The single bore multiple anchor system

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INTRODUCTION

An anchor tendon with a 10m fixed length in soil or rock, will, at test load, need to extend some 30mm at the proximal end of the fixed length before any load will be transferred to the distal end of the tendon. It is unusual for the elastic behaviour of the grouted soil around the anchor tendon to be compatible with the elasticity of the tendon and allow a uniform distribution of load along the fixed length. Thus, it is widely acknowledged that, in the majority of circumstances, debonding at the tendon/grout or the grout/ground interface must occur as anchor load increases and prior to any load being transferred to the distal end of the fixed length. This phenomenon is commonly known as progressive debonding and is associated with grossly non-uniform distribution of bond stress along the fixed length at all stages of loading. Information has been published by a multitude of researchers on this topic.

Progressive debonding generally results in a highly inefficient use of the in situ ground strength; in the load condition where the ground strength deep in the fixed length is being utilised, the ground strength above has been exceeded and only a residual strength is available there at the anchor soil interface (Fig 1). However, a system that can transfer the load simultaneously to a number of short lengths in the fixed anchor bore without the occurrence of progressive debonding, will mobilise the in-situ ground strength efficiently and result in a considerable increase in anchor capacity (Fig 1). This is the principle of the single bore multiple anchor.

Fig 1a) Progressive debonding along a normal anchor fixed length
b) Single Bore Multiple Anchor ensures simultaneous loading of a number of short unit fixed lengths in a single borehole
2.0 THE SINGLE BORE MULTIPLE ANCHOR CONCEPT

The system involves the installation of a multiple of unit anchors into a single borehole. Each unit anchor has its own individual tendon, its own unit fixed length of borehole, and is loaded with its own unit stressing jack. The loading of all the unit anchors is carried out simultaneously by a multiple of hydraulically synchronised jacks which ensures that the load in all unit anchors is always identical.

In a situation where the load transfer mechanism from tendon to grout eliminates progressive debonding, or where the unit fixed lengths are short enough to be unaffected by the progressive debonding, then in a homogeneous stratum the maximum ground strength can be mobilised (by bond) uniformly and simultaneously over the entire fixed length. Furthermore, with such a system there is no theoretical limit to the total overall fixed length utilised whilst, in normal anchors, little or no increase in load capacity is expected with fixed lengths greater than 8 to 10m.

In the case of non-homogenous soil conditions in the fixed length, each unit fixed length can be designed for the appropriate condition. If the soil is weaker in the upper fixed length, then the proximal unit anchors will have longer unit fixed lengths than those at greater depth such, that when equal load is applied to each unit anchor, each one is mobilising the same percentage of the ultimate grout/ground bond capacity, or such that each failure occurs simultaneously. Albeit, if the unit anchors are founded in soil conditions with different creep characteristics, the unit fixed lengths would be designed such that each unit anchor design complies with the appropriate creep criterion in its particular working condition.

The SBMA system can also be designed for the encounter of soil with strength reducing with depth, or with strength varying throughout the fixed length, or even for the encounter of very weak bands of soil at irregular depths. In the latter case, the number of unit anchors is designed to allow for a potential failure of one or two unit anchors, whilst the remaining intact unit anchors will still sustain the total anchor working load with an appropriate factor of safety.

3.0 HISTORY

The idea of staggering the location of bonded strand lengths in the fixed length may have been considered in the early days of anchor development, but research has revealed no data published confirming the use of the concept. In 1978, the writer carried out investigation pull-out tests on very short resin encapsulated lengths incorporating enclosed end grips and strand vice connectors (Ref 1). This confirmed that load could be fully transferred from the strand to short encapsulated lengths and then on to the anchor grout. The incorporation of 3 such units, staggered in a 2m gun barrel, may have marked the first test of a single bore multiple anchor.

Some ten years later Messrs Greenwood and McNulty (Ref 2) published a report on their shear tube anchors. This system also involved a lock-off system located on the strand to ensure full load transfer over a short length. However, these shear tubes were located not in individual encapsulations, but at staggered depths with a single 6m long pregrouted encapsulation. The system was first used on a commercial scale with test anchors installed in silty sand in Shrewsbury, where the multi-strand anchor was loaded with a normal multi-strand stressing jack. A fifty percent increase in capacity over an adjacent normal 6m encapsulated anchor was exhibited. The shear tube system, although it has some commonality with the SBMA, is not in fact a multiple anchor system. The maximum length
over which the load can be transferred is limited by the length of the single prefabricated
encapsulation that can be handled without damage. Furthermore, like other multi-strand
anchors, it is stressed by a single multi-strand jack that does not accommodate the uneven
extension exhibited by a multiple of unit anchors.

