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by D.A. Bruce
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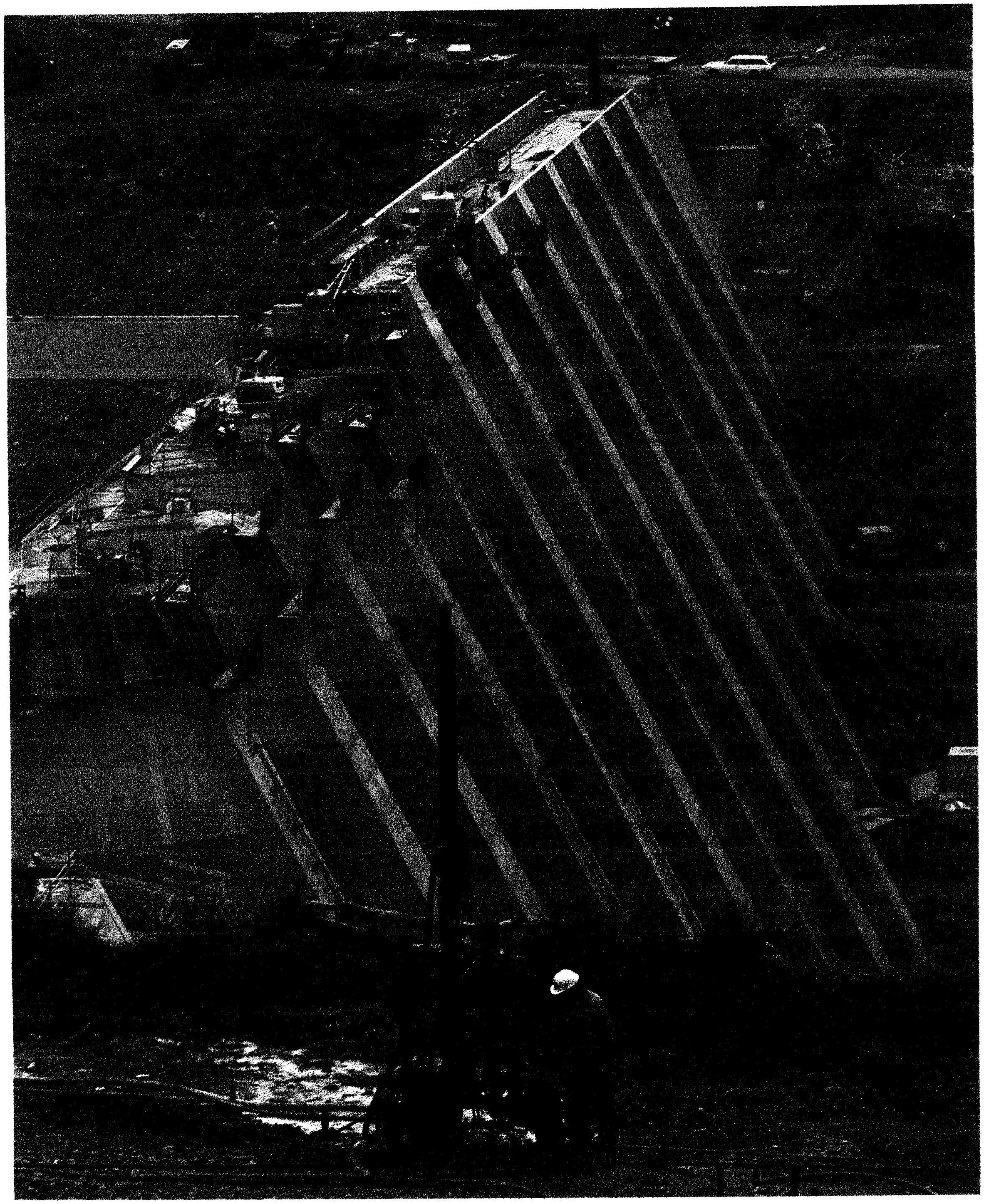

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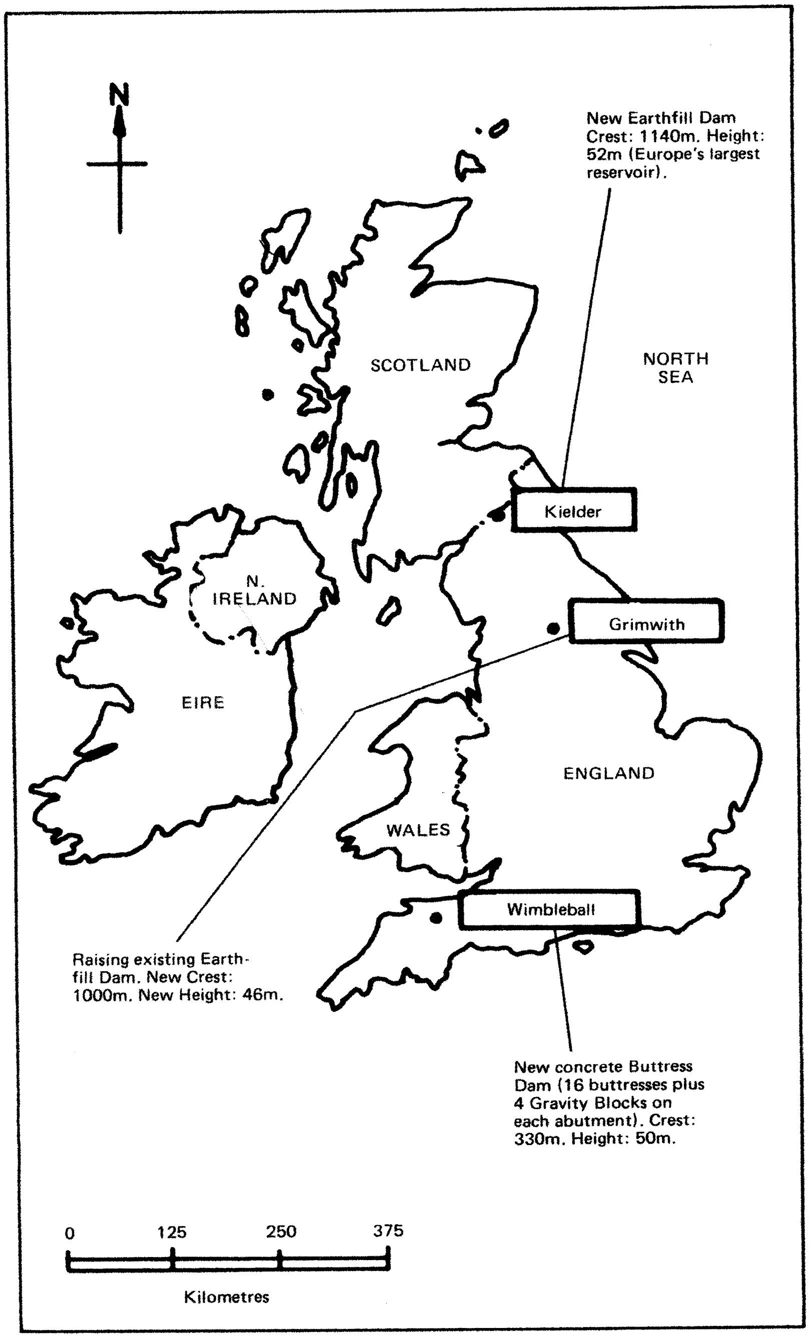

