Maintenance and monitoring of anchorages: guidelines

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The maintenance and monitoring of permanent anchorages are important, particularly for anchorages installed over 30 years ago that may have been designed with inferior or inadequate corrosion protection. Following a review of tendon corrosion failures and observed anchor head conditions after 28–33 years of service in aggressive environments, guidelines on good practice for inspection, testing, maintenance and service behaviour monitoring are presented. Topics include designer responsibility, outer and inner anchor head inspection, component and material testing, grease assessment, monitoring with load cells, load lift-off checking using multi-unit and mono-unit jacks, on-site cyclic loading acceptance testing, anchor head design to facilitate monitoring, extent and frequency of inspections and service behaviour monitoring, and associated records. Current national, European and international recommendations are also summarised.

1. INTRODUCTION

The purpose of this paper is to provide guidelines on good practice in maintenance testing and service behaviour monitoring of individual ground anchorages.

As permanent anchorages in service become older, the subject is of growing importance, particularly for anchorages installed over 30 years ago, which may have been designed with corrosion protection considered inferior or inadequate by today’s standards—for example reliance on cement grout cover alone, where the grout has been injected remotely under pressure or by gravity displacement to encase the tendon in situ. Even more recently installed anchorages are not immune, owing to the employment of inappropriate protective materials and occasional shortcomings in the quality of workmanship, combined with an absence of rigorous quality assurance/quality control (QA/QC) procedures in the field.

Routine programmes of inspection and monitoring, where satisfactory condition and service performance are confirmed, can extend the service life of anchored structures, such as post-tensioned dams, dry docks, bridges, sports stadiums and multi-storey buildings, stabilised slopes, earth-retaining walls, river and seawall coastal defences, reinforced tunnels and underground caverns, which represent key elements of a country’s infrastructure.

Alternatively, in cases where an inspection highlights unacceptable tendon exposure to corrosion, or service behaviour monitoring confirms tendon overstressing, the results can provide an early warning of the need to carry out precautionary or remedial measures, in order to safeguard the integrity and performance of the anchored structure.

In spite of these benefits, insufficient attention is paid to routine maintenance inspections and service behaviour monitoring in current practice, and the potential consequences should not be ignored.

Water levels reached 150-year highs during August 2002, with associated flooding across central and eastern Europe, so the importance of anchored river and seawalls cannot be overemphasised. Winter storms are now judged by the insurance industry to represent the largest potential event loss in Europe.1 The Association of British Insurers has identified that, in London alone, 500 000 houses, 200 schools, 16 hospitals and eight power stations are located in floodplains.2 Elsewhere in the UK there are numerous examples of waterside infrastructure incorporating anchored quay and wall structures. These include ports and harbours along the east coast of Scotland and England, the Thames Barrier, structures along the Thames Estuary, ports and harbours along the south coast of England, the Bristol Channel, the Welsh coast and west Scotland.

Elsewhere in the world, the highest potential losses are associated with earthquakes and typhoons. Given torrential rainfall, anchored slopes are vital in resisting landslides and rock avalanches. In Japan, for example, where the ground anchorage market is US$650 million per annum, 64% of an average of 2277 km of anchorages installed each year is devoted to landslide prevention and slope stabilisation.3

2. FAILURES OF ANCHORAGES IN SERVICE

In the 1980s the Fédération Internationale de la Précontrainte (FIP)4 carried out a worldwide search of anchorage failures, and published a study of 35 case histories of failure, primarily by tendon corrosion, relating to ground anchorages installed over the period 1934 to 1980. The detailed findings and records are published in the literature.5,6

The findings may be summarised as follows.
Corrosion is localised, and appears irrespective of type of tendon, in that nine incidents involved bar, 19 involved wire and eight involved strand.

The period of service before failure ranged from a few weeks to many years for each tendon type; short-term failures after a few weeks of service were due to stress corrosion cracking or hydrogen embrittlement.

In terms of failure location, 19 incidents occurred at or within 1 m of the anchor head, 21 incidents in the free length, and two incidents in the fixed length.

Both fixed anchor problems were caused by inadequate cement grouting of the multi-strand tendon bond length, exposing the tendon to corrosion. In Switzerland, where the groundwater contained chlorides and sulphides, tendon failures led to the collapse in 1981 of a 60 m span pipeline bridge over the River Thur at Dietfurt after 5 years (Fig. 1). In South Africa, unacceptable pitting up to 1 mm in depth was discovered after 2 years on a poorly grouted tendon (cement grout cover range = 0–6 mm) founded in fill, and led to rejection in 1974 of all anchorages restraining a cantilevered grandstand.

Failures in the free length occurred owing to factors such as tendon overstressing, inadequate or no cement grout cover in an aggressive environment, and inappropriate choice of protective material, such as chemical grout containing nitrate ions, and hygroscopic mastic.

Failures at or immediately under the anchor head were due to various causes, ranging from absence of protection to inadequate cover due to incomplete filling initially or slumping of the protective filler during service (Fig. 2).