The writer’s research into the use of short load transfer lengths from strand to grout within
short encapsulation continued through the early 1980s. The first full-scale commercial single
bore multiple anchors, in which each unit anchor encapsulation was isolated from others in
the overall anchor fixed length, and each unit individually loaded, was at Southampton in
1988 (Ref 3). A total load of 1337kN was recorded on the annular anchor load cell during
testing of five unit anchors founded in clayey Bracklesham Beds. Development and
refinement of multiple anchor techniques has continued over an eight year period and some
25,000 unit anchors have been successfully installed and tested (Photo 1).

4.0 PRACTICAL CONSTRAINTS

4.1 General

Theoretically, the multiple anchor system would work to its maximum efficiency when utilising
a large number of low load capacity unit anchors, each with relatively short unit fixed lengths
over which no progressive debonding exists. However, the following constraints control the
number of unit anchors and the unit anchor capacities:

i The bond length, or the bond mechanism, used at the tendon/grout interface of each unit
to allow safe use of the full tendon capacity;

ii The diameter and type of the corrosion protection of the fixed anchor (encapsulation);

iii The influence of the passage of the free length tendons from the deep unit anchors
(distal) on the bond capacity of the shallower unit anchors (proximal) and the resulting
congestion in the borehole;

iv The arrangement at the anchor head of the multiple of individual jacks in the
hydraulically synchronised stressing system. (All unit anchors have different free lengths
and hence require different amounts of extension and ram travel).

4.2 The unit anchor tendon
The difficulties in handling and coupling rigid bars, and the extremely low capacity of a single wire tendon, immediately exclude both types of tendon from consideration.

Strand is readily available in three sizes, 12mm, 15mm and 18mm, with a type variety in each group (normal, superstabilised and dyform or compact). Extensive research information from strand and encapsulation pull-out tests has allowed a number of options of bond mechanism to be considered. These range from non-deformed strand to deformed strand, or deformed tendon, or to mechanical locking devices. For permanent works requiring the encapsulation of the strand within a double plastic corrugated duct system (developed to comply with the corrosion protection requirement of BS 8081 (Ref 4), the deformed strand is the preferred system, whilst for temporary works either deformed strand or a mechanical device for removable anchors is available (Ref 5).

Although research has established that the full capacity of the entire range of strands could be achieved within the encapsulation lengths of 1 to 1.5m, in practice, the unit encapsulation lengths have been standardised in the 2 to 3m range as a general safeguard.

Further research has determined that encapsulation size, complete with a double plastic layer, could be as little as 22mm, but the common diameter now in use is 50mm for ease of fabrication.

Initially unit anchors contained only single strands, but the demand for higher unit tendon capacity to ensure failure at the ground/grout interface in preliminary trial anchors necessitated incorporation of two strands. Subsequent development has confirmed that a multiple of strands may be incorporated satisfactorily into the double protected encapsulations of individual unit anchors to allow mobilisation of even higher unit anchor loads.

4.3 Multiple stressing jack and load measurement arrangement
The initial choice of the unit anchor tendon system determined that the range of test loads required in production unit anchors was between 200 to 300kN (75% characteristic strength of strands). In order to demonstrate factors of safety in the range 2 to 3 in the test loading of preliminary trial anchors, or to achieve failure at the ground/grout interface, unit anchor test loads up to 600kN have accordingly been required.

In utilising a multiple of hydraulically synchronised jacks, the arrangement which maintains the unit anchor tendons on the minimum pitch circle diameter has been found to be most appropriate. This allows use of normal 150mm to 200mm diameter ducts at the head of the anchor, with only nominal deviation of the strand alignment. Safe loading to test loads of 4200kN can now be carried out utilising a specially designed seven-unit jack arrangement (Ref 5).