Fig 1. Details of subject dams

Abstract

As a means of illustrating certain aspects of contemporary British cement grouting practice in rock, three recent English dam grouting projects are reviewed. The first, a large concrete buttress dam, involved over 94km of drilling and 3,500 tonnes of grouting materials. Details regarding selection of grouting methods, curtain geometry, mix design, pressures and plant are provided, together with guides to analysis and assessment. On this project, the extremely poor nature of the bedrock in one particular area necessitated additional grouting and the conduct and effectiveness of this work are also described. Data are cited from the second example, Kielder Dam, to highlight the relevance of special Lugeon water testing programmes as a means of independently assessing the effectiveness of curtain grouting. The third project, Grimwith Dam, provides a good example of the application of Tube à Manchette grouting – a system adopted when the originally foreseen method of descending stage proved inappropriate in the variable drift deposits encountered in a section of the curtain near the original stream course.

1. INTRODUCTION

Particularly in North America there has been a tendency to regard dam grouting as a fully developed and established science. For example, Polatty (1974) reviewed his experience in the subject and concluded there had been very little change in Specifications over 30 years: "And, this is good". More recently, however, grouting engineers have become involved with complex remedial domestic works and with large schemes on new overseas projects, often with foreign grouting specialist contractors. Much has been made of the traditional differences between U.S. and European grouting procedures, in terms of techniques and equipment, and the relative merits of the different approaches have often been examined (e.g. at Asilomar, 1974). However, the Author's experience supports Rigny's statement at that Conference, that the most important contrast is now contractual as opposed to technical. For instance, it is now common on overseas dams for the Engineer to adopt an "open mind" approach by, for example, permitting the Grouting Contractor to select optimum methods, often on the basis of short test programmes.

Relatively few papers have been published in the last decade illustrating current British cement grouting practice in rock. American engineers may, therefore, be unaware of current methods and developments. Since space does not permit a comprehensive survey in this contribution, the more important, or potentially controversial, aspects are highlighted from works completed recently by my Company.

The first, Wimbleball Dam, Somerset, is essentially a straightforward statement of blanket (consolidation) and curtain grouting design, construction and assessment, although the importance of post-completion monitoring is underlined clearly. This project involved over

94km of drilling and 3,500 tonnes of injected materials.* At Kielder Dam, Northumberland, a full scale Lugeon water test programme was conducted to determine the effectiveness of the curtain grouting and to investigate the relationships between water test values and levels of grout acceptance. The potential of these techniques was fully realised at Grimwith Dam where they permitted potential problems with a supposedly routine grout curtain to be highlighted at an early stage. As a consequence, an alternative grouting technology, Tube à Manchette as opposed to descending stage, was employed most successfully.

2. WIMBLEBALL DAM

2.1 Geology

The dam is located in a deep v-shaped valley incised into Upper Devonian sediments, mainly hard sandstones, siltstones and mudstones. Dips vary from 45° on the North Bank to 14° on the South. From site investigation studies, including seismic refraction, deep sub-vertical shatter and crush zones were inferred, striking oblique to the line of the dam and becoming more frequent towards the South Bank. Although extreme vertical and lateral lithological variations were noted, a common feature across the site was the closely fractured nature of the bedrock.

2.2 Design

This very fissured nature of the rock mass, with its attendant potential for hole instability, dictated the use of descending stage grouting methods for the curtain. The relative merits of descending and ascending stage procedures were described recently by Bruce and George (1982), but it may be noted that very few British dam sites have enjoyed foundation rock sufficiently hard, massive and competent to permit the latter method. In addition, the shallower blanket (consolidation) grouting by its nature automatically favoured descending stages. The blanket grouting preceded the curtain in each area, to a maximum depth of 15m. The 3m stage length which was selected typifies British practice, although allowance is frequently made to increase this in late phases of grouting when grout consumptions may be expected to be lower. Hole diameter for rock fissure grouting has no significant influence on the efficiency of the injection within the normal range of diameters (40-100mm), and commonly, 50mm is regarded as the best practical and economic compromise.

Mix designs were finalised during early injection tests and ranged from w/c (OPC) ratios of 5 (apparent viscosity 1.4 centipoise) to 0.5 (37 centipoise), both by weight. Occasionally, Specifications require starting mixes as thin as 20:1 but rarely in practice do they exceed 8:1. In cases where stages were still accepting the thickest mix freely, after a total cement injection of 1,000kg, fine sand was added up to a 1:1 ratio by weight to cement. Even then, however, final grouting of the stage was accomplished by reverting to the neat cement mix to ensure the fullest treatment of the finer fissures (down to 160μ) incapable of being filled with sand particles (Littlejohn, 1975). Stages which did not come up to pressure after a total material injection of 3,000kg were abandoned for 24 hours prior to the resumption of the neat cement grouting sequence as before.

