Rock anchors - state of the art
Part 3: Stressing and testing

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Introduction
PRESTRESSING AN ANCHOR automatically tests the installation, confirms to a certain degree design safety factors, and ensures satisfactory service performance. This is equally true for prestressed anchors and those subsequently intended to act as "passive" unextension members, and in both cases an initial stress history often enhances subsequent behaviour.

In addition, acceptance criteria based on standardised tests gauge the suitability and effectiveness of the installed anchor with respect to the intended application. Possible errors made in either the design or construction stages will be pinpointed immediately and potentially dangerous and expensive consequences avoided.

Incorporating these important precepts, this third part of the rock anchor review describes anchor stressing techniques, the monitoring and presentation of data, and provides guidance on the interpretation of stressing results. This basic information is intrinsic to anchor testing.

The authors believe that a standard approach to the testing and analysis of anchor behaviour should be established, relating to both short and long-term behaviour. Accordingly, the following basic types of test and quality control are recommended for consideration, and are described in detail:

1. precontract component testing,
2. acceptance testing of production anchors,
3. long term monitoring of selected production anchors,
4. special test anchors, and
5. monitoring of the overall anchor/rock/structure system.

A final section deals with aspects of long-term service performance, and reviews the relatively small number of case studies published to date. These highlight various phenomena which influence anchor behaviour in the long term.

STRESSING

Mode of stressing
There are basically two methods of applying stress to an anchor tendon:

(i) torque, applied via a torque wrench to some form of anchoring nut threaded on to a rigid bar tendon (Fig. 1a), and
(ii) direct pull, which may be applied to the tendon by a jack seated for example on a stressing stool or chair (Fig. 1b).

Torquing is normally restricted to small capacity (150kN max.) single bar tendons i.e. rock bolts of various types. In practice care must be taken to ensure that torsional stresses are not incidentally applied to the tendon, since they may combine with the tensile stresses and reduce the effective strength of the bar. This disadvantage can be alleviated by introducing a friction reducing material e.g. a molybdenum disulphide based lubricant, beneath the lock-nut prior to stressing.

The required torque to produce a specified load is usually expressed empirically in the form

\[ \text{Tensile load (kN)} = C \times \text{torque (kN.m)} \]

but whilst C may be defined within narrow limits under controlled laboratory conditions, experience suggests that variations of ± 25% can be expected for the value of C under field conditions. In addition the installed load is subject to variations due to a number of conditions related to control of alignment, friction between mating parts and size of bar tendon. Bearing in mind also that torquing is usually accomplished with the aid of an air driven impact wrench, the output of which is subject to variation in airline pressures, it is not surprising that the equipment needs frequent calibration and that good maintenance is vital. For reliable results therefore it is recommended that a calibrated hand wrench be used as a check in all cases. Nevertheless, the equipment is light, compact, easy to handle, and the stressing procedure is simple, and cheap. As a result the torqueing method of stressing rock bolts is very popular in practice, and for the interested reader more detailed information can be found in the ISRM draft publication "Suggested methods for rockbolt testing" (1974).

By far the most common and indeed for the vast majority of anchors the only suitable method is stressing by direct pull. Strand is now much more commonly used than wire, and as a result multistrand and monostrand direct pull jacks are the most common systems used today in prestressing. Monojacking relates to single strand stressing and the individual tendon units are tensioned in turn (Fig. 2a). Multistrand jacks permit all the strands of the tendon to be stressed simultaneously. These jacks may be of solid or hollow ram design (Figs. 2b & c).

Practical aspects of stressing
In order to introduce the reader to some basic procedures and concepts, as well as

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Fig. 1. Stressing by (a) torque wrench, and (b) direct pull

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the stressing jargon, the following description deals with practical aspects relating to anchor stressing in the field.

Top anchor movements should be kept ideally to a minimum. Therefore the bearing plate may be placed directly on to strong competent rock, or alternatively embedded in a mass concrete block to spread the anchor forces in the case of weak rock. For anchors with design loads in excess of 150kN it is important, prior to start of stressing, to check that the steel bearing plate has been correctly bedded centrally and normal to the tendon. This check can eliminate chaffing of the perimeter tendon components in the case of multiwire or strand tendons which splay outwards in the zone of the top anchorage or jack assembly (Fig. 3). This problem does not appear to be recorded for the case of parallel rigid bar groups.

Once the anchor grout has reached a specified strength, stressing may proceed. The authors recommend a crushing strength of 28N/mm² (see Part 2: Construction). For solid bar or single unit tendons, the stressing assembly may be fitted on to the tendon as soon as it has been thoroughly cleaned. For multi-unit tendons however it is important to verify that the wires or strands are not crossed within the free-length before fitting the anchor block and jack assembly (Fig. 4a). The correct alignment of strands is best accomplished by providing a form of comb grillage or fork (Fig. 4b), and the use of guide cords with caps is particularly beneficial on high capacity multi-unit tendons.