Each of the jacks is coupled via a central manifold to a single hydraulic power pack. Thus, during load application, the load in each unit anchor is always the same. The hydraulic pressure is measured by a pair of matched calibrated gauges and, based on the ram area of the identical jacks, the applied load is known. Any error in measurement of pressure is identified immediately by observation of discrepancy between the two gauge readings, and by checking the gauge pressure on the power pack itself. Any friction within the “system” can be established
by carrying out loading and unloading cycles. Owing to continual difficulties over a 15 year period in achieving compatibility between loads established from pressure gauge readings with those recorded by load cells (strain gauged, vibrating wire or hydraulic), more emphasis has now been placed on determining loads by accurate reading of hydraulic pressure gauges alone.

In the case of preliminary trial anchors, each individual jack also has its own pressure gauge and lock-off valve. If, from the load/extension data, the failure or onset of failure of a unit anchor is suspected then its valve is closed and the load in that unit can be observed independantly while further testing of the other unit anchors is continued.

4.4 Unit anchor fixed lengths
Having established from the multiple jack arrangement the optimum number of unit anchors, and from the tendon system the range of working and test capacities of unit anchors, then the design of the unit anchor lengths can be made. Fixed lengths of double that of the short encapsulation may be accommodated and still ensure efficient mobilisation of the ground strength (Ref 6). This subjects the anchor grout to shear and compression above the encapsulation and shear and tension below the encapsulation. However, it should always be borne in mind that in the vast majority of conditions shorter unit fixed lengths (2 to 4m) are more efficient than longer unit fixed lengths (4 to 8m), and thus an appropriate choice of borehole diameter is also relevant; typically 200mm dia. in stiff clays, 140mm dia. in stronger glacial clays and weak rocks and 140mm dia cased holes in medium dense fine sands.

4.5 Effect of adjacent tendons on proximal unit fixed anchor lengths
All mechanisms which transfer load from tendon to grout, or encapsulation to grout, subject the grout to bursting stresses. Owing to the very limited tensile strength of cementitious grout it is, in the majority of cases, the surrounding soil or rock which effectively confines the grout and prevents the grout column bursting at low loads. The presence of a number of strands in close proximity and within a compressible sheath, adjacent to the bond system of the proximal anchors, provides a considerable weakness in the grout column and reduces the effective confinement. Research has been carried out to investigate the influence of the presence of the adjacent strands on the bond capacity of both the encapsulations and mechanical devices (Ref 7). In soil conditions where confining stresses are limited, a system of surrounding the adjacent strands in non-compressible sleeves, and reinforcing the grout, has been developed to ensure these problems do not result in low capacity pull-out failure.

From the testing of the numerous anchors, it has been established that friction within the free length of the strands of the distal anchors can, due to their passage of upper encapsulations, be greater than that in proximal anchors. For this reason, it is recommended that the lower limit of the apparent tendon free length acceptance criterion is 80% (or strand extensions are less than 80% theoretical). This limit is consistent with that specified in the new European Standard (Ref 8) and nominally less than that adopted by the British Standard, BS8081 (Ref 9). It should be borne in mind, however, that via the nominal friction the load is still transferred into the overall fixed anchor length.

4.5 Effect of load change in a production single bore multiple anchor.
It has been normal practice in the U.K. for over a twenty year period to apply a preload of 110% of the working load to production anchors.

This generally provides more than a reasonable overload to ensure that, within the life of the anchor, load loss due to soil creep or tendon relaxation does not cause the load to fall below the
designed working load. This procedure complies with BS8081 and as such is applied to more than 95% of installed anchors. However, there are occasions in which the full working load is not applied to an anchor, and subsequent load change results entirely from the amount of movement of the anchor head in the axial direction.

Where SBM anchors are installed for use in the normal applications, where full working load is applied, then no special considerations are necessary. However, where the anchors are intended to be partially or fully loaded by structural movement of the anchor head, then consideration must be given to the designed variations in the unit anchor free lengths. When the anchor head moves, the load increase in the proximal unit anchor will be greater than that in a distal unit anchor due to its shorter elastic length; thus the load locked into each unit anchor at a datum, or an intermediate level, must be varied such that when the calculated amount of movement necessary to load the anchor occurs, then after this movement the unit loads will be equal, and no individual unit anchor overloaded.