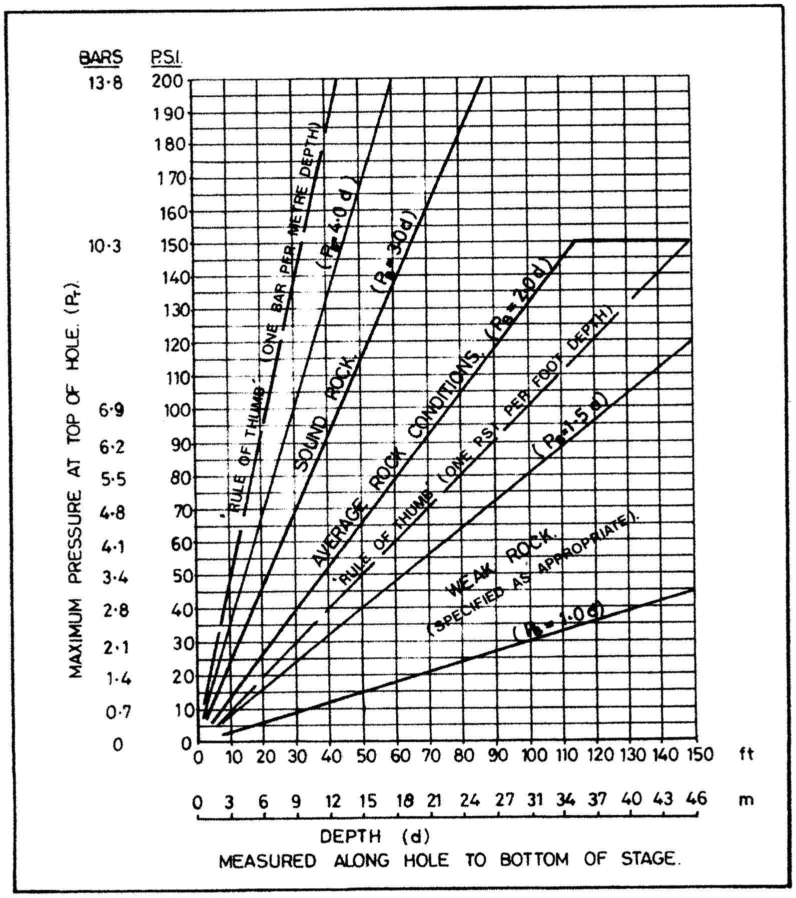

Fig 2. Typical permissible Grout Pressures for various foundation conditions (Pressures shown are at surface; P_B denotes pressure at bottom of stage, and d is the depth to there). (After Houlsby, 1977).

Average Lineal Grout Consumption (kg/m)	Designation
400+	Very High
200 – 400	High
100 – 200	Moderately High
50 – 100	Moderate
25 – 50	Moderately Low
12½ – 25	Low
0 – 12½	Very Low

Table 1. Proposed grout consumption classification (after Deere, 1976)

Refusal pressures were carefully designed to prevent the possibility of any structural uplift occurring during injection. Since most of the grouting was conducted early in the construction of each buttress, maximum pressures (as measured at the top-hole packer) were restricted to the effective theoretical overburden pressure at the top of the stage, to an overall maximum of 3.5 bar. The work of Houlsby (1977) suggests that this approach at Wimbleball may seem unduly conservative (Fig 2), but wherever there is a possibility that horizontally bedded strata exist at shallow depths, particular consideration and caution must always be exercised to avoid structural movements (e.g. Weyerman, 1977).

Since clay infilling of joints was recognised from investigatory boreholes as being neither extensive, nor significant from a geomechanical viewpoint, no major programme of clay expulsion by air and water flushing was specified. This decision again typifies current British practice, the tenent being that such attempts merely create a "pipe" between the boreholes in question, whilst not removing significant amounts of joint infill material.

Since unstable grout mixes were used (i.e. those with a very high bleed capacity due to their high w/c ratios) consumptions were recorded in terms of kg/m or kg/m². Regarding the former measure, Deere's classification (1976) is gaining acceptance in Britain (Table 1).

Grouting was conducted using "Split Spacing" (closure) procedures, each successive phase being at least two stages in arrears of the preceding one. Examination of absolute and relative phase takes formed the basis of determining the intensity of grouting: the former, Deere's recommended (1976) "Low" average consumption was the target for the last phase, whilst Reduction Ratios (e.g. the ratio of average Secondary to Primary takes) in the range 25-75% (Cope, 1978) were sought.

Conclusions on the "tightness" of the rock at any point were confirmed with simple stage water tests. In general, a target permeability equivalent to 3 Lugeons was required (1 Lugeon= 1 litre/m/min at a pressure of 10 bar).

The dam curtain was formed in a vertical plane descending continuously from concrete scarcements on the upstream side of the dam. Locally, holes were angled at 15° to encourage intersection of subvertical fissures or shear zones. It is noteworthy that inclined drilling is more expensive than vertical drilling and should be specified only on sound geotechnical or practical grounds.

The dam curtain was extended laterally for 270m as the North Wing (orientated 40° downstream for technical and financial reasons) and 318m as the South Wing (extending out along the dam centre line).

A single row of closely spaced holes was designed since (i) large amounts of erodible joint fill material were neither foreseen nor

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*SI units are now invariably used in British practice. Relevant conversion factors are provided at the end of the paper for easy reference.

recorded, (ii) no phase of chemical treatment was envisaged to achieve the target permeability, (iii) there was no evidence to suggest that the variably orientated fissures would be more successfully intercepted by a multiple row curtain than by an intensive single row. In addition, there was limited access on the narrow dam scarcements and this would have restricted markedly the potential "width" of a multirow curtain, bearing in mind the extent of lateral grout travel believed to occur (Champion, 1961).

Prior experience in similar rock suggested that final interhole spacings in the range 0.75 to 0.90m would be necessary to provide the target degree of curtain grout and water-tightness. In order that the progress could be monitored over three phases (i.e. Primary, Secondary and Tertiary) a Primary spacing of 3m was selected. As noted in Section 2.4, this estimate was in general well-founded, although the extremely poor rock encountered under some southern buttresses required Quaternary treatment to certain depths giving locally a final interhole spacing of 0.375m.

In general, the curtain depth was to be equal to at least 75% of the maximum depth of the reservoir when full and in detail this was varied depending on drilling, grouting and water take observations. This rational selection of appropriate curtain depths is obviously facilitated in practice by the use of descending stage techniques. Rarely are curtains extended to depths in excess of the storage head.

2.3 Plant

Grout hole drilling was conducted exclusively by the rotary percussive method with water flush. A variety of air- and hydraulic-powered wheel and track-mounted rigs was used depending on access and depth considerations (to 110m). Air flushed rotary or down-the-hole drilling was permitted only for Relief Wells, Piezometers or standpipe holes. This widespread use of rotary percussion was formerly one of the major contrasts between American and European practice (e.g. Gebhart, 1976), but increasing amounts of experimental data (e.g. Doty 1970) have led to a more equivocal view in both camps. Pure rotary drilling is two to five times more expensive than rotary percussion (Deere, 1976) and so merits consideration in only exceptional circumstances in Britain. For example, a certain number of Primary curtain holes may be cored to provide additional geotechnical data. It is considered that flush characteristics are often more critical in terms of subsequent hole "groutability" than the actual drilling mode.

Grouting featured the use of diesel driven Colcrete colloidal mixers (Fig 3) linked via storage tanks to Colcrete Evans Pumps, operating on reciprocating ram principles (Gourlay and Carson, 1982). Rock grouting is considered by European engineers to require a pulsating pressure flow to inhibit premature blockages arising from the temporary build-up of coarse grout particles in the fissures ("pressure-filtration"). The hydraulic Evans pumps also permitted the maximum stage grouting pressures to be pre-set, so avoiding the possibility of accidentally exerting excess pressure in any stage – an extremely valuable feature in all dam grouting applications.