To simplify the description the remaining practical comments will relate primarily to multi-strand stressing using a hollow jack.

If the tendon is to be subjected initially to a special test overload to prove its design capability, then the permanent grips are normally omitted from the anchor block at this stage of the work. The jack is now fitted over the strands and the temporary stressing units (Fig. 4a) are then assembled. The jack chair or stool which provides a support for the jack is placed centrally over the tendon and the side opening should be in a convenient position to allow the operator to inspect the anchor head during the stressing operation (Fig. 2c).

The jack is now fitted manually or by a mechanical lifting device. Mechanical lifting and handling equipment is recommended for jacks weighing in excess of 80kg, and a guide relating the approximate weight of hollow ram steel jacks to their maximum rated capacity is given in Table 1.

**TABLE 1: APPROXIMATE WEIGHT OF HOLLOW RAM STEEL JACKS**

<table>
<thead>
<tr>
<th>Maximum-rated capacity (kN)</th>
<th>Approximate weight (kg)</th>
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<tbody>
<tr>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>500</td>
<td>40</td>
</tr>
<tr>
<td>1000</td>
<td>80</td>
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<tr>
<td>2000</td>
<td>150</td>
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<tr>
<td>3000</td>
<td>200</td>
</tr>
<tr>
<td>4000</td>
<td>300</td>
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</table>

It is important, prior to stressing, to verify that the elongation at the top anchor will be in excess of 30mm for the maximum load to be applied, otherwise the reusable grips (wedges) in the temporary loading head (Fig. 4c) cannot be freed on destressing. Where extensions of 30mm or less are envisaged the jack piston should be advanced to 30mm before placing the temporary loading head. The re-usable grips must be lightly lubricated with high pressure grease prior to their fitting. These grips are finally home to give a tight fit, by a gentle tapping with a special ring or U-shaped hammer. Stressing may now proceed.

It should be emphasised immediately that the space in front of the jack, and in line with the tendon axis must be kept free of personnel during the prestressing operation. Alternatively, a properly designed small aperture steel mesh cage should be provided for protection of the operators or passers-by.

A hand pump is the simplest means of pressurising the jack system to advance the ram but where many tendons need to be stressed and a high output is required a motor-driven pump is advantageous.

Bearing in mind that the stressing system may have been designed to operate at high pressures (quoted test pressures of 600 atmospheres by manufacturers are not uncommon), it is not always practical to monitor pump pressures below 40 to 50 atmospheres. The initial position of the jack piston is therefore noted at this pressure which is also considered sufficient to take up any slack in the tendon. The actual zero reading for the piston can be found by extrapolation when the ram extensions at subsequent higher pressures are noted (Fig. 4c). Throughout the stressing operation, both extensions and gauge pressures are recorded but this aspect is discussed in more detail below.

Where a test load has to be held for a period of time a slight fall in gauge pressure will be noted even though the extension of the piston remains constant. This
loss is internal to the system and a gentle application of pressure to the original reading will in most cases produce the same extension as initially recorded. For long-term stressing a lock valve at the jack is recommended.

On completion of the initial stressing operation, the double-acting ram retracts and leaves the temporary loading head in position to allow its removal. Gentle tapping with a wooden or rubber mallet is usually sufficient to release the grips which should now be re-greased and kept in a clean condition ready for the next stressing operation.

In order that load can be finally locked into the tendon, permanent grips must be inserted into the permanent anchor block. This should be possible without the total removal of the jack and chair from the ten-

Fig. 4. (a) (above), Anchor block and components of jack assembly; (b) (below left), Fork for alignment of strands; and (c) (below right), Stressing through the temporary load bearing plate (photos, courtesy, Cementation Ground Engineering Ltd.)

Fig. 5. Basic stressing mechanism at the top anchorage

Fig. 6. Jack arrangement for shimming

don, although the temporary grips will have to be removed until the permanent grips are fitted.

During stressing the chair provides a reaction head (Fig. 5) restricting the upward movement of the permanent gripping wedges. When the desired pump gauge reading is attained, the jack ram is retracted and immediately the wedges are drawn or pulled in around the tendon as it tries to retract, and so load is locked off. It is noteworthy that when this final load is considered insufficient (for reasons described below) the anchor may be restressed, and if necessary steel spacers or shims of various thicknesses can be inserted beneath the anchor block to raise the load at lock-off by increasing the tendon extension (Fig. 6).

Choice of stressing system

Multistrand stressing is swift and simple in operation once the jack has been correctly located, and requires relatively little data recording and back analysis in most cases. Nevertheless, multistrand stressing cannot provide a high degree of control over the behaviour of individual tendon units, or, at final lock-off, a guarantee of equal load in each unit. This is particularly important in anchors of free length less than 10m, where extensions are relatively small and so variations in the amount of wedge pull-in, for example, will represent proportionately larger load discrepancies than in a longer tendon.