5.0 TEST ANCHOR PROGRAMMES
One of the major benefits accruing from the installation and testing of preliminary trial anchors using the multiple anchor system, is that each unit anchor provides a full and comprehensive set of data with regard to its own elastic and non-elastic behaviour and bond capacity; i.e. a six unit anchor provides six times as much data as a normal anchor (Fig 2). Attempts have not been made to fully isolate the grout column associated with each unit anchor, and it is accepted that some upward transfer of load may exist between unit anchors during normal loading. However, in the trials carried out to date, the determination of failure capacity of some middle or lower unit anchors has not been prevented by this phenomenon. Furthermore, after reaching a general stage of failure, subsequent tests have been carried out to substantiate the information from individual unit anchors. The proximal anchor is loaded to failure first, and the associated grout column pulled away remote from

Fig 2 - A six-unit anchor provides six sets of load extension data and six sets of information on
bond stress. Note 3648kN without failure.

the one below. This is repeated, working progressively towards the distal anchor. In addition
to the trials carried out to establish ultimate capacities, in the majority of cases, load holding
tests have been carried out at locked off loads of 1.1 x working load, to ensure load loss does
not exceed 1% load per unit time over 8 time periods (5, 15, 50, 150, mins; 8, 24 hours; 3, 10
day) in order to comply with the requirements of BS8081. Apart from one particular site,
where tendon contamination was experienced, no SBM unit anchors tested to date have failed
this criterion, and generally losses have been well within these limits.

6.0 DEVELOPMENTS IN ANCHOR DESIGN
Current recommendations in the British Standard for the design of anchors in rock, in sand and
in clay, all involve a design equation in which the load capacity of the shaft component of the
anchor is directly proportional to the fixed length of the anchor. This consideration is based on
the assumption that "transfer of the load from the fixed anchor to the rock ... or soil [added] ...
occurs by a uniformly distributed stress acting over the whole of the perimeter of the fixed
anchor". It is generally acknowledged that in the majority of rock and soil conditions this
assumption is incorrect. Owing to the incompatible elastic properties of tendon, the grout and
grouted ground, the progressive debonding at either or both of the tendon/grout or ground/grout
interfaces prevents such uniform distribution. The evaluation of a mathematical expression to
correct for this phenomenon is complex, however the extensive data provided in single bore
multiple anchor tests has allowed a relatively simple but accommodating correction to the
current empirical formulae:-

Current expression: \[ T_f \propto L \] (1)

\[ T_f = \text{ultimate anchor load} \]
\[ L = \text{fixed anchor length} \]

May be changed to: \[ T_f \propto L.f_s \] (2)

where \( f_s \) is the efficiency factor which relates the efficiency of the anchor in mobilising bond
capacity to the fixed length of the anchor.

The current design rules applied to non-postgrouted shaft anchors in clay generally follow those
developed for bored piles in the equation:-

\[ T_f = \pi D L \alpha Cu \] (3)

\[ T_f = \text{ultimately load in kN} \]
\[ D = \text{bore diameter (m)} \]
\[ L = \text{fixed anchor length (m)} \]
\[ \alpha = \text{adhesion factor} \]
\[ Cu = \text{average undrained shear strength over the fixed anchor length kN/m}^2 \]

Recommended values of \( \alpha \) established from piling are in the 0.2 to 0.5 range whilst a range of
0.3 to 0.6 has been achieved in normal anchoring. For anchors in London Clay a value of
0.45 is often considered appropriate. It is accepted in the piling and anchoring industries that
the adhesion factor, \( \alpha \), allows for variation of founding stratum and variation in drilling and
construction techniques. To accommodate another variable within this acknowledged factor,
and for anchors only, would be confusing. Thus it is appropriate to introduce an "efficiency factor", "fs", in place of $\alpha$ for relating efficiency to length of fixed anchor:

\[ T_f = \pi \cdot D \cdot L \cdot fs \cdot Cu. \quad (4) \]

Many of the SBM anchors installed and tested have been founded in stiff to very stiff clays. The unit fixed lengths tested have ranged from 2.5 to 7m, whilst fixed length of normal anchors has ranged from 10m to as much as 23m grouted length in clay. This data has allowed evaluation of the efficiency factor values for use in equation 4.