2.4 Grouting Analysis

The blanket treatment involved over 22km of drilling, 4,450 stages, 742 tonnes of cement and 65 tonnes of sand. Overall lineal consumptions per buttress ranged from 19kg/m in the North, to over 154kg/m under South Gravity Block 1 – over three times the overall average blanket consumption. This evidence of marked rock mass deterioration southwards, suggested by site investigation, was further confirmed by an increase in holes per buttress, stages per hole and the use of sand, in that direction. However, despite this great inhomogeneity – from "Low" to "Moderately High" characteristics – special instrumentation of the dam during and after impounding confirmed the satisfactory response of the structure.

Regarding the dam curtain, the salient figures were 20km of drilling, 5,888 stages, 597 tonnes of cement and 7 tonnes of sand. The pattern of lineal grout consumptions was similar to that of the blanket: 19kg/m rising southwards to over 92kg/m under South Gravity Block 4. When the corresponding average areal takes per buttress were reviewed, the deterioration was even more acutely marked: 22kg/m^2 to 279 kg/m^2. In addition, it is significant that Quaternaries were required only from Buttress 13 south, i.e. for four buttresses and the four South Gravity Blocks.

The efficiency of the dam curtain in operation was confirmed by data provided by Casagrande Piezometers, Relief Wells and standpipes. The piezometers registered no excess head under the structure, whilst the Wells gave low flows (up to 2 litres/sec) except in the southern section (up to 10 litres/sec). The standpipes allowed the phreatic surface along and across the curtain to be monitored.

Data from the North and South Wings confirmed their geotechnical continuity with their contiguous dam curtain sections and on the South Wing the highest individual stage takes ("Very High") of the whole programme were recorded. The overall areal consumption of 24kg/m^2 on the North Wing contrasted with the figure of 82kg/m^2 on the South Wing.

The pattern and scale of grout takes, coupled with the Relief Well flows strongly suggested that more intensive additional grouting be done on the South side, and this need was underlined with the appearance of a series of Springs some 200m downstream on that Bank. Their flow varied with reservoir level and extrapolation showed that it could reach 114 litres/sec. at full reservoir level. Chemical analyses suggested that 23 litres/sec. of this was a run-off "constant", whilst the data from the standpipes confirmed the likelihood of a major seepage path in the vicinity of the southern end of the dam. This quantity of flow together with its potentially detrimental effects on the stability of the valley side was unacceptable, and a further phase of grouting was agreed, extending under approximately 100m of the Southern section of the dam.

It was reasoned that the high Well and Spring flows were occurring through fissures which were locally orthogonal to the line of the curtain, and had, therefore, "combed" through it, escaping full treatment during the original grouting. In such circumstances, a multirow solution is considered preferable and the additional grouting was conducted as a second parallel row of holes, 1.5m upstream, with a Primary spacing of 3m. In an effort to further increase the zone of influence of the curtain holes, grouting pressures were raised by 25%. Flows and piezometric levels were monitored closely throughout the work, to optimise its conduct in technical and economic terms. In total, a further 6.5km of grout hole drilling, 1,887 stages, 482 tonnes of cement and 95 tonnes of sand were involved. Reduction ratios of 50% dropped the Tertiary average lineal take to 28kg/m whilst 62% of the Tertiary stage takes were in the "Low" to "Very Low" range. The overall areal take averaged 70kg/m^2. The effectiveness of this treatment may be examined after three important intervals (Fig 4). During the first phase, major open "pockets" were located and treated, mainly in the upper sections of the curtain, and the average flow reduction was 3.7 litres/sec/working week. Over the same period, Well flow dropped by 50%. In Phase 2, the curtain was lengthened by 30m and deepened by several stages but with an average reduction of 1.1 litres/sec/week, whilst Phase 3 consisted of local "weakspot" Tertiary grouting (average flow reduction 0.9 litres/sec/week). Thus, by the end of the treatment, through flows had been dropped by a factor of three to 30 litres/sec, Well flows by the same ratio, and the piezometric contours showed a markedly increased gradient across the curtain line. By analysing the Phase 3 grout takes, it was concluded that this residual flow was occurring through small fissures (i.e. less than 160μ) or in deeper fissures more distant from the dam. To have further reduced it would have required either a different grouting material or more extensive conventional treatment. On balance, neither alternative was considered cost effective, and the additional grouting was discontinued at this point.