Conversely, with respect to anchor block lift-off checks — detailed later — the multistrand jacking system alone can show the total load on the anchor in one stressing operation. Furthermore, for cyclic loading and unloading programmes, this system is easier and quicker to employ and gives more control, especially during the destressing stage. Some engineers also consider that a multistrand jacking system alone is capable of economically supplying prestressing loads in excess of 3000kN.

This view is based on the larger number of individual time-consuming stressing operations, and the larger spacing required to separate the strands in the anchor block if a monjack is employed.

On the other hand monostand stressing is a relatively popular method for tensioning tendons of up to six strands, and close control over the force in each individual strand can be achieved. Since the development of high speed front gripping jacks, and bearing in mind the limited number of strands, the method is not unduly time consuming. In addition, most single strand stressing jacks are light and easy to handle, which is a major advantage on most sites.

There are however important points concerning monostand stressing operations which are widely recognised but remain largely unexplained. For example, when Mitchell (1974) monitored with strain gauges the load fluctuations in two adjacent strands of an anchor tendon, he observed that the load in the first tensioned strand decreased steadily during the stressing of the adjacent strand (Fig. 7). This effect was in fact exaggerated because in this experiment the load was not incrementally applied to each strand in sequence as recommended in practice. Nevertheless the results clearly justified Mitchell’s subsequent advice that after application of a nominal seating load to each strand, the remaining load should be applied in four or five equal increments to each strand in turn, in a specific sequence to ensure a uniform distribution of load.
across the tendon. Mitchell also found that in a six strand tendon, at the completion of each stage of incremental loading, the greatest and least load losses monitored always occurred on the first and last strands loaded, respectively. This phenomenon has also been personally observed by Barley (1974) and the authors. In practice, after the final increment of one stressing sequence, the uneven distribution of the loading can be minimised by conducting a final stressing round to bring all strands up to the required load.

In general, it is wrong to recommend one stressing system over the other. Realistic comparisons, made to effect a choice, should only be attempted when the stressing and testing specification, and the environmental considerations e.g. accessibility, are known.

Whichever system is used, it is important in many cases to verify that the applied prestress is actually being resisted by the grouted fixed anchor zone, and further that the method of applying the tensile load is relevant to the particular application. For example the load may be applied remotely through a simply-supported beam by prestressing through a plate or pad bearing directly on the rock overlying the fixed anchor being tested. In the latter case, the tensioning procedure may simply prestress the rock and/or grout column between the fixed anchor and pad. This may have serious consequences if the test is supposed to check the stability of the pad against uplift, if it performs in service as the footing of a transmission tower for example. No work has been published on this phenomenon in rock, to the authors' knowledge, but current research being conducted by the Universal Anchorage Co. Ltd., and the Geotechnics Research Group suggests that, for shallow anchors installed in horizontally bedded, flaggy sandstone, the load is resisted locally by the rock mass in the grouted fixed anchor zone, where the slenderness ratio (depth to top of fixed anchor/hole diameter) exceeds 15.

Monitoring procedures
The prestressing of any anchor, either production or special test, presupposes the graphical plotting of anchor load against tendon extension. Such a plot facilitates judgement as to the anchor's competence and efficiency. Therefore, it is most important to be familiar with the parameters to be investigated, and methods of their measurement, presentation, and interpretation.

The parameters
The two basic parameters are, obviously load and extension. The former is self-evident, being the actual amount of prestress locked into the tendon at any one time. The tendon extension, however, involves other measurements, not always recognised as being significant in load — extension analyses. An extension, as measured before lock-off may be regarded as the "gross extension". At lock-off in the case of a wedge grip type top anchorage (Fig. 3a), pull-in of the wedges (and strand) will occur until the system is "tight". After lock-off, there may be movements due to bedding-in of the top anchor block and bearing plate, deflection of the structure, and/or permanent displacement of the fixed anchorage, in addition to the elastic extension of the tendon under load.

Long term monitoring may necessitate the recording of ground or air temperature, as variations in temperature will affect tendon prestress, and instrumentation such as vibrating wire gauges.

With regard to the recording of load-extension data Mitchell (1974) has recommended in practice that the details should be noted over four or five equal increments during loading or unloading cycles. However, Hanna (1989) considers that for a load extension diagram to be of "engineering use" it is essential that the load increments are small e.g. 10-20% of the working load (T.). In this connection the Nicholson Anchorage Co. (1973) describe the stressing of test anchors at Greenwich, Connecticut, in six equal increments, after an initial seating load.

In general, it would appear that in any one stressing stage, at least five load increments should be monitored in routine production anchor tests. In special tests however, where a more basic analysis is being attempted, extensions should be monitored at load increments equivalent to 10% or less of the maximum load for each stage in the stressing investigation.