Unfortunately, it is not always economic for the site investigation to provide full and comprehensive data on the clay shear strength over the full depth range. In an increasing number of situations, particularly in boulder clays and glacial tills, only standard penetration test data is available. Such data can be used in two ways to design the fixed length of the anchor:

i) Make use of the relationship and factors recommended by Stroud (Ref 10) to allow clay shear strength to be estimated:

\[ Cu = f_1 \cdot N \quad (5) \]

where $f_1 = \text{factor ranging from 4.4 to 6.0.}$

$N = \text{Standard penetration test value}$

Thus make use of the derived clay shear strength value in the previous equation (2).

ii) On the basis of failure loads exhibited in the trial anchor, determine a direct relationship between bond stress and $N$ for anchors in clays and;

\[ \tau_f = f_{10} \cdot N \quad (6) \]

where $\tau_f = \text{ultimate bond stress}$

where $f_{10}$ is one of a number of proposed new factors relating ultimate bond stress to standard penetration test values.

Such relationships have previously been proposed by Littlejohn for anchors in chalk (Ref 11), and Barley for anchors in chalk, mudstone and sandstone (Ref 12).

Consistent with design approach above (equation 4), incorporating the efficiency factor, $fs$, relating efficiency to the choice of fixed length, the ultimate anchor load in clay can be represented by:

\[ T_f = \pi \cdot D \cdot L \cdot fs \cdot f_{10} \cdot N \quad (7) \]

A similar approach introducing efficiency factors into the existing design formulae for anchors in non-cohesive strata and rocks, is currently being evaluated (Ref 13), whilst the utilisation of a relationship between bond capacity and standard penetration test values is ongoing.

7.0 DATA ANALYSIS, EVALUATION OF EFFICIENCY FACTOR AND SBMA DESIGN
From the 61 unit anchors tested, 21 unit anchors and 2 normal anchors were failed, which
allowed calculation of failure bond stresses. Of the 21 unit failures, site investigation data presented clay strength in terms of Cu values (or reasonable interpolation of such) in the depth range of 11 units. Use of recommended values of \( f_i \) (4.4 in London Clay) allowed reasonable estimate of clay shear strength at the depths of 3 other units. This data allows

![Figure 3 - Efficiency Factor \( fs \), versus length of fixed anchor in very stiff clay](image)

the presentation of Fig 3, showing the values of efficiency factor, \( fs \), against fixed length. This indicates that the full clay shear strength can frequently be mobilised in bond when short length unit anchors (2.5 to 3.5m) are installed (\( fs = 0.95 \) to 1.0). However, in the 3.5m to 4.0m range \( fs \) can vary from 0.66 to 1.0. With fixed lengths greater than 4m there is a continual fall-off in efficiency. The use of Equation 4, along with efficiency factor values presented in Fig 3 allows a more accurate estimate of the ultimate capacity of straight shaft anchors founded in clay than those obtained from Equation 3 recommended in BS8081. Furthermore use of Equation 4 is particularly appropriate for the design of SBM anchors, where optimisation of the bore diameter and the unit fixed length may now be made with due consideration of bond efficiency.

Figure 3 provides a full worked example of such a design, where the relationship between Cu and depth in London Clay is established from S.I. data. The example is represented schematically for clarification.

Of the 21 induced failures of unit anchors, 11 took place in founding strata where ground strength was represented by a range of N values at the relevant depth. Values of \( f_{10} \) ranged from 3.2 to 5.0 in London Clays, and 4.1 to 5.0 in the Boulder Clay. In the Glacial Till in Newcastle \( f_{10} \) ranged from 6 to 8 without anchor failure. A design example for anchors founded in Glacial Till utilising N values as the design parameter is provided in the paper describing the Newcastle anchors (Ref 14).
8.0 SUMMARY
The introduction of the patented single bore multiple anchor system has allowed considerably more efficient use of soil strength, with or without soil strength enhancement, than previously achieved.

In the S.B.M.A. design it acknowledges the existence of ground strength variability and increase in efficiency with reduction in unit fixed length. The system allows full use of overall fixed lengths of up to 30m, and can be designed to accommodate differing founding materials within a single anchor bore.

The preliminary testing of multiple anchors has provided extensive information on ground to grout bond. The analysis of this data has allowed considerable advancement in the simple design approach to anchors, by the application of an efficiency factor which quantifies load reduction with increase in fixed length.

Anchor working loads in the 1000kN to 2000kN range are now available in the majority of soil conditions. Multiple anchors can be utilised for permanent usage, complete with double plastic corrosion protection or, for temporary usage, supplemented by total removal of the multiple of strand tendons after use.

Fig 4 - Worked example of design of Single Bore Multiple anchor in clay, based on known shear strength values

REFERENCES

Ref 8 EN1537: "Execution of special geotechnical work - Ground Anchors" - European Standard.