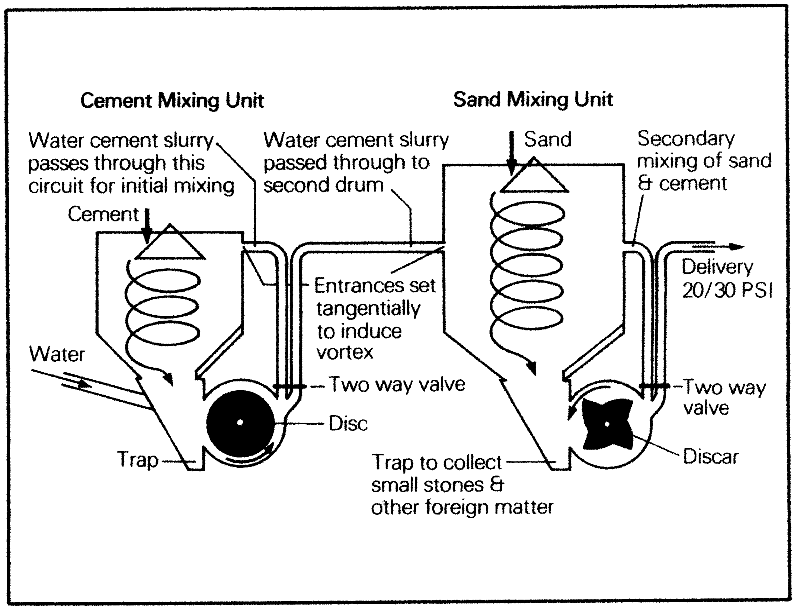

Fig 3. Operating principle of Double Drum colloidal mixer

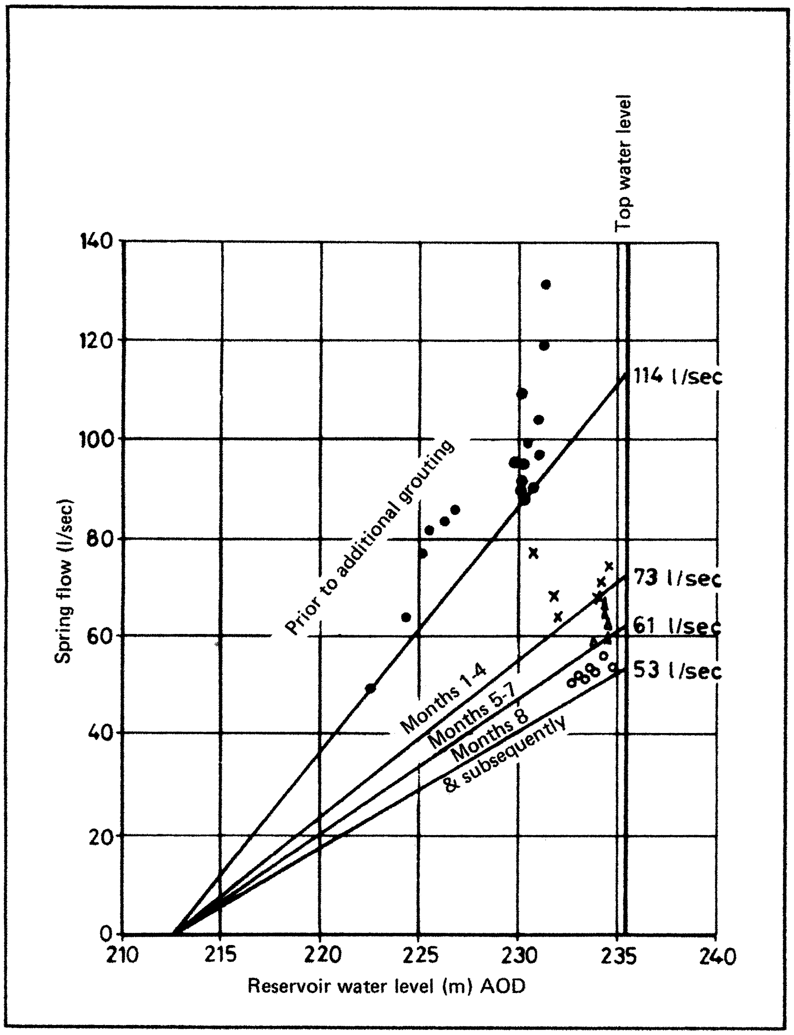

Fig 4. Relationship between Reservoir Level and Interpreted Spring Flow, illustrating effect of grouting at different periods

3. KIELDER DAM

3.1 Geology

The North Hillside of the valley comprised gently dipping Lower Carboniferous sediments, mainly sandstones, but with mudstones, shales and thin coal beds. The whole mass was closely jointed and faulted and expected to be highly permeable. The overall dam design featured a clay core linked to an upstream clay key by a clay blanket, to minimise underseepage. However, the high permeability of the North Hillside, in addition to allowing high reservoir leakage, could have threatened the integrity of the clay by piping, and a grout curtain was therefore planned in that area.

3.2 Design

The orientation of the major discontinuities, often gouge filled, led to the selection of a multirow curtain. Two Primary rows, 3m apart, with the same interhole spacing, extended over a length of 150m. It was foreseen that an intermediate row of Secondary holes would be required with any Tertiary treatment also being on this central line. The holes were vertical, 50mm in diameter and from three to ten 3m descending stages into rock with the option to deepen if necessary to terminate in relatively impermeable mudstone. Neat cement grout mixes with w/c ratios in the range 14:1 to 0.7:1 by weight were specified, with provision for sand to be added in the case of especially large takes. Early tests reduced the range to 7 to 0.49, to be thickened in ten gradual steps as necessary. A minimum of 3m of clay had to be placed before grouting, both to provide a reaction when treating the upper layers and to permit grouting of the clay-rock contact. Maximum grouting pressures were to be as high as was consistent with minimum surface displacement or splitting of the rock. These were verified by special test holes into which water was pumped at successively higher pressures and the pressure-flow relationship observed. No hydrofracture was noted despite pressures equivalent to over two times theoretical total overburden pressure being used, and grouting pressures were set conservatively at overburden pressure plus 0.4 bar (as measured at the top of the hole). It may be emphasised that here British practice is decidedly in contrast to the hydrofracture ("claquage"), high pressure grouting methods favoured by certain other European countries.

This project was remarkable in that the permeability of the rock mass before and after grouting was to be gauged in independent water test holes, following the methods of execution and interpretation proposed by Houlsby (1976). The general philosophy of the dam was "controlled underseepage", and, bearing in mind the presence of the clay blanket, it was held that the curtain need not be engineered to extremely "tight" standards (as at Wimbleball). A general target of around 10L was considered acceptable. Equally, it was not anticipated therefore that successive phases of grouting would be conducted until Deere's "Low" figure for final phases would be met. The general precept was that although specific procedures had been detailed, early results would be assessed with a view to amending or optimising the execution of the work.

3.3 Execution and Results

Standard rotary-percussive drilling plant and colloidal mixers with ram pumps were again used. Only where the clay thickness exceeded 10m was casing required to rockhead to permit the insertion of the plastic standpipe, and for this the ODEX eccentric overburden drilling method was adopted (Fig 5). This system had been used in Britain for the first time on a large production scale (viz. 75km of drilling) only recently before in conjunction with a mine infill

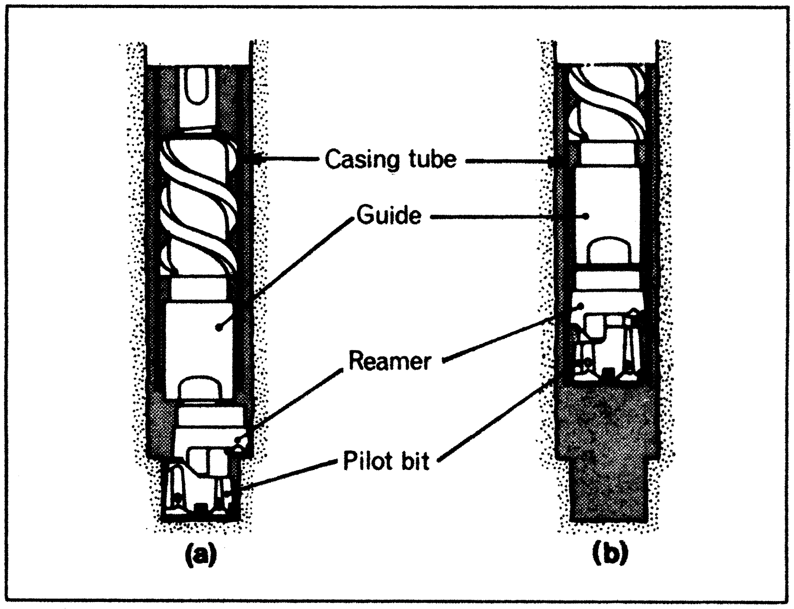

Fig 5. Major features of ODEX drilling system

project in South Wales (Patey, 1977), and again proved extremely effective in this more restricted application.

Overall, 175 grout holes were drilled, involving 4,530m of rock drilling, 1,365 stages and over 306 tonnes of cement. Full Secondary treatments were carried out in especially fractured areas where average Primary hole takes over 120kg/m were recorded, although their "Moderately Low" nature permitted 6m Secondary stage lengths to be used. A few Tertiary holes were also installed locally. Overall, the Primary holes averaged 85kg/m and others 44kg/m. The average areal take was 78kg/m^2.