In one example in Hong Kong, delays on site between completion of stressing and encasement of the anchor head in concrete exposed the tendon to a humid and slightly saline atmosphere, and caused up to 2–7% and 12% loss of wire diameter after delays of up to 8 and 36 months respectively. Reports have also recorded problems with anchorages specific to Hong Kong and installed in the 1970s, when site supervision and quality controls on site were generally poor.

Studies have been published of anchorages installed in the 1970s and 1980s in South Africa, when different techniques were employed, reflecting the variable knowledge of contractors. Based on observed field performance, aspects of ground anchorage corrosion protection and installation requiring particular attention to avoid long-term service behaviour problems are highlighted, and include:

- assessment of environmental conditions during service
- the need for meticulous care in applying protection to both the inner and outer anchor head
- the use of skilled operatives to carry out the works coupled with close supervision.

Recent examples of anchorage problems in service leading to progressive failure of sea and river walls include the Langkawi seawall in Thailand, the Kiunga loading wharf in Papua New Guinea, the 21-year-old sheet pile quay wall on the River Thames in London, and the 19-year old Chef de Baie Quay in La Rochelle harbour, France.

On the River Thames, progressive failure of the quay occurred...
in 1990 over a 142 m length (Fig. 3) owing to overstressing and corrosion of the multi-strand tendon at the anchor head caused by inadequate under-head grouting and failure of the epoxy resin coating on the outer head. At La Rochelle harbour, tie bar overstressing during backfilling behind the front wall led to horizontal displacements up to 400 mm over a 100 m length of wall in 2001. Regular visual inspections and service load monitoring would have highlighted corrosion and overstressing at an early stage and permitted timely remedial measures to avoid progressive failure. Most recently, failed structural steel tie bars up to 75 mm in diameter have been found in 2005 at the 490 m long East Arm Port Stage 1 Darwin Wharf in Australia, where the wharf has been in service since 1999. In essence, a brittle heat-affected zone from welding combined with severe bending of the tie bar created a crack and led to a brittle ‘single event’ fracture of the bar. Subsequent to discovery of three bar failures, non-destructive ultrasonic testing located a further two failures. On-site acceptance testing of the tie bars (in accordance with the recommendations of BS 8002 and BS 8081) after backfilling behind the seawall would have permitted early recognition of the nature and potential extent of the problem.

3. GENERAL CONSIDERATIONS FOR MAINTENANCE TESTING AND SERVICE BEHAVIOUR MONITORING

Maintenance testing involves inspection of the condition of materials and components of the anchorage and, where appropriate, testing to determine the nature and severity of the condition—for example, metallurgical and tension tests to assess the type and significance of a corroded tendon unit. The prime purpose of maintenance testing is to establish whether the anchorage has suffered corrosion or mechanical damage, and whether the conditions recorded are within acceptable limits.

Service behaviour monitoring focuses on the performance of (a) the anchored structure with respect to overall movement and local deformation, and (b) individual anchorages, with particular reference to residual load and anchor head displacement.

The prime purpose of service behaviour monitoring is to establish whether the anchored structure has recorded any trend in terms of overall movements and local deformations, and whether or not individual anchorages have maintained their design load in compliance with acceptance criteria.

The essential elements relating to routine maintenance testing and service behaviour monitoring include

(a) visual survey of the physical condition of the anchored structure
(b) measurement of overall movement and local deformation of the anchored structure
(c) visual survey of the physical condition of all protected individual anchorages
(d) inspection of the anchor head above and below the bearing plate of selected anchorages
(e) measurement of residual load (and preferably load–displacement behaviour) of selected anchorages.

The extent and frequency of maintenance testing and service behaviour monitoring depend on the type and scale of the anchored structure under consideration. Critical structures, where excessive deformations or failure might lead to loss of life or wide-scale damage to property, such as adjacent buildings and service networks, will demand the greatest attention during service. In addition, the effect of one, two and three adjacent anchorages failing should be quantified, with particular reference to the risk and consequences for service behaviour of the anchored structure and its overall stability. All operations involving maintenance testing and service behaviour monitoring should be in accordance with a specification created for the project; the works should be carried out by a competent specialist contractor, and be supervised by an engineer experienced in this type of investigation.

4. RESPONSIBILITY OF THE DESIGNER

For any permanent anchored structure where the consequence of anchorage failures is serious, the designer should indicate clearly at the outset the value and necessity of maintenance testing and service behaviour monitoring.

The designer should provide a method statement or performance specification for such works. In the specification, the designer should prescribe the inspection/monitoring programme in terms of anchorage number, location, frequency, acceptance criteria specific to both the condition and service behaviour of the anchored structure and individual anchorages, and reporting procedures for both maintenance testing and service behaviour monitoring.

For residual load lift-off checks, the designer should ensure an adequate protruding length of tendon at the time of installation to permit subsequent stressing. Alternatively, restressable or detensionable heads can be specified, augmented where appropriate by load cells. Where the importance of the structure warrants it, consideration may be given to the provision of extra anchor head locations at the design stage, for example the base slab of a dry dock.

In maintenance testing the designer should determine the type and level of damage and corrosion that can be tolerated and what is unacceptable that would lead to de-rating of the anchorage, for example tendon unit kinking (Fig. 4), or anchorage rejection, for example environmentally assisted stress corrosion cracking of the tendon unit(s). In service behaviour monitoring the designer should determine the maximum loss or gain of load that can be tolerated in any anchorage during its service life, taking into account the design of the individual anchorages and anchored structure.

