ABSTRACT: The new concept of installing a multiple of unit anchors in single bore hole has allowed a considerable increase in anchor capacities in soils and weak rocks. Fixed anchor lengths as much as 30m long can now be efficiently utilised to achieve failure loads of 2000 to 3000kN in clays. Where circumstances demand, the anchors can be double protected for permanent works, or for temporary works the steel tendons can be fully withdrawn after use.

ZUSAMMENFASSUNG: Das neue Ankerkonzept des "SBMA-Ankers" beinhaltet den Einbau mehrerer Einzelanker in ein Bohrloch und ermöglicht dadurch eine beträchtliche Erhöhung der Ankerkräfte in Lockerboden und verwittertem Fels. Es können Haftstreckenlängen bis zu 30m hergestellt werden und es besteht die Möglichkeit Ausziehkkräfte von 2000 bis 3000kN in tonigen Boden zu erzielen. Der "SBMA-Anker" kann sowohl als Daueranker mit zweifachem Korrosionsschutz oder als Temporaranker mit kompletter Ruckgewinnung der Stahlteile ausgeführt werden.

a) INTRODUCTION

A typical ground anchor tendon with a 6m fixed length will, at test load, need to extend some 15 to 20mm at the proximal end of the fixed length prior to any load being 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.

b) 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 homogenous 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 the 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.

c) PRACTICAL CONSTRAINTS

a. 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 actual number of unit anchors and the unit anchor capacities:

- d) The bond length or bond mechanism used at the tendon/grout interface of each unit to allow safe use of the full tendon capacity;
- e) The diameter and type of the corrosion protection of the fixed anchor (encapsulation);
- f) The influence of passage of the “free” length tendons from the deep unit anchors (distal) on the bond capacity of the shallower unit anchors (proximal) and their congestion in the borehole;
- g) 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).
a. 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 (Ref 1). 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 BS8081 (Ref 2)) the deformed strand system was chosen, whilst for temporary works either deformed strand or a mechanical device for removable anchors is available (Ref 3).

Although research has established that the full capacity of the entire range of strands could be achieved within 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 satisfactorily incorporated into the double protected encapsulations of individual unit anchors to allow mobilisation of even higher unit anchor loads.

b. Multiple stressing jack and load measurement arrangement.

The initial choice of the unit anchor tendon system determined that the range of test load 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 of 2 to 3 in the test loading of preliminary trial anchors, or to achieve failure at the grout/ground 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 through the jacks. The five-unit jack arrangement shown in photo 1 has been most appropriate but an alternative using seven jacks is also feasible.

Each of the jacks is coupled via a central manifold to a single hydraulic powerpack. Thus, during load application the load in each unit anchor is always the same. The hydraulic pressure is measured by a pair of matching 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 with the gauge pressure on the powerpack itself. Any friction within the "system" can be established by carrying out load 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 independently while further testing of the other unit anchors is continued.
c. 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 unit anchor
lengths can be made. However it should always be borne in mind that in the vast majority of conditions the
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.

d. 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 (Ref 4). 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 encapsulations
and mechanical devices (Ref 5). 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 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 not less than 80% theoretical). This limit is consistent
with current European practice, but somewhat less than 90% recommended in §BS8081. It should be borne
in mind that via the nominal friction the load is still transferred into the overall fixed anchor length.

e. Effect of load change in a production

SBM anchor It has been normal practice in the U.K. for over a twenty year period to apply a preload of
110% of 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 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.

When 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 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 occurs, necessary to load the anchor, then after this movement the unit loads will
be equal, and no individual unit anchor overloaded.

h) 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 five unit anchor provides five times as
much data as a normal anchor. 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 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. No SBM unit anchors tested to date have failed this criterion and
generally losses have been well within these limits.

i) DESIGN APPROACH AND DESIGN DEVELOPMENT FOR ANCHORS IN CLAY

The current design rules applied to non-postgrouted shaft anchors in clay generally follow those developed
for bored piles in equation:
\[ T_f = \pi \cdot D \cdot L \cdot \alpha \cdot C_u \]  
(1)

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

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. Although it is acknowledged in anchoring that the proportion of the clay shear
strength mobilised reduces with increase in fixed anchor length, the above formula makes no allowance for
such a phenomenon. 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 reintroduce an "efficiency factor", \( \text{fs} \), in place of "\( \alpha \)" for this purpose (originally
recommended by Bassett (Ref. 6) but not specifically for relating efficiency to length of fixed anchor)

\[ T_f = \pi \cdot D \cdot L \cdot \text{fs} \cdot C_u \]  
(2)

The majority of SBM anchors installed and tested were drilled with open hole, water flush techniques, but
some in the London Clay were augured. 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 lengths in clay.