3.4 Lugeon Testing

An independent programme of Lugeon water test holes was planned to assess the effects of the grouting, in terms of the permeability of the curtain zone. Eight vertical holes were involved, on the centre line of the curtain, comprising four pre-grouting (37 stages) and four post-grouting (38 stages). Each hole was drilled and tested in 3m descending stages, each isolated by a pneumatic down-the-hole packer. Each stage was tested at five pressures in the sequence "a b c b a" with the flow over a 10 minute period at each pressure being recorded. In this case, the maximum pressure (c) on the deepest stage was 10 bar, with the lowest steps (a & b) being 0.4 and 0.7 times this maximum respectively. An equivalent Lugeon value was calculated for each test pressure, and then a representative value selected for that stage with regard to Houlsby's chart (Fig 6) based on inferred type of flow regime.

Regarding the pre-grouting tests, a wide scatter of values was obtained ranging from impermeable (shale/coal) to over 100L in especially fractured sandstone. Although 49% were 5L or less, 35% were above 20L, and these stages, like the very tight ones, tended to congregate in distinct pockets. The post-grouting values did range to a 28L maximum, but 74% were 5L or less, and barely 5% were above 20L, confirming the effectiveness of the grouting as executed.

Houlsby (1976) notes that geological factors such as well roughness, frequency, orientation and geometry, strongly influence flow through fissures. One consequence is a considerable variation in results from even neighbouring holes in apparently uniform areas. On these grounds alone, close correlation may not be expected between water test results and earlier or subsequent grout consumptions. Detailed examination of the test hole and adjacent grout hole data does, however, lead to the following conclusions for cementitious grouts:–

(i) Even when water test holes are as close as 1.5m to grout holes, close correlation of grout and water test patterns may not be noted.

(ii) A low water take will indicate a subsequent low grout consumption but a high water take will not necessarily be followed by a high grout consumption.

(iii) The relative magnitude of Lugeon values is no certain guide to the magnitude (relative or absolute) of the subsequent grout takes.

(iv) When an area is grouted to refusal as indicated by cement consumptions, it may still yield moderate to high Lugeon values.

The explanation for these conclusions is related to the particulate nature of cement grouts. It may be assumed that the minimum fissure width which can be reliably treated with OPC (Type I) is 160μ (Littlejohn, 1975). A 3m stage with one such fissure, will give a Lugeon value of 10L. Conversely, a stage with five 100μ fissures will also give a value of 10L. Thus, although the first case will be groutable, the second will not, and so a post-grouting Lugeon test near the first stage will show tight ground, whereas one near the second will still show 10L. It is significant that of the 31 post-grouting stages of permeability 10L or less, 71% exhibited the "Laminar" flow characteristic, compatible with "fine" fissures.

These tests confirmed, therefore, that only the fine fissures remained untreated in the zone of the curtain, and that the great majority of the wider fissures encountered had been effectively sealed. They also highlighted the importance of considering grout and water test data together when attempting to analyse the effects of such grouting projects.

4. GRIMWITH DAM

4.1 Geology

With the incorporation of the existing 23m high earth-fill dam into the upstream shoulder of the new structure, a grout curtain was to be formed in the permeable strata present beneath the base of the clay core on the eastern side of the valley. The clay core was to be carried only to limited depths below existing ground level. Geological conditions beneath the western side of the valley were such as to render a grout curtain unnecessary there. On the eastern side of the valley the bedrock comprised alternating Carboniferous sandstones (or gritstones) and shales (or mudstones) with occasional interbedded coal seams which had been worked many years previously. This sequence overlay alternating limestones and shales (or mudstones). The strata dipped generally in an upstream direction at a small angle, and the sandstones in particular were extensively fissured and jointed. The solid rocks were overlain by a variable thickness of superficial deposits, thinning from the western, or "stream", end of the curtain (CH.800), to virtually zero thickness on the higher ground of the eastern valley side (beyond CH.900). The purpose of the curtain was to control possible seepage through the Upper Millstone Grit sandstones (estimated mass permeability 10^{-5}m/s), present in the west abutment of the dam, and it was anticipated that it would descend to terminate in relatively impermeable shale (or mudstone) at a maximum depth of 45m.

4.2 Design

A single row of 45 Primary and 45 Secondary vertical holes was planned originally, giving a total curtain length of 250m. Again, descending stage methods were adopted, reflecting the expected nature of the rock, and standard cement grout mixes and pressures were employed. As at Kielder, the overall design of the curtain did not require it to have an extremely high degree of efficiency or relative impermeability since some clay blanketing was also to be placed within the reservoir basin. A general target figure of about 10L was again considered adequate.

4.3 Results

Using conventional rotary percussive drilling rigs, and colloidal grouting plant, an intensive first phase was executed. The "Very High" Primary and Secondary takes required the installation of a further 81 Tertiary holes, located (due to the detection of clay in major fissures) in a second row, 0.75m upstream of the first. Some of these Tertiaries were locally inclined at 30° to ensure intersection of suspected subvertical fissures (as at Wimbleball). Overall, 5,013m of grout holes were drilled, and 1,597 tonnes of material injected at an average of 317kg/m or 225kg/m^2.

Although satisfactory reduction ratios of 52-78% had been recorded, the Tertiary average was still 255kg/m (vertical holes) or 133kg/m (inclined holes). In addition, surface breakout of grout was noted, even at lowest pressures, and there were instances of stages collapsing before grouting could commence. Simple stage water tests also pointed to erratic and high Lugeon values after Secondary grouting. Eighteen full scale vertical Lugeon test holes were then installed, at an average spacing of 15m along the line of the grouting, and their results precipitated the decision to conduct a second major phase of treatment, off-set 1m upstream of the original.

These holes, plus evidence from further core holes, confirmed the viability of descending stage grouting in the eastern 160m of the curtain and the subsequent re-treatment of that area proceeded with the same methods as before. After the phase, post-grouting Lugeon values were considerably below 10L. However, the same sources indicated that the western 90m of the original curtain did in fact comprise a major geological complexity, possibly in the form of a large sandstone and shale slump, intimately immersed in the clayey overburden and resting on massive limestone. Due to this area's lithological heterogeneity, its remnant high and variable permeability, and the inherent problems in relation to hole stability, descending stage grouting was reckoned not to be the most appropriate system. An alternative technology in the form of Tube à Manchette* was agreed. Since this obviously constituted a radical change in method, it was decided to test its efficacy in the most westerly (and poorest) area, extending for a length of approximately 60m. The section between there and the major "descending stage" length was to proceed simultaneously with further descending stages, but with the effect carefully assessed by Lugeon test holes. There was thus the option of selecting Tube à Manchette for this middle section also.