For all programmes related to maintenance testing and service behaviour monitoring it is highly desirable to obtain detailed records covering the original anchorage design, construction and testing, in order to appreciate, for example, the corrosion protection provided and the original design assumptions. Preferably, records should include
(a) site investigation data  
(b) records of any pre-construction anchorage tests on site  
(c) anchorage number and location  
(d) anchorage design and geometry, including design free length  
(e) design working load and load safety factor(s)  
(f) tendon type, elastic modulus and characteristic tensile strength  
(g) tendon corrosion protection  
(h) grout design, including material constituents  
(i) anchorage construction details, such as drilling, water testing, tendon installation, and grout injection  
(j) specifications for all anchorage materials and components  
(k) initial mode of stressing and procedure  
(l) initial on-site suitability and/or on-site acceptance test results  
(m) lock-off load, that is, initial residual load in service  
(n) anchor head type and its corrosion protection after stressing  
(o) all relevant QA/QC records.

Subsequent results of on-site inspections, surveys and individual anchorage loads, together with the type, accuracy and calibration data of monitoring equipment, should be recorded using standard approved forms.

Maintenance testing and service behaviour monitoring records, in accordance with the designer’s specification, should be copied in a timely manner to persons with the knowledge and authority to instruct nil, precautionary, supplementary or remedial actions, as appropriate.

5. INSPECTION AND MAINTENANCE TESTING OF INDIVIDUAL ANCHORAGES

Where individual anchor heads are inspected, the condition of all components and materials should be recorded. If feasible, a sample number of anchor heads should be exposed to permit examination of the tendon, particularly in the region of the inner head immediately below the bearing plate, for example via fibrescope camera. This is particularly important where anchorage load monitoring is not possible.

All tendon units within the tensioned free length exhibiting localised corrosion—stress corrosion cracking/hydrogen embrittlement and significant pitting, for example—should be rejected. General corrosion should be accepted only where measurements of tendon unit cross-sectional dimensions confirm losses no greater than the allowable manufacturing defects of the tendon unit—for example, longitudinal cracks or depressions <4% of the nominal diameter of the tendon component or 1 mm maximum depth of depression, whichever is the lesser.5,12,13

Where doubt exists, selected anchorages can be partially exhumed to provide access to the upper free length and the area immediately behind the anchor head. In such circumstances liaison with the designer is recommended before deciding on the appropriate anchorages for intrusive testing. In this regard it is noteworthy that, on important projects, a few redundant anchorages may be considered at the design stage to facilitate this type of extensive test work during service.

Performance tests on the gripping efficiency of barrel and wedge components for multi-unit tendons can be carried out, together with metallurgical, tensile and bend tests, on representative tendon unit samples to determine whether there is any loss of strength. The results can determine whether the tendon unit is accepted, de-rated or rejected.

Where wedges gripping strands or wires within the stressing head have experienced significant corrosion, particularly on the serrated faces (Fig. 5), individual wedge units should be replaced (assuming available access) by jacking over a chair to increase the strand load and thereby release the existing wedges. In this regard, new wedge/tapered hole interfaces should be oiled or greased, to lubricate the gripping mechanism and provide a seal to prevent corrosion and ingress.

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Fig. 4. Protruding strands above anchor head with one kinked strand that may be judged redundant

Fig. 5. Serrations of wedges infilled with corrosion products that inhibit gripping efficiency after 33 years of service in a marine environment in the UK
of deleterious materials such as cementitious products that can reduce grip efficiency. Severe corrosion of the serrated face of wedges can lead to strand slippage or loss in service (Fig. 6).

Where appropriate, severed tendons can subsequently be reinstated using replacement tendon unit lengths, barrels, wedges, couplers and corrosion protection. For an anchored diaphragm wall where the stressing head was encased in cement grout, strand slippage was recorded within 12 months of anchorage installation (Fig. 7).

A visual survey of protected individual anchor heads should include assessment of corrosion, distortion or damage. Where protective caps have been damaged mechanically or by corrosion (Fig. 8), they should be removed to permit inspection of the outer head and protruding tendon, in order to establish whether the anchor head has been affected.

For steel outer caps, DIN50 929 Part 3\textsuperscript{14} provides guideline values for estimating mean corrosion rates depending on the corrosivity of the environment. For example, unalloyed and low-alloy steel caps subjected to marine conditions and (particularly) tidal effects can suffer removal rates as high as 0.1 mm/year and a maximum penetration of 0.5 mm/year.

Given this evidence, consideration should be given to the use of fibre glass protective caps fabricated to recognised standards, for example ISO 12215-1.\textsuperscript{15} Such anchor head caps were introduced to the UK anchorage industry in the early 1980s to improve protection against corrosion.

Grease checks should be carried out every 5 years on a selection of anchorages. Where corrosion-inhibiting grease is emulsified by the presence of water, or exhibits signs of ageing due to oxidation, it should be replaced with fresh material of the same specification. Alternatively, grease sampling and testing of properties should be carried out to check for compliance with the specified requirements, for example grease properties in BS 8081\textsuperscript{12} or EN 1537.\textsuperscript{16} This approach is recommended when grease is located in zones where it cannot easily be replaced, without the aid of steam jetting.