The various levels of measurement sophistication understandablely reflect the time, money and personnel available. For load measurement, load cells have been installed on occasions to monitor anchor performance in both long and short term experimental programmes. Such cells are expensive, relatively fragile, and require regular care and maintenance, if reliable performance is to be guaranteed.

Hanna (1973) discusses load measurement in considerable detail and this reference is strongly recommended to the interested reader, since many load cells are described which are applicable to anchor situations. By way of introduction Hanna indicates that the choice of load cell is usually controlled by three factors:

(i) cost
(ii) environment e.g. access, temperature, humidity, susceptibility to damage, and
(iii) nature of load and accuracy required.

In summary, the major types of cell applicable to anchors are:

- mechanical — based on proving ring systems (up to 2 000kN)
- force measuring blocks (up to 5 000kN)
- cup springs (greater than 4 500kN),
- strain gauged elements (up to 5 000kN), and
- vibrating wire systems (up to 10 000kN).

Other methods involving photoelasticity, hydraulics and springs have also been used in practice. In all cases at least 1% accuracy is preferable and, regardless of the cell type, eccentric loading of the cell should be either assessed or prevented. The upsetting effects of eccentricity on load cell readings in the field are well illustrated by McLeod & Hoadley (1974) referred to later. It is also imperative that load cells are calibrated prior to and after use in the field.

An alternative and cheaper method for measuring anchor load is to use the pre stressing equipment available, together with a distressing stool or chair. The method is applicable to any longitudinal strands or the tendon as a whole. In both cases the principle is the same: a feeler gauge of specified thickness (0.1mm) is inserted under the anchor block or individual strands, and pulled down until it comes into contact with the stool to a certain load. The jack pump pressure at the earliest moment of insertion is recorded, and the minimum load at "lift-off" is thus evaluated. This initial residual load is commonly referred to as the "lock-off" load. The method is very common in practice, if somewhat crude, but an accuracy of ± 2% can be obtained by a careful operator. In the case of a single unit tendon the accuracy can be improved since the access to the tendon often permits the moment of "lift-off" to be registered by a dial gauge reading to 0.01mm (Fig. 8). In this connection it is noteworthy that the Czech draft code (1974) suggests that the jack operation accuracy should be ± 1% as measured from two gauges. In the case of torquing, the lift-off load is related to the reading on the hand torque wrench when the locking nut is just in motion.

In a similar way to load measurement there are a number of levels of sophistication in measuring the tendon extension. The
Fig. 8. Jack arrangement for mono-unit stressing and measurement of residual load (after da Costa Nunes, 1966)

Fig. 9. Direct method of measuring fixed anchor movement

simplest, and least accurate, method is to measure the jack ram extension. Even if the correct null extension point is noted — when the jack has fully gripped the tendon or strand — there is no guarantee that the jack extension thereafter is the same as the strand extension. This is particularly the case where slip of the strand relative to the temporary grip wedges on or in the jack occurs. Usually, therefore, the true tendon extension is overestimated by this method.

A preferable method of measurement is the one whereby a piece of adhesive tape or some other means is used to mark all or a representative number of strands at some distance above the permanent load bearing plate. The difference between this distance in the unloaded condition and that measured at successive load increments provides the basic data for a load-extension graph. For single strand stressing, this distance is measured after lock-off at each load increment when the jack has been removed. Where a solid ram multistrand jack is used no lock-off or jack removal is required at intermediate load increments. In the particular case of hollow ram multistrand stressing it may be more convenient to measure the distance between the strand mark and the temporary load bearing plate. This approach permits an accurate measurement of gross extension without removal of the jack, provided that the distance between the temporary and permanent bearing plates is recorded. These distances are usually measured with a stiff steel rule, and an accuracy of ±1 mm can be attained. In this connection the Czech draft code stipulates an accuracy of ±0.1 mm.

More refined methods, often associated with special test anchors, include the use of dial gauges attached to a simply supported datum beam, in order to monitor movement of the temporary bearing plate. In very special cases, strain gauges of either mechanical or electrical types are installed.

Remote survey is the method of accurately determining the movement of the permanent load bearing plate and should be considered whenever possible. Knowing these movements, gross extensions can be corrected to give extension data dependent solely on tendon elasticity and fixed anchor movements. The Czech draft code stipulates that precise observations be made of vertical and horizontal movements of the structure and those of the rock. Also, the supports for all measuring instruments should be such that they are independent of the structure and not influenced by deformations produced by the prestressing operations. Usually for anchors in competent rock, and prestressed against a properly designed bearing plate system, top anchorage movements provide a very small proportion of the total tendon elongation. PCI (1974) recommends that bearing plate movements greater than 13 mm should be taken into consideration. There is no disagreement with this statement but the authors believe that the significance of the actual value of movement can only be appraised when the free length of the anchor is known. For example, a plate movement of only 5 mm would be sufficient to lose 20-25% of the initial prestress in the case of a free length of some 4 m. In general however where the top anchorage movement represents less than 5% of the tendon extension it is usually ignored in the routine stressing of production anchors.