4.4 Tube à Manchette

This system features the use of a plastic tube (Fig 7), with groups of holes drilled at regular intervals along its length, protected by rubber sleeves (manchettes). This tube is fixed into the ground with a "sleeve" grout – a weak clay-rich mix. Normally the ground is too unstable to support an "open hole", and has to be cased when drilling to permit tube installation. This casing is withdrawn as the sleeve grout is added. After a suitable period, grouting of the ground is then conducted via a double packer lowered through the tube to isolate each sleeve location in turn. The grout forces the rubber sleeve open, flows through the sleeve grout and then exits into the surrounding ground. Upon cessation of grouting, the sleeve closes, and prevents ingress of injected grout. The system permits sleeves to be reinjected if required, and with a variety of materials.

During the first phase of (descending stage) grouting, the western area had 16 holes each with three to five 3m stages commencing from 9-15m below the surface (i.e. at interpreted rock head). Overall, the average lineal take was 359kg/m. Post-grouting Lugeon tests confirmed unstable holes of high permeability, with the great majority of test stages giving values above 20L. In addition, analysis of the test characteristics indicated "Wash out" phenomena (Houlsby, Group "D", Fig 6).

A line of 40 vertical Tube à Manchette holes was then located 1m upstream of the original, with an interhole spacing of 1.5m. Sleeves were located on the 48mm o.d. tubes at 500mm vertical intervals, and the assemblies installed in ODEX cased holes of 84mm diameter. A sleeve grout of composition (by weight) Bentonite: OPC:Water = 1:10:20 was used at an average consumption of 19kg/m of tube annulus. This mix gives a 28 day strength in the region of 2-4N/mm^2. Alternative holes were designated Primary and Secondary, and the sleeves in each likewise. This permitted the progress of the

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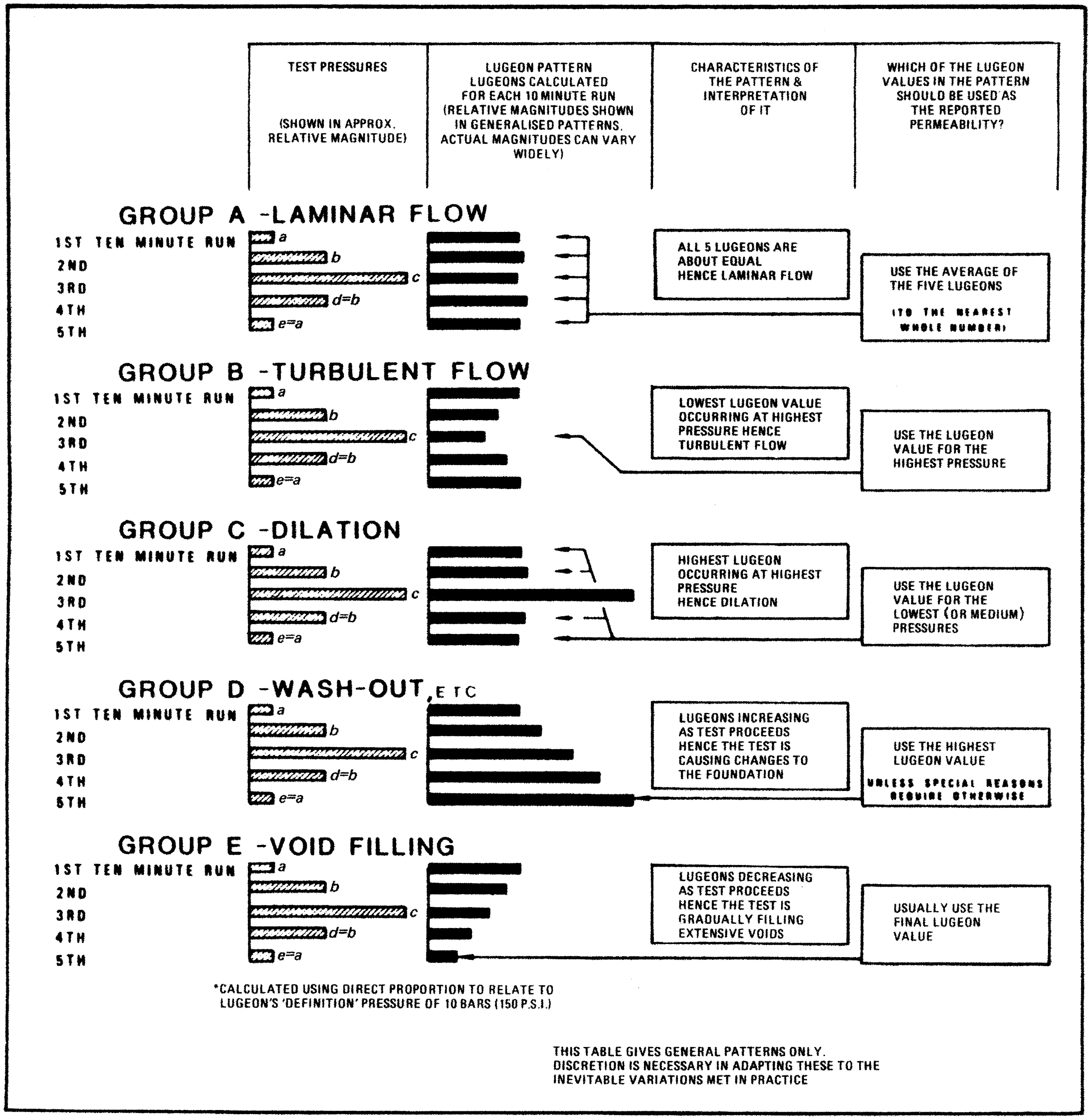
*Also known as "Sleeved Pipe" e.g. Rigny (1974).



GROUP A -LAMINAR FLOW: ALL 5 LUGEONS ARE ABOUT EQUAL HENCE LAMINAR FLOW. USE THE AVERAGE OF THE FIVE LUGEONS (TO THE NEAREST WHOLE NUMBER)

GROUP B -TURBULENT FLOW: LOWEST LUGEON VALUE OCCURRING AT HIGHEST PRESSURE HENCE TURBULENT FLOW. USE THE LUGEON VALUE FOR THE HIGHEST PRESSURE

GROUP C -DILATION: HIGHEST LUGEON OCCURRING AT HIGHEST PRESSURE HENCE DILATION. USE THE LUGEON VALUE FOR THE LOWEST (OR MEDIUM) PRESSURES

GROUP D -WASH-OUT, ETC: LUGEONS INCREASING AS TEST PROCEEDS HENCE THE TEST IS CAUSING CHANGES TO THE FOUNDATION. USE THE HIGHEST LUGEON VALUE UNLESS SPECIAL REASONS REQUIRE OTHERWISE

GROUP E -VOID FILLING: LUGEONS DECREASING AS TEST PROCEEDS HENCE THE TEST IS GRADUALLY FILLING EXTENSIVE VOIDS. USUALLY USE THE FINAL LUGEON VALUE

*CALCULATED USING DIRECT PROPORTION TO RELATE TO LUGEON'S 'DEFINITION' PRESSURE OF 10 BARS (150 P.S.I.)