Where water ingress is encountered, sampling and testing for corrosivity are required—for example pH, chloride, sulphide and sulphate content—and the source/entry point and rate of ingress should be recorded. If the entry point for ingress is above ground level and outside the anchor head, the point of

Fig. 6. Strand loss and slippage at exposed anchor head after service of 33 years in a marine environment in the UK

Fig. 7. Removal of cement grout cover above stressing head to permit measurement of protruding strand lengths for slippage, and to facilitate restressing, if necessary

Fig. 8. Severe corrosion up to 10 mm deep recorded on protective steel cap after 28 years in a marine environment in the UK
ingress should be sealed or isolated immediately. The condition of the tendon and anchor head will determine whether the anchorage should be accepted, de-rated or rejected. Where the ingress comes from within the anchorage, for example at the sheathing/grease or grease/tendon interface, the anchorage should be rejected unless the rate of ingress and corrosivity of the water are judged by corrosion specialists to be passivating, or sufficiently benign to accommodate the design life of the structure.

When the inspection of the outer head is complete, a new base seal should be fitted before replacing the outer protective cap, and any contaminated, weathered or lost grease should be replaced with fresh material.

Inspection records for each identified anchorage should include

(a) observations before removal of the protective cap, with particular regard to the condition of the adjacent ground/structure, anchor pad, protective cap, base seal and bearing plate
(b) observations after removal of the protective cap with respect to the condition of the inside of the cap, the base seal, grease, anchor head, and locking-off components, such as wedges, bearing plate and protruding tendon
(c) close-up photographs of the anchor head assembly before and after removal of the protective cap and grease
(d) the results of any measurements and tests.

6. MONITORING SERVICE BEHAVIOUR OF ANCHORED STRUCTURE

The overall performance of the anchored structure should be monitored as a whole, involving regular surveys of selected points on the anchored structure to check for general movement and local deformations. The information should be plotted and analysed on each occasion so that cumulative plots with time are produced and the results compared, in order to highlight trends and patterns.

It is important to ascertain the movement of the anchored structure in order to help determine the cause of any change in the anchorage load. Permissible limits for total movement and local deformation should be established that may be related to the original design assumptions. Where groundwater levels are a critical factor in design, they should be monitored by means of piezometers. Data loggers can be used at reasonable cost to monitor continuously or at a suitable frequency. Regular sampling for chemical analysis may also be prudent, particularly on sites where the groundwater may be aggressive.

7. GENERAL CONSIDERATIONS FOR MONITORING SERVICE BEHAVIOUR OF INDIVIDUAL ANCHORAGES

Service load monitoring should ideally be carried out via readings from load cells, installed at the time of construction, or lift-off measurements using a multi-unit jack (Fig. 9) or mono-unit jack (Fig. 10). The use of load cells is preferred since there is no disturbance to the anchorage and its corrosion protection system, particularly at the anchor head (Fig. 11). The use of load cells should also be considered where difficult access would present problems in attaching stressing equipment for lift-off tests.
8. SERVICE BEHAVIOUR MONITORING USING LOAD CELLS

Annular load cells are used primarily to monitor anchorage loads regularly during service, and can be invaluable in assessing seasonal fluctuations, overall trends with time, and the effect of significant events such as landslips, subsidence, flooding and earthquakes.

As cells have been employed with various degrees of success, reliability and longevity are the overriding requirements when selecting the type and make of cell for monitoring load on a permanent anchorage. Generally, this is attained via simplicity of system, high-quality design and the use of durable materials, as opposed to lowest cost. The main types of load cell currently in general use are mechanical, hydraulic, vibrating wire and electrical resistance. Detailed descriptions of the different types of load cell that are available commercially, their advantages, limitations and guidelines on their use are given by Dunnicliff.17

Of particular importance when using annular load cells are eccentric loading and end seating effects. Load misalignment in rock bolts can be avoided with swivel bearing washers, and vibrating wire and electrical resistance load cells require four to six gauges at equal intervals around the perimeter, so that the average of the strain readings compensates for eccentric loading. Errors in hydraulic load cells due to uneven seating or flexible bearing plates are mitigated by the use of rigid flat end plates.

To quantify the reliability issues and assist choice, tests should be carried out by the manufacturer on each type of cell—for example, sensitivity of readings to uneven bedding, eccentric loading, sustained loading, temperature and humidity—so that the basic characteristics are known for a range of applications and environmental conditions.12,18,19 Wherever possible, the actual read-out equipment, bearing plates and cabling intended for use in the field should be calibrated along with the specific load cell.

When a load cell is first installed, it is normally checked over a range of load–unload increments against readings from a hydraulic jack and compared with the manufacturer’s calibration. During regular readings of the load cell, fluctuations due to seasonal effects, such as temperature, and long-term trends, such as tendon relaxation or ground consolidation, that do not cause concern will be recorded. In the event of exceptional changes in the load cell readings that cannot be explained, the readings can be checked by a load lift-off test and by overall surveying of the anchored structure, before incurring any unnecessary expenditure.