A direct, as opposed to interpretative, method of measuring the amount of fixed anchor movement involves the embedment of a wire in the fixed anchor. The wire is decoupled over the free length and extends out of the top anchorage assembly. With the wire loaded in tension, simply to keep it taut, the wire movement indicates fixed anchor movement (Fig. 9). Alternatively a redundant tendon unit may be used in place of the wire. This method has been used successfully by Liu & Dugan (1972).

Another parameter involving measurement of the tendon is the strand wedge pull-in at lock off. It should be emphasised however that this parameter is solely monitored as an indirect means of establishing the amount of lock-off loss and the resulting residual load at that time.

By careful measurement, the amount of strand wedge pull-in can be estimated to at least ±1 mm accuracy. With a multistrand stressing system the difference between the prestress at lock-off and just after lock-off is the amount of pull-in. With monostress stressing, this amount can be readily judged by close observation of the strand near the jack nose during the lock-off operation.

If accurate monitoring is required it is considered advisable to measure in the field the amount of wedge pull-in and express it as a distance in mm, rather than as contributing a certain prestress loss, since the magnitude of this loss is directly proportional to the free length of the tendon in question.

This point can be illustrated by reference to data: two tests of monostress reported by Barron et al (1971) and shown in Table II.

Recent research conducted jointly with the Universal Anchorage Co. Ltd. has led the authors to conclude that the amount of wedge pull-in increases linearly with load in the strand, after a comparatively large initial pull-in at loads up to 30kN/strand. At 200kN/strand for 15.2mm Dyform, the amount may be as high as 6mm but mostly averages between 2-4mm in fair agreement with Fenouil and Portier (1972) who estimated 2-3mm.

It has also been found that the amount of wedge pull-in is less in monostress compared with multistrand stressing. This is due to the practice of topping home the individual grip wedges immediately prior to lock-off, in the monojacking operation.

Presentation

All data relating to the stressing operation should be collected and carefully preserved. The list of items given in Table III is recommended for inclusion in a full stressing record. The data describes the rock anchor, jacking equipment and personnel, in addition to the load/stroke movement readings which should be recorded during stressing, as already described.

There is limited published data on the stressing records recommended for torqueing but a brief list of requirements is suggested in the ISRM draft document.
TABLE II. LOCK-OFF LOSSES (after Barron et al, 1971)

<table>
<thead>
<tr>
<th>Anchor</th>
<th>Free length</th>
<th>Applied load</th>
<th>Load at lock-off</th>
<th>Lock-off loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.96m</td>
<td>1352kN</td>
<td>937kN</td>
<td>30.7%</td>
</tr>
<tr>
<td>2</td>
<td>10.67m</td>
<td>1427kN</td>
<td>1256kN</td>
<td>12.0%</td>
</tr>
</tbody>
</table>


Although the final graph of load against extension will be based on corrected data, the original monitored data should also be presented on the stressing record since this information will not only provide historical data and facilitate back-analysis, but it will permit interpretation by other analysts.

When plotting the load against extension, another variable to define clearly is the point of origin of the graph. In most cases, the “zero” extension is recorded after the application of a certain seating load to the tendon, and not actually at zero load. The seating load is supposed to take up the slack in the tendon and jack, and compensate for friction and other losses in the jack/pump assembly thereby giving a more accurate measure of load-extension data.

For instance Larsson et al (1972) begin extension readings at 12% T_{e}, “to take up slack” — but also assume a zero extension of 2.5mm. On the other hand Longbottom and Mallet (1973) simply recommend starting at 10-20% T_{e}, and N.A.C. Ltd. (1974) commonly begin reading from 10% T_{e}. The biggest seating load published to date is 25% T_{e}, on anchors at the Frigate Complex, Devonport (Short 1975).

Most anchor codes e.g. Czechoslovakia and Germany advise reading from 10% T_{e} although P.C.I. (1974) recommends a start from 10% T_{e}. In the authors’ view it would appear more realistic to try and gauge the actual seating load required for any particular anchor/jack assembly in order to optimise the measurement of residual displacements, e.g. due to fixed anchor movement at zero load. Nevertheless, the above recommendations are simple and although zero readings are extrapolated the method is probably adequate for routine short term testing.

The final presentation of load-extension should indicate the maximum possible measurement errors in each parameter. Thus, when the line corresponding to the extension of the theoretical tendon length is drawn from the relationship

\[
\text{extension} = \frac{E_{\text{steel}} \times \text{cross-section area}}{\text{length} \times \text{load}}
\]

a meaningful and sensible comparison between actual and theoretical extension characteristics is permitted.