THIS TABLE GIVES GENERAL PATTERNS ONLY.
DISCRETION IS NECESSARY IN ADAPTING THESE TO THE INEVITABLE VARIATIONS MET IN PRACTICE

Fig 6. The interpretation of Lugeon Test Results (after Houlsby, 1976)

grouting to be assessed over four initial phases of sleeve injections.

After initial experimentation, the maximum amount injected through each sleeve was limited to five batches (i.e. 250kg OPC, 5% bentonite by weight of water), provided the limiting flow pressure, for that depth of sleeve, had not been reached already. This refusal pressure was taken to be the same as in the descending stage grouting (i.e. approximately overburden pressure). Most sleeves required a higher *initial* pressure (up to 10 bar) to open them and fissure the sleeve grout, although some sleeves, owing to the "tightness" of the adjacent ground, scarcely accepted any grout at all. The grouting of each sleeve commenced with a mix of w/c ratio (by weight) 4:1, thickening to 2:1 as injections proceeded. Those sleeves which had accepted the original five batch injections were later selected for reinjection, to refusal (up to three further injections for some sleeves). 26% of the original 1,013 sleeves were injected following the initial phase of treatment.

Overall, 142 tonnes of cement, 14 tonnes of bentonite and 1,356 sleeve injections were involved (average 114kg/injection). Regarding the four steps of the initial phase of sleeve injections: –

(i) Average sleeve takes decreased progressively (223 to 73kg) and satisfactorily (reduction ratios 63-76%).
(ii) The percentage of "maximum batch" sleeves decreased (42 to 10%), and those which were completely "tight" increased (16 to 35%).
(iii) The rate of grout acceptance decreased from about 590kg/hour to 310kg/hour.
(iv) The cement:bentonite ratio (by weight) decreased steadily from 12.4 to 7.1 mirroring the fact that fewer sleeves took the full five batches (ending in cement-rich mixes) as treatment proceeded.

After all sleeves had been subsequently grouted to refusal, Lugeon water test holes showed results in stark contrast to the pre-grouting values: a maximum value of 6L with half 1L or less. In addition, no hole stability problems were recorded during the "open hole" Lugeon testing, further underlining the effectiveness of the grouting method.

Meanwhile, in the adjacent area, 58 additional holes had been grouted in three phases of descending stage work, interspersed with Leugeon testing. Although a slight overall improvement in permeability and hole stability was achieved, particularly by the last phase of inclined holes, test stages of up to 38L were still encountered. These descending stage treatments had involved 747m of drilling and over 130 tonnes of materials (average consumption

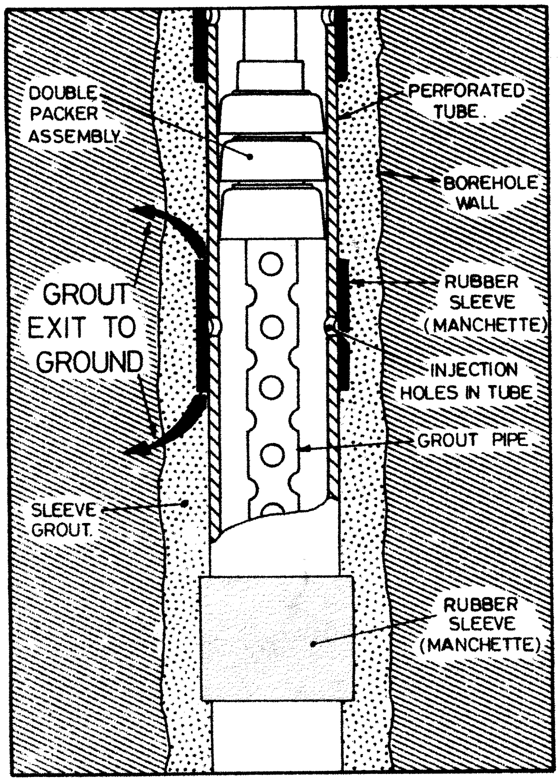


Fig 7. Operating principle of Tube à Manchette grouting system

174kg/m). These data, plus the notable success of Tube à Manchette in the first area, led to the adoption of the alternative technology in this area also. Using identical methods and procedures, post-grouting water tests on twelve stages showed eight of 1L or less, three of 2L and one of 4L. No collapse of holes was encountered.

5. SUMMARY AND CONCLUSIONS

Principally due to the quality of the bedrock, British dam grouting projects nearly always feature descending stage grouting. Stage length may vary depending on economic and technical considerations, but is usually 3m. Grout holes are drilled rotary percussive, with water flush, typically 50mm diameter, and depart from the vertical only for sound geotechnical reasons. Cement grouting is conducted with mixes most commonly in the range 8:1 to 0.5:1 (w/c by weight), although inert fillers may be added in the case of large takes, and small proportions of bentonite may be incorporated depending on the fissure characteristics. Refusal pressures, as measured at the top hole packers, are generally conservative by European standards, although trials are often conducted to optimise grouting procedures. "Split Spacing" techniques are employed, with due regard to lineal and areal consumptions, reduction ratios and final phase average consumptions. High speed grout mixers linked to fluctuating pressure ram pumps predominate. Grouting effectiveness is generally reflected in Relief Well flows, Piezometer readings, and simple stage water tests. More recently, the worth of independent Lugeon test hole schemes has been clearly indicated. Where the ground is too unstable even for descending stage work, Tube à Manchette grouting has proved extremely effective, usually linked with the ODEX method of poor ground drilling.

Measure	S.I.	British or Conventional Metric Unit
Length	1mm	0.0394in.
	1m	3.281ft.
	1km	0.621 mile
Mass	1kg	2.205lb
	1 tonne (≡1Mg)	0.984 ton
Volume	1 litre	0.220 U.K. Gal.
Pressure	1N/mm²	0.145x10³lbf/in² 10.20kgf/cm²

ALSO

1. To approximate w/c ratios by weight to w/c ratios by volume, multiply the former by 1.5.
2. 1 bar is approximately 14.5 psi. (0.1 N/mm²)
3. 1 micron (μ) = 10^{-3}mm
4. 1 kg/m ≡ 0.672lb/ft
5. 1 kg/m² ≡ 0.205lb/ft²

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