In relation to accuracy, the manufacturer’s quoted value for cells ranges typically from 0.5% to 1%, but in the field much depends on the quality of the installation. The loss of accuracy for a variety of cells when subjected to uneven seating and temperature changes is described by Adams.19 In order to maintain accuracy in such circumstances, the normal recommended operating range of 10–100% of the cell’s rated capacity may be reduced to 30–70%. Generally, the load capacity of the cell should at least equal the yield load of the anchorage tendon, so that the risk of bearing failure of the cell is avoided in routine service. Accuracy of measurement of absolute load in the field ranges from ±2–10%, but a relative accuracy of ±0.5–1% should be anticipated where deviations from the measured value are recorded, that is, accuracy of measurement where small changes in anchorage load are monitored against time.

Longevity is primarily a matter of appropriate choice of materials (often stainless steel), sealing and corrosion protection. If the exposed material of the cell is likely to suffer corrosion due to the environment, then the cell requires the same degree of protection as the anchor head. The cell manufacturer should provide a manual describing the frequency and type of maintenance for accessible components of the cell, field terminals and readout equipment.

For long-term measurements, and given adequate access to the anchor head and protruding tendon, the reading of the load cell, including its zero value, can be checked as and when judged appropriate via a lift-off test. If there is any doubt regarding the reading, the cell can be re-calibrated or replaced. Where the bore of the annular cell is greater than the locking nut or head, the incorporation of split shims can permit replacement of the cell without unloading the anchorage in service.

9. SERVICE BEHAVIOUR MONITORING USING CHECK-LIFTING

Where monitoring takes the form of measuring the residual lift-off load on a tendon by applying a stressing jack to the
anchor head, care must be taken to ensure minimal disturbance to the anchor tendon, and to ensure that the act of monitoring does not jeopardise the safety of the anchorage, either by forming weak links in the corrosion protection, or by overloading any part of the system. In this regard, the lift-off load is the minimum load monitored during a re-stressing operation that permits a locking nut to turn on a bar tendon, or provides a nominal clearance or lift in the case of a multi-wire or multi-strand tendon.

The distance the anchor head is raised is normally in the range 0.5–1 mm for minimal disturbance. This distance should be specified and measured using a feeler or dial gauge to provide a consistent procedure. The method of measurement should ensure that all sides of the stressing head are clear of the load distribution bearing plate. For load lift-off checks without a load cell, an absolute accuracy less than 5% is unlikely unless at least three lift-off observations confirm a consistent load, in which case the accuracy of the measurement is related to the accuracy of the calibrated jack and associated pressure gauge of 1–2%. It is recommended that gauges incorporate a large-diameter face of at least 150 mm and, where possible, some form of dual electronic readout to facilitate accurate measurement.

Initial lock-off loads for ground anchorages range typically from 1.0 to 1.15 times the design working load \(T_w\), although there is a case for locking off at higher loads, 1.2\(T_w\), for example, where this can be justified by the measurement of a high cohesive/frictional resistance within long free tendon lengths during the initial cyclic loading phase of an on-site suitability or on-site acceptance test. This case can be applicable to post-tensioned dams.

In certain circumstances, ground anchorages are locked off at only a nominal load, such as 0.1\(T_w\), where the permanent load in service is developed only as backfilling is completed behind the anchored retaining wall. It may be necessary to wait a specific time period to permit the full development of passive resistance behind the restraining element such as a sheet pile or concrete 'deadman'. On completion of such anchored structures it is essential to at least carry out load lift-off checks, and preferably on-site acceptance tests, incorporating proof load and load–displacement monitoring, in order to ensure that the anchorages comply with design assumptions.

Subsequently, for anchorages in service, no attempt is made to alter the loads being monitored, unless significant load changes are recorded. The maximum load loss or gain that can be tolerated in any anchorage during service should be indicated, unless the reasons are known--structural movement, for example--the causes and consequences should be analysed.

Supplementary lift-off checks, coupled with inspection of anchor heads, should be carried out when significant changes in load behaviour are recorded via load cells. In the event of a significant impact on the anchored structure, or a seismic event, all anchorages fitted with load cells should be monitored daily for at least 10 days to confirm no significant change in load, or until the loads have sensibly stabilised.

Replacement criteria during service—that is, permissible load loss or gain, or limiting range of movements—should be indicated at the design stage. By way of example, remedial action, which may involve partial de-stressing or additional anchorages, is recommended where load gains approach 0.4\(T_w\) for anchorages, where the original proof load factor and load safety factor for the tendon are 1.5\(T_w\) and 2.0\(T_w\) respectively. If the original proof load factor and load safety factor are 1.25\(T_w\) and 1.6\(T_w\) respectively, remedial action, which may involve partial de-stressing or additional anchorages, is recommended where load gains approach 0.2\(T_w\). If de-stressing is anticipated then shims should be placed under the stressing head at the time of anchorage installation.

Lift-off checks should be carried out in accordance with published recommendations. In this regard, factors such as tendon relaxation, consolidation of the ground between structure and fixed anchor zone, movement of the anchored structure, and seasonal temperature changes should be taken into account. In addition, due allowance should be made for external conditions, where appropriate, such as tidal levels, surcharges and local excavations that might affect stress conditions in the ground.