Similarly, a graph of load against time should have superimposed the theoretical relaxation curve for the tendon in question, as computed from the manufacturer’s data. In this connection it is noteworthy that elevated temperatures occurring naturally or artificially e.g. adjacent to concrete nuclear reactor vessels, considerably increase the rate of loss. It is not generally appreciated that for wire and strand at 40°C the relaxation losses are at least 50% greater than at 20°C.

**Interpretation**

The fundamental property of the load-extension curve to be adjudged is its elastic behaviour, whether linear or non-linear. Due to limits on the accuracy of the monitored data collected, it is rare to obtain a perfectly linear plot, even for the most efficient anchor. However, if the deviation from linearity is both marked and consistent in trend, it is most likely that this is due to one or both of two factors:

(i) debonding in the fixed anchor at the grout/tendon interface, and
(ii) fixed anchor movement.

The latter phenomenon is unusual in all but the weakest rock strata, but unless some form of direct measurement (Fig. 9) has been incorporated, it can only be confidently dismissed by cyclically loading the anchor at least once to ensure that the load-extension characteristics of the anchor are reproducible.

Assuming allowance has been made for the top anchorage and fixed anchor movement, an interpretation can be made with respect to the amount of partial or total debonding within the fixed anchor zone, by calculating the effective free length to produce the true elongation of the tendon actually monitored at different loads. In practice, this analysis is facilitated by drawing construction lines, equivalent to the extension of different free lengths, on the load-extension graph (Fig. 10). During the initial loading of an anchor the characteristic trend of the measured load-extension curve is to approximate to lines of short free length initially, but to progressively intersect one of longer free length with increasing load.

Cyclic loading not only highlights fixed anchorage movement, but generally facilitates back analysis, and confirms the determination of the reproducibility of the elastic load-extension characteristics. It should be noted that when drawing straight, theoretical extension lines on such diagrams involving cyclic loading, a family of these lines should be drawn through the zero load point, following the last loading cycle thereby eliminating the permanent set produced in the anchor by previous stressing.

The refined cyclic method is described by Fenoux and Portier (1972), which they consider to be systematic, easily conducted, and economic. The principle is that by careful stressing and restressing, without real change in tendon elongation, a value of load equivalent to twice the total frictional effects in the anchor can be deduced.

The method and interpretation is shown in Fig. 10. Assuming that X and X’-Y and X’-Y’ are sensibly parallel, the line X-Y represents the true values of loads corresponding to measured extensions since losses due to friction have been compensated. The point X’-Y indicates the true final load sustained by the anchor. The method also permits lock-off losses to be readily determined.

Different failure modes within the anchor may be recognised during stressing and from the analysis of load-extension data. For example, a continuous cumulative permanent displacement indicated either by rapid load loss or from a cyclic loading plot usually indicates interface failure in the anchor. Whereby this rock-grout or grout-tendon failure may be verified by loading each tendon unit with a monojack and comparing load-displacement characteristics.

Discrepancies between the theoretical and actual extensions are more often the rule than otherwise. Commonly, the amount of discrepancy permitted on any one site reflects the allowable anchor movements bearing in mind proximity of adjacent structures, the load safety factors, and the allowable tolerance of the actual errors in measurement, and the consequences if failure occurs.

P.C.I. (1974) states however, as a general rule, that, where the measured and theoretical elongations have more than a 10% difference, “investigation shall be made to determine the source of the discrepancy”.

Numerous potential sources of error can be listed. For instance, as noted in Part I — Design, the E values given by the manufacturer for his prestressing steel, and based on short lengths may be in error.

Furthermore, Janische (1968) found that in extension measurements on long lengths of strand (100m) the extension for any particular applied load varied considerably, yielding E values in the range 180 000 — 220 000 MN/m², averaging 196 000 ± 9 000 MN/m². Variations of this order were noted in strand lengths for prestressing the Wyifa nuclear reactor, but even more relevant was the observation that the elongations of tendons were comparatively much greater than their constituent strands.
Jansche attributed this to the possibility that with the stressing of multistrand tendons, taking a longer period in the field than the testing of individual strands a plastic deformation occurs in the steel in the former application giving it a larger extension and so, apparently, a smaller $E$ value.

Further information is supplied by Leeming (1974) who felt that instead of a possible maximum variation of $\pm 5\%$ (three standard deviations from the mean), quoted by manufacturers, the total variation is more probably $\pm 7\%$. He also highlighted the difference between valuation of $E$ when testing long and short specimens, by noting that the value for a $137\text{m}$ specimen was some $9\%$ less than that for a short test piece of the same strand.

On a less sophisticated level, overdrilling or underdrilling of the hole will alter the free length in practice, and the accuracy and reliability of the recording — as distinct from the accuracy of the instrument — should always be considered.

