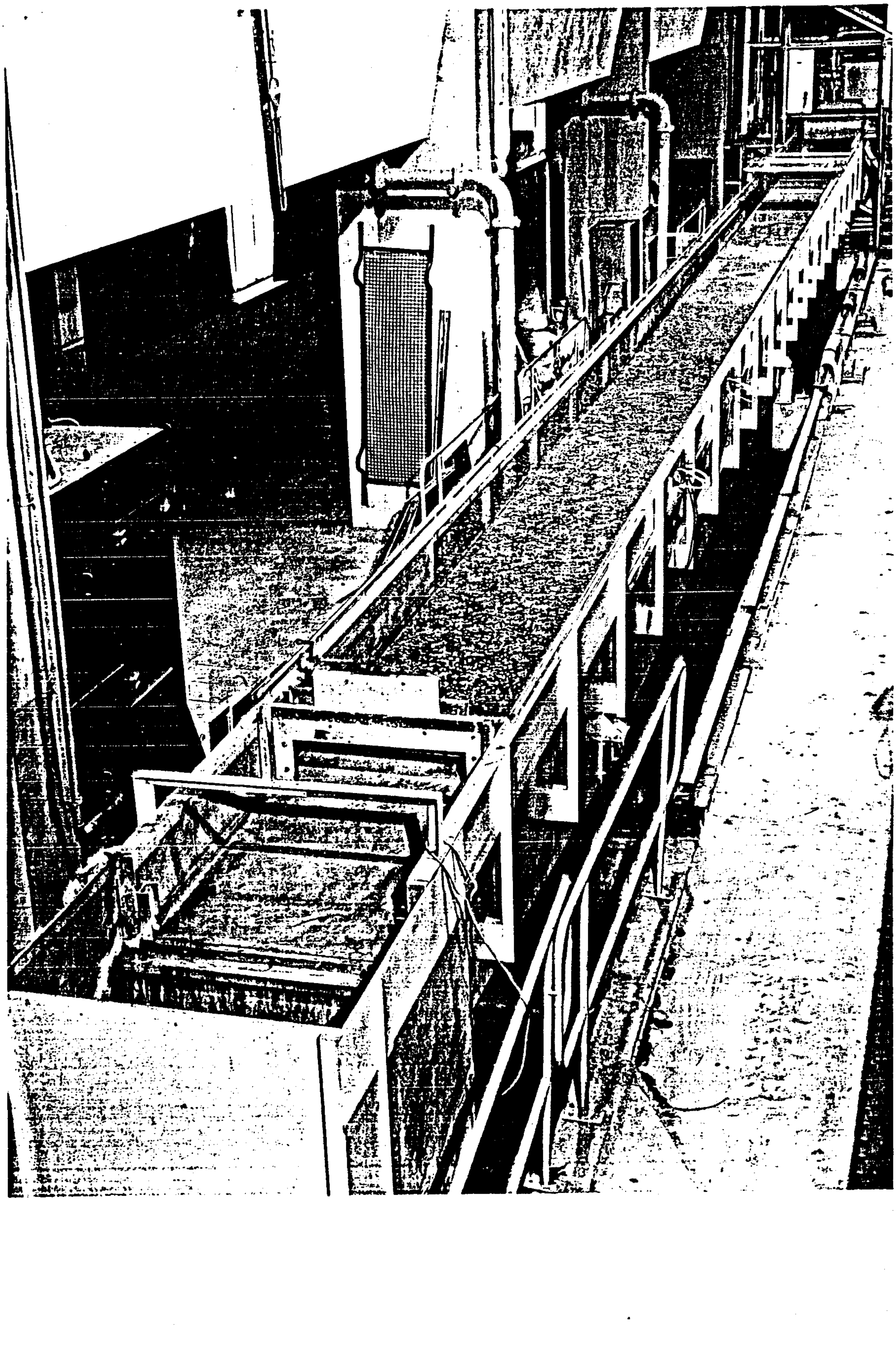


Plate 1 Layout of flume

PLATE 2 Multiple arch bridge with different soffit levels.

PLATE 3 Flow through multiple arch bridge.