10. SERVICE BEHAVIOUR MONITORING USING ON-SITE ACCEPTANCE TESTING

Where high load losses are judged to be due to consolidation of the ground, then a remedial stressing programme is considered advisable, whereby the original residual load–1.1\(T_w\) for example—is regained, and on-site acceptance test service load monitoring is repeated (that is, residual load against time or displacement against time at residual load, in accordance with national standards) to determine whether the original design and on-site acceptance criteria can be restored.

Where the requirement during service monitoring is to determine or reconfirm a measured margin of safety (via a proof load) and the efficiency of load transfer (via apparent free length check), cyclic loading (residual load → proof load → residual load) with tendon displacement measurements should be carried out. Proof-loading above 1.25\(T_w\) is not often recommended in Europe, bearing in mind the minimum proof loading requirements of 1.25\(T_w\) in EN 1537.\(^{16}\)

Cyclic loading over the range residual load → proof load → residual load is preferred to detensioning (where this is feasible) in the case of multi-strand or multi-wire tendons, since detensioning permits the indented tendon units (indentations caused initially by serrations of the gripping wedges located within the permanent stressing head) to enter the free tendon length that is subsequently tensioned.

At least two complete load–unload cycles should be carried out, in order to confirm consistent reproducible behaviour that can be relied upon. The number of cycles may be increased to
three where the observed behaviour during the first cycle is not reproduced: for example, where the first application of additional load creates some fixed anchor displacement or has to overcome friction within the stressing head or free tendon length.

Residual load checks will not detect the onset of corrosion in tendons. However, they will reveal failure of the tendons where this is not otherwise obvious, and they may also indicate failures of individual strands or wires. Where bond failure is suspected in multi-unit tendons, both multi-unit jack and mono-unit jack stressing operations (Figs 9 and 10) should be carried out to permit assessment of the location of the bond failure, that is, ground/grout or grout/tendon interface.

Where a defective or failed anchorage is encountered, consideration may be given to the possibility of gleaning safely additional information, such as tendon displacement over a nominal load increment and decrement cycle, in order to check the elastic and permanent displacement components of the anchorage. In this way it may be possible to justify a reduced safe load in service. Where an anchorage fails at a fixed anchor interface, a first estimate of the new de-rated working load may generally be taken as the maximum load at failure divided by a specified load safety factor, for example 2.0 for permanent anchorages.

Thereafter, consideration should be given (wherever feasible) to a standard on-site acceptance test using an appropriate proof load factor, such as \(1.25 \times \) de-rated working load, in order to determine whether to accept or reject the anchorage at its de-rated value. When a de-rated anchorage is accepted, the residual load should be checked thereafter at each routine monitoring period for the project.

For closely spaced anchorages, for example at 1–3 m centres, simultaneous stressing operations on individual anchorages should be carried out only where the anchorages are remote from each other and preferably restrain a separate element of the anchored structure; otherwise there is the potential for one stressing operation to influence the results of another during the monitoring programme.

II. ANCHOR HEAD DESIGN TO FACILITATE SERVICE BEHAVIOUR MONITORING

Where specified, individual anchor heads should be designed to facilitate accurate service behaviour monitoring. Appropriately designed protective caps should be provided on all standard, restressable and detensionable anchor heads to facilitate service load monitoring and increase or, when required, decrease the tendon load at any time after installation.

Anchorages that may require controlled detensioning need protruding strand lengths equivalent to the recorded strand extension plus approximately 300 mm. Extended protective caps are required in these circumstances.

On occasions where inadequate protruding strand lengths are encountered beyond the stressing head (Fig. 12), consideration can be given to the use of a wedge-secured circular externally threaded stressing head block (Fig. 13). This allows the fitting of stressing equipment comprising a hub puller, stressing jack and stressing stool (Fig. 14). Load checks can subsequently be carried out by jacking the whole tendon. If the requirement is to recover losses in load, then the stressing head can be lifted, and purpose-made shims fitted to maintain the increased anchorage load.

If at least 80 mm of strand has been left beyond the stressing head, beneath the protective cap, then load checks may be carried out on individual strands using a coupler, stressing stool and calibrated monojack.
12. RECORDS OF ANCHORAGE SERVICE BEHAVIOUR

The maintenance of accurate service behaviour monitoring records represents good practice, and should include:

(a) anchorage number, type, characteristic tensile strength of tendon, design free tendon length, elastic modulus of tendon, maximum proof load, design working load and initial residual load immediately after lock-off.

(b) identification numbers and up-to-date calibration tables/graphs of jacks, gauges, pumps and load cells.

(c) residual load in service (and lift-off movement, e.g. 1 mm, if stressing is employed).

(d) total change in load as a percentage increase or decrease of initial residual load.

Detailed records using standard approved forms are necessary when assessing the condition and service performance of individual anchorages in a consistent manner.