Friction is another major source of error. Even if allowance for friction losses in the jack is made — some manufacturers quote a figure of $1\%$ over the whole loading range — friction still occurs along the free length, particularly in long sheathed tendons surrounded by a protective grout surcharge column, and around the grip assembly of the top anchorage.

Such friction will act to reduce the measured extension simply by dissipating a proportion of the applied load which can act over the total tendon length. This results in an extension corresponding to a free length apparently less than is actually present. For example, Hennequin & Cambefort (1966) describe stressing details from a contract near Paris. They noted that the measured extensions were markedly lower than those estimated theoretically, and concluded that on average, only about $70\%$ of the total applied prestress was transmitted over the whole tendon length (Fig. 11). Such frictional losses can often be overcome simply by overloading by an amount particular to each anchor type.

Fenoux & Portier (1972) have also discussed friction in anchor systems and detail three types:

(i) constant value,
(ii) proportional to load, and
(iii) variable.

Each type acts on the load extension graph form as shown schematically in Fig. 12. Friction around the top anchorage is thought to have two distinct sources:

- **(a)** between tendon and grout due to the bending of the tendon units under the bearing plate; this is of the order of $3-6\%$ and can be alleviated by efficient lubrication;
- **(b)** between tendon and bearing plate, which may be up to $50\%$ if the bearing plate and anchor block are badly positioned.

Commonly however, up to $10\%$ total frictional losses in the top anchorage assembly may be expected.

Data on errors in prestressing measurements have been supplied by Longbottom & Mallett (1973). This information suggests that the difference between the observed and the theoretical force may be as much as $15\%$ when dealing with rock anchors (Table IV).

### TABLE IV. ESTIMATED ERRORS ASSOCIATED WITH THE PRESTRESSING OF ROCK ANCHORS

<table>
<thead>
<tr>
<th>Source</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Different type of manometer</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>Typical manometer error</td>
<td>$\pm 2%$</td>
</tr>
<tr>
<td>Internal jack friction</td>
<td>$\pm 2%$</td>
</tr>
<tr>
<td>Error in reading extension</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>Stress-strain &amp; production tolerance of tendon</td>
<td>$\pm 6%$</td>
</tr>
<tr>
<td>Calculation error</td>
<td>$\pm 3%$</td>
</tr>
</tbody>
</table>

However since these values will rarely act together, a more likely error is estimated to be $\pm 5\%$.

**Remarks**

It is encouraging to observe the increasing use of prestressing to load anchors, thereby subjecting the overall system to a stress history and so improving subsequent performance in service.

Measurement of anchor load in the field is generally regarded as a simple operation, although more regular calibration of
jack and pressure gauge equipment would undoubtedly lead to a higher degree of precision. Accurate monitoring of extensions is the exception rather than the rule, because these measurements in the field are often considered to be awkward or time-consuming. Insufficient attention is paid to the interpretation and consideration of the monitored load-extension data. As a result there is little real progress in the understanding of basic anchorage behaviour with particular regard to component movements of the overall anchor system.

In spite of the background technology available today in prestressed concrete, there is currently a lack of awareness concerning the sources of discrepancies between the theoretical and field results for rock anchors.

The stressing operation safety standards would be considerably improved by the use of protective barriers and warning signs.

TESTING

Precontract component testing

Prior to use on site, manufactured components such as the tendon and top anchor assembly should be tested in the independent testing establishment to guarantee component safety factors and ensure efficient performance. Alternatively, it may be acceptable on occasions when employing the standardized form of component to obtain test certificates from the manufacturers in order to facilitate or substantiate the choice of appropriate components.

With regard to the testing of the tendon steel, manufacturers should be requested to supply load-extension characteristics for each reel or batch of material delivered. In the UK, testing and the supply of test certificates and stress/strain diagrams should be carried out in accordance with BS 2691 “Steel wire for prestressed concrete” and BS 3617 “Seven-wire steel strand for prestressed concrete”. Useful guidance will also be found in FIP “Recommendations for proof load, supply and acceptance of steels for prestressing tendons”.

To confirm that the specified minimum stress/strain values have been met, the permanent extension method is used by manufacturers for proving. In the case of steel the non-proportional elongation, quoted in the definition of proof stress*, is equal to the permanent elongation which remains after the proof load has been removed. In the case of the permanent elongation is less than that defining the proof stress (e.g. less than 1.0%), then the specification has been met.

The normal test procedures is as follows:

(1) A initial tensioning stress of 10% of the specified minimum tensile strength is applied to the test piece (gauge length = 0.6m).

(2) The extensometer is set at zero.

(3) The load is increased to the specified proof stress, and held for 10 seconds.

(4) The total extension is noted.

(5) The load is reduced to just below initial stress, and then increased to the initial stress.

(6) The permanent extension is noted, and

(7) By plotting the results, the modulus of elasticity may be calculated using the linear function of the proportional stress/strain relationship.