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 7) to allow clay shear
strength to be estimated:

\[ C_u = f_1 \cdot N \]

where \( f_1 \) = factor ranging from 4.4 to 6.0.  
\[ N = \text{Standard penetration test value} \]  
(3)

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;

\[ f = f_1 \cdot N \]  
where \( f = \text{ultimate bond stress} \]  
(4)
T_f = \pi \cdot D \cdot L \cdot f_{10} \cdot N \quad (5)

where \( f_{10} \) = factor.

Such relationships have previously been proposed by Littlejohn for anchors in chalk (Ref 8), and Barley for anchors in chalk, mudstone and sandstone (Ref 9). Consistent with design approach above \( \delta \) (equation 2), it should be possible to incorporate the same or similar efficiency factor, \( f_s \), related to the choice of fixed length.

\[ i.e. \quad T_f = \pi \cdot D \cdot L \cdot f_s \cdot f_{10} \cdot N \quad (6) \]

Attempts have been made in the analysis of test data from 2 normal anchors and 61 unit anchors to substantiate the above design criteria and establish values of the recommended factors \( f_s \) and \( f_{10} \) (Clause 7.0)

j) TEST ANCHORS IN CLAYS

a. Hampton, Surrey

Two 20m deep 105mm diameter holes were augured 13.5m into stiff to very stiff London Clay. A normal 5 strand encapsulated anchor tendon was installed in one hole whilst 5 unit anchor tendons were installed in the second (Fig 7). Identical tremie grouting techniques were utilised. The normal anchor achieved a failure load of 370kN, whilst the SBMA achieved 660kN during multiple loading. During subsequent tests which progressively loaded each individual unit anchor from top down, the summation of unit capacities was 8905kN, and failure bond stresses ranged from 146kN/m² in the proximal anchor to 303kN/m² in the distal anchor. Two longer anchor holes were augured to 30m (23m into the London Clay (Fig 7)). The normal anchor achieved 470kN, whilst the SBMA achieved 980kN. The summation of the unit anchor capacities when failed individually was 1280kN, and failure bond stresses ranged from 78kN/m² in the longer proximal anchor, to 227kN/m² without failure in the lower anchors. Thus, during direct loading against a load cell, the multiple anchors achieved capacities of 178% and 208% of the capacities of normal type anchors in 20m and 30m deep anchor holes, whilst the actual summation of unit anchor capacities (which would have been achieved using the currently available synchronised jacking system) achieve in excess of 240% that of normal anchors.

Soil strength information from an adjacent borehole allows direct comparison of the failure bond stresses with the range of undrained shear strengths of the clay. Eight out of the ten unit anchors were failed as were both normal anchors. Fig 8 indicates that all of the short 2.5m unit anchors mobilised bond stresses equivalent to the full clay shear strength. Considering the full 13.5m of normal anchor grouted in the clay as being effective, then some 40% of the average clay strength was mobilised. Fig 9 suggests that the 4m unit anchors utilised 70% of the clay strength at failure, whilst the full 23m grouted length of the normal anchor attained a bond stress of 22% of average clay strength. Considering only 10m of the 23m being effective, this rose to 36% (neglecting any contribution from the upper 13m at failure).

b. Chingford, North London

A single inclined trial SBMA anchor was open bore water flushed to 40m through overlying materials and into London Clay. A total fixed length of 20m in a 190mm dia bore was utilised by 6 No. unit anchors, each within 3.3m fixed length. The anchor achieved a maximum load of 1450kN recorded on a single anchor load cell when the synchronised jacking system was not available. Unit anchor capacities during induced progressive failure were 220 and 230kN on the two proximal units, but the other units could not be failed at 250kN. Failure bond stresses of 8110kN/m² were in the range of 70 to 78% of the clay shear strength (140 to 160kN/m²) in the relevant depth range. Lower unit anchors achieved bond stresses of 45 to 65% of the clay shear strength without failure. During a load hold period of 10 days, load losses at 660kN reached 3.1% of lock off load, considerably less than the 8% acceptable in BS8081. The 28 production SBM anchors were subsequently proof loaded to between 675 and 900kN without difficulty, and no problems occurred during the load test periods.
6.3 Heathrow, West London

A single inclined SBM anchor was open bore water flushed through overlying gravels into stiff to very stiff London Clay. A total fixed length of 28m in a 190mm bore was mobilised by 5 unit anchors. Unit fixed lengths were varied, 7, 5, 7, 5, 4m to investigate efficiency of unit fixed lengths and influence of increasing clay shear strength. Using the synchronised jacking system, a total load of 2144kN was achieved. The two proximal anchors failed during this operation at 375 and 463kN. Subsequent controlled loading, which progressed failure top down, achieved a failure load of 446kN on the third unit anchor, and no failure at 539kN and 590kN on the distal units. Mobilised bond stresses were 90, 155, 107kN/m² at failure and 181 and 247kN/m on the non-failed units.

The information on clay shear strength in the SI report is limited but standard penetration tests have been carried out throughout the depth of the London Clay. This has allowed the investigation of a direct relationship between ultimate bond stress of the unit anchors in the clay and the N value at the relevant depth (fio factor).