13. EXTENT AND FREQUENCY OF MAINTENANCE INSPECTIONS

For important anchored structures, where the environment is aggressive or failure of the anchored structure would risk life and cause significant damage or disruption, visual inspections of the anchored structure and the exterior of the individual anchor head caps (wherever practicable) should be carried out every year. Where cap damage is observed, or the cap is lost (Fig. 15), the anchor head and protruding tendon units should be exposed and examined, and their condition recorded. In such circumstances all exposed anchor head units should be cleaned, the bearing plate should be provided with a protective coating such as bitumen, and a grease-filled repaired or new cap should be fitted with a new base seal and the likely cause of the cap damage or loss reported, in order to avoid a recurrence.

14. EXTENT AND FREQUENCY OF MONITORING ANCHORAGE SERVICE BEHAVIOUR

The recommended proportion of permanent anchorages to be monitored for service behaviour ranges in practice from 5% to 15%, the vast majority lying within the range 5–10% for projects involving more than 100 anchorages.

The frequency of service behaviour monitoring over the long term generally ranges from 1 to 5 years. In some cases monitoring may be required to ascertain ground or structural movements in the early life of the anchored structure, and then to detect failures (potentially due to corrosion) during its later life. In these circumstances tests should commence at short intervals of 3–6 months, with later tests at longer intervals depending on results, gradually becoming less frequent until they are carried out at not less than 5-year intervals for the life of the anchored structure.

For important anchored structures, where failure would risk life and cause significant damage or disruption, current good practice suggests that 10% of the anchorages be tested each year. Where anchor heads are detensionable or restressable, there is a growing trend to monitor all anchorages in important structures, such as nuclear-licensed naval dockyards, within a set period of time (e.g. 10 years) or at least within the design life of the anchored structure.

Where a significant number of representative anchorages (e.g. 5–15%) are fitted with load cells, more regular monitoring (e.g. every six months) is becoming common, and even shorter intervals of one month, if remote data logging is installed. The more frequent monitoring permits assessment of the effect of seasonal variations such as temperature, particularly over the first 2–3 years of service.

15. NATIONAL RECOMMENDATIONS

For readers interested in long-term monitoring and observed service behaviour of rock anchorages installed in the 1960s and 1970s, reference can be made to Littlejohn and Bruce. More recent individual case histories of ground anchorage behaviour in service can be found in the proceedings of the International Conference on Ground Anchorages and Anchored Structures in London.

National recommendations that are in use today are summarised below for a selection of countries where topics such as maintenance inspections and service behaviour monitoring are addressed. Although the recommended proportion of anchorages and the frequency of inspection and monitoring vary from country to country, the basic objective on any anchorage project should be to investigate a representative number of each type of anchorage employed, such that it is possible to assess the probable condition and behaviour of all anchorages at the site.

15.1. Australia

In New South Wales all anchorages must have provision to enable the anchorage load to be monitored, detensioned and restressed at any time. In addition, production anchorages (at least 1 in 50) must be fitted with a load cell, plus any critical anchorages detailed in the design, or as agreed with the client’s representative.
Up to the end of the maintenance period (not specified in the RTA standard), all anchorages subjected to proving tests and on-site suitability tests, those fitted with a load cell, and a further 10% of the remaining anchorages must be monitored by the contractor. Where concerns exist about the reliability of load cell readings, greater reliance has been placed on the use of confirmatory lift-off testing. RTA\textsuperscript{23} states that one should ‘measure by lift-off test the residual load where readings from a load cell are not reliable.’

The monitoring frequency is at 7 days, 14 days, 1 month, 3 months, 6 months and at 6-monthly intervals thereafter.

15.2. France
Since the issue of French Recommendations TA72,\textsuperscript{24} the extent of monitoring is typically 10% of anchorages installed for 1–50 anchorages, 7% for 51–500 anchorages, and 5% for more than 500 anchorages).

The service behaviour of permanent anchorages is monitored for at least 10 years; generally, anchorages are inspected every month in year 1, every six months in year 2 and annually thereafter.

15.3. Hong Kong
Based on GEOSPEC\textsuperscript{1,25} the minimum number of permanent anchorages and frequency of monitoring by visual survey, anchor head inspections and residual load measurements during service are illustrated in Table 1. A visual survey includes inspection of all visible components of individual anchorages, the anchored structure and any associated drainage system, in order to identify any areas of actual or potential distress, such as cracks in bearing pads or rust stains from the anchor head.

Inspections of selected anchorages comprise a survey of anchor pad, adjacent anchored structure, protective cap and the visible

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**Fig. 15. Sequence of remedial measures for corroded anchor head after loss of protective cover in service**

(a) (b) (c) (d) (e) (f)
components of the outer anchor head after removal of the grease. Where grease is removed, it should be sampled and its properties tested for compliance with the requirements of GEOSPEC. Grease properties are similar to those required in BS 8081.

When the protective cap is removed, the residual load should also be measured to verify that it remains acceptable.

### 15.4. Japan

Based on current draft guidelines of the Japan Anchor Association,

regular visual inspections should be carried out on 10% of anchorages (or more than three, whichever is the greater number) within the first three years of completion. The recommended frequency of visual inspections is annual during the first three years and thereafter every 3–5 years. If the anchorages are important or old (e.g. not corrosion-protected in accordance with the 1988 standard, which is reflected in the Guidelines for the Design and Application of Ground Anchorages, published in 1990 by the Japanese Geotechnical Society), annual visual inspections are maintained.