Very little has been published on the effect of low temperatures on the ultimate strength of prestressed steel. For example, at 0.60 N/mm² steel wire a slight increase in strength occurs as the temperature falls. Sub zero temperatures (Farenheit scale) would, however, be necessary to produce a 5% increase in tensile strength, without the elongation being affected.

Apart from any question of the effect of temperature change on mechanical properties, it is useful to remember that a change in temperature of 1°C will produce a change in stress in a fixed wire of the order of 1.9 to 2.2N/mm². For applications where a significant range in temperature may be recorded in the anchorage zone, it is clear that provision of a coefficient of thermal conductivity will facilitate the analysis of test results.

Data on fatigue resistance of prestressing steels is also limited, and the manufacturers do not supply endurance diagrams for their products as a routine procedure. As Longbottom (1974) has stated, the provision of such data requires the investigation of a series of stress ranges each about a second. See for example FIP “Recommendations for proof, supply and acceptance of steels for prestressing tendon”.

In practice ground anchors are seldom subjected to fluctuations of stress of any magnitude relative to the prestress, but if in a particular case significant alterations of stress are predicted, these can be accommodated in the design of the tendon and top anchor assembly by provision for stressing to the service load plus the fluctuating stress. The successful application of prestressed concrete and steel in railway and highway bridges in resisting impact and fatigue (Lee, 1973) is ample evidence that satisfactory solutions can be produced. Eastwood (1957), Baus & Brenneisen (1968) and Edwards & Picard (1972) have described the fatigue strength of rolled thread bar anchorage and prestressing strand and some types of wedge grip top anchorages.

With reference to the top anchorage system, which may be regarded as a combination of the top anchorage, grip, anchor block and load bearing plate or waling acting together, both the grip components which secure the bar, wire or strand within the top anchorage and the complete top anchor block are subject to the cyclic action in accordance with BS 4447 “The performance of prestressing anchorages for post-tensioned construction”. Useful guidance is also given in FIP “Recommendations for acceptance of application of post-tensioning systems”.

The British Standard describes three methods of testing prestressing anchorages for prestressing applications.

(i) Test of load capacity of the anchored tendons, consisting of a short term static tensile test on the proposed anchorage attached to the tendon. The load efficiency must not be lower than 92%, where the average UTS of the tendon is determined in accordance with BS 18 “Methods of testing metals” and BS 4545 “Methods for mechanical testing of steel wire”, as appropriate.

The characteristic strength of the anchored tendon is calculated as the characteristic strength of the tendon times the actual efficiency. In this test limits of percentage elongation are stipulated.

(ii) Test of dynamic behaviour of the anchored tendon where a fluctuating force between 0.60 and 0.65 fpu at a frequency not exceeding 10Hz is applied for a minimum of 2 × 10⁶ cycles. Loss of initial cross-sectional area of the tendon due to fatigue must not exceed 5%. It is considered that this dynamic test is only relevant where the tendon is subject to fluctuating stresses which are transmitted to the tendon.

(iii) Test of force transfer to the load bearing block, consisting usually of a short term static compressive test on the complete top anchorage assembly to ensure that the load bearing block can continuously support a minimum force of 1.1 fpu.

It is suggested that the test of force transfer to the load bearing block of the form described in BS 4447: 1973 should be applied to all types of top anchorage assembly so that bearing plates, waling, and the top anchor block (if any) acting on the concrete diaphragm wall are subject to the same design and performance checks that are currently applied to reinforced concrete load-bearing blocks in prestressed concrete. The design of the load bearing block is currently covered by the recommendations of CP 115 “The structural use of prestressed concrete”.

Bearing in mind the application of rock anchoring to excavation or precasting it is noteworthy that the German DIN 4125: 1972 stipulates that the anchor head should be in a position to bear secondary stressing imposed by unforeseen flexure with adequate safety e.g. a factor of safety of 1.5 applies to the excavation structure or by angle deviation from the planned axial direction of the tendon.

With reference to anchoring equipment the authors are unaware of any concrete code which specify test procedures. In the light of discussions with jack and pump manufacturers it is recommended that all jacks and ancillary equipment should be tested in the factory to prove their design and construction and that jacks are tested to at least 1.25 times the rated capacity. Overloading above the maximum rated capacity must not be permitted in the field and the choice of jack should be such that the reloading is less than 85% of the characteristic strength of the largest tendon (largest tendon unit for a monopack) in the group of anchors being considered.

When new equipment is delivered certificates concerning proof testing, internal losses and load-pressure conversion charts or factors should be supplied by the manufacturer.

To ensure that the monitored data is accurate, pressure gauges, like the equipment, must be well maintained and calibrated regularly. It is recommended that the gauges should be calibrated for the start of every contract and then checked on site against a control gauge at monthly intervals or every thirty production anchors depending on usage. Independent calibration of jack equipment is recommended every three months.

(3 Part of this series will be concluded in our next issue)