Given the results of such visual inspections, integrity investigations are carried out. The protective cap is removed to permit a closer examination of the stressing head on 20% of anchorages (or more than five anchorages, whichever is the greater number). The examination comprises visual checking of grease, protruding tendon, locking unit(s) and bearing plate, and is carried out once within 5 years from completion or once every 2–3 years for extremely important ground anchorages.

For service behaviour monitoring, load lift-off tests are carried out on 10% of anchorages (or more than three, whichever is the greater number). The frequency of lift-off tests is once within 5 years of completion, or for extremely important anchorages every 2–3 years.

Detailed examination of the anchor head plinth, bearing plate, stressing head, wedges and tendon units for corrosion and damage is carried out on 5% of anchorages (or more than three, whichever is the greater number). The examination also checks the volume of grease and the sealing condition to prevent water penetration. In addition, a series of tests are carried out to confirm that the tensile strength of the tendon and the resistance to withdrawal of the fixed anchor exceed the design specification. The frequency of these examinations and tests is once within 5 years of completion or, for very important anchorages, every 2–3 years.

### 15.5. South Africa

In the case of permanent anchorages that are not fully grouted over their free length, the South African code SAICE recommends, as a prudent measure, load-monitoring of 10% of anchorages over the first year of their effective life, followed by a further 10% at the end of another year, after which the degree of monitoring should be determined by an assessment of the risk from failure of any of the anchorages.

Should anchorage load gains be recorded at any stage of lift-off testing, monitoring should continue to ensure stabilisation of anchor service load within a load increment of 0.1Tn. In
the event of a larger increase, the cause should be investigated and the overall anchored structure monitored.

15.6. UK
Where the purpose of monitoring is the detection of corrosion, at least 10% of anchorages should be monitored on projects with less than 100 anchorages. On larger projects at least a further 50% of the excess over 100 should be monitored. Testing should be carried out at not greater than six-month intervals for a period of 3 years and thereafter at longer intervals of not greater than 5 years throughout the service life of the anchored structure.

15.7. USA
Depending on the number of anchorages and the importance of the measurements, typically 3–10% of the anchorages (or more if desired) are monitored for service behaviour on any given project. In general, monitoring commences at short intervals of 1–3 months and later at intervals not greater than 2 years, depending on the results. When an anchorage load gain is measured, monitoring should continue until the load stabilises. If the load in the anchorage approaches the original proof load, the anchorage is destressed to the design working load \( T_w \), additional anchorages are installed and the overall anchored structure is monitored until the overall system stabilises.

15.8. European Union (25 countries)
EN 1537\(^{16}\) contains no specific advice on maintenance testing or service behaviour monitoring, other than to confirm that ground anchorages should be installed with a monitoring facility. Where a structure is sensitive to changes in load or ground movement, the number of anchorages to be monitored and the intervals between measurements must be specified. In addition, the corrosion protection of all accessible parts of the anchor heads must be inspected periodically, and renewed if necessary.

15.9. Fédération Internationale de la Précontrainte
International recommendations for type, duration, frequency and extent of monitoring of the service behaviour of anchorages\(^{5}\) are identical to those of the UK—that is BS 8081.\(^{12}\)

16. FINAL REMARKS
In spite of the published national, European and international recommendations, which provide excellent guidance, there is little evidence that these recommendations are put into practice, to the obvious detriment of anchored structures in service.

Anchored structures represent key elements of a country’s built environment, and more attention should be paid to programmes of maintenance inspection and service behaviour monitoring in current practice, particularly where failure would risk life and cause significant damage or disruption. Such programmes can provide confidence in relation to ongoing behaviour, and potentially extend the working life of the anchored structure. Alternatively, the results can highlight the need for precautionary or remedial measures in order to ensure the ongoing integrity and performance of the individual anchorages and overall structure.

For new anchored structures the designer should indicate clearly at the outset the value and necessity of regular inspections and testing. Annual visual inspections of anchor head caps are recommended, and where significant mechanical damage or corrosion is observed the protective cap should be removed to permit assessment of the condition of the anchor head, and the need for further investigations, as appropriate.

It should also be borne in mind that many anchored structures were designed and installed over 30 years ago, when the corrosion protection provided might be considered inferior or inadequate by today’s standards. For these older structures reliance should not be placed on purely visual inspections of the outer protective caps. The condition of the stressing head should be assessed and load lift-off tests carried out on a representative sample of anchorages to check that the residual loads in service are in accordance with the original design criteria.

Out of the millions of ground anchorages that have been installed around the world over the past 80 years, it is reassuring that there have been relatively few failures recorded to date. With the passage of time, lessons have been learned and standards improved, which augurs well for the future. However, there is no room for complacency, and engineers must continue to apply high standards in design and construction. In the future, rigorous maintenance inspections and service behaviour monitoring should be included to complete sensibly the engineering requirements for important permanent ground anchorages.

ACKNOWLEDGEMENTS
The authors wish to thank Tony Barley (Director, SBMA Ltd) for providing photographs of anchor heads exposed during 2005 in the UK, where the anchorages were installed in the 1970s prior to the establishment of the draft British Standard DD 81 in 1982.

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