The failure bond stresses of the two 7m unit anchors equated to 3.7 and 3.1 times the average "N" value at the relevant depth, whilst that of the 5m unit anchor equated 5.3N. The two lower anchors with unit lengths of 5 and 4m did not fail at bond stress values of 4.9N and 6.1N.

a. Portsmouth
A preliminary trial anchor was drilled with water flush and fully cased to a 28m depth. The anchor achieved 1056kN over a 17.5m total fixed length in London Clay utilising 5 units with 3.5m fixed lengths. N values ranged from 28 to 45. Failure bond stress on the proximal three unit anchors were 116, 116 and 140kN/m² whilst lower anchors did not fail at 156kN/m². fi factors relating bond stress to N ranged from 3.6 to 4.1 whilst efficiency factors (fs) calculated from Cu = 4.4N ranged from 0.72 to 0.83.

b. Southampton (Ref. 10)
A single inclined test anchor was installed using water flush and full length casing with a total fixed length of 17.5m in the Bracklesham Beds (firm to stiff silty clay with bands of silty clayey e.g. fine sand). Over the depth of the five 3.5m long unit anchors the clay shear strength ranged from 152 to 200kN/m² and SPT values from 29 to 44. (This indicates fi factors from 4.5 to 5.2). End of casing grouting was carried out with pressures up to 7 bar. At 1337kN, failure of the proximal anchor occurred (168kN) but lower anchors could not be failed at 284 to 300kN. Failure bond stress of 155kN/m² and non-failure bond stresses of 8205kN/m² equated to the clay shear strength with fs = 1.0 and fio value at failure of 5.3.

c. Boston, Lincolnshire
Two trial anchors were installed for testing to failure in very stiff clay with chalk gravel and occasional cobbles, using fully cased water flush system. The 16m fixed lengths consisted of 5 unit anchors with 3.2m unit lengths. The anchors achieved 1400 and 1480kN with only four of the total 10 unit anchors indicating failure. Failure bond stresses ranged from 188 to 210kN/m² and six unit anchors did not fail at 216kN/m². Only limited standard penetration test results were available indicating 20 in upper firm/stiff clay and 38 in very stiff clay zone. With interpolation of this data, (N = 34 at level of failed unit anchors) an fio factor of 5.5 is calculated at failure, and fio of 5.7 in the non-failed anchors.

d. Newcastle Stage 1
Two trial anchor holes were open hole drilled using water flush to construct a 20m total fixed length in very stiff sandy gravelly clay (Glacial Till). Soil strength was considered to be represented by the increase in N values with depth. This relationship was N = (15 + 3.1Z) where Z = depth in metres. The unit fixed lengths were designed on the basis that anchor bond stress is proportional to N. Unit fixed lengths of 7.0, 5.2, 4.2 and 3.6m were installed, and the trial anchors tested to 1923 and 2037kN without any unit failures. Bond stresses of between 180 and 8322kN/m² were achieved without failure and these equated to fio factors of 6 and 8 without failure.
e. Newcastle Stage 2
The two trial anchors were constructed at a lower depth in the Glacial Till than those in Stage 1, and this involved the penetration of granular glacial deposits for the distal anchors (dense sand and gravels). Thus it was necessary to fully case the borehole to depth albeit with the same finished hole diameter (140mm) as Stage 1. Inspection of plotting of N value with depth indicated strength development relationship of $N = 25 + 3.9Z$. Design unit fixed anchor lengths were 6.5, 4.5, 4.0, 3.0, 3.0, with the last two lengths founded in the granular stratum. Trial anchors achieved 2915 and 3062 kN without failure and mobilised bond stresses ranged from 204 to 467 kN/m.

One trial anchor, identical to those taken to test load, was subjected to load hold tests over a 10 day period. The two proximal unit anchors lost 1% and 2% load over 6 time periods (to 24 hours) as compared with the tolerable loss of 6%. The distal anchor had lost 2% load at 3 days and no further loss after 10 days. The behaviour was very satisfactory.

b) DATA ANALYSIS AND DESIGN RECOMMENDATIONS

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 depth of 3 other units. This data allows the presentation of Fig 11 showing the values of efficiency factor $f_s$ 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 ($f_s = 0.95$ to 1.0). However, in the 3.5m to 4.0m range $f_s$ can vary from 0.66 to 1.0. With fixed lengths greater than 4m there is a continual falloff in efficiency. The use of Equation 2 along with efficiency factor values presented in Fig 11 allows a more accurate estimate of the ultimate capacity of straight shaft anchors founded in clay than those obtained from Equation 1 recommended in BS8081. Furthermore use of Equation 2 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 confidence with due consideration of bond efficiency.

Figure 12 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, and 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. In trial anchors where unit fixed lengths were varied, only a few failures occurred, thus it has not been possible to produce an efficiency factor ($f_s$) relationship specifically for anchor designs based on standard penetration test values. However, in the absence of such direct data the use of Fig 11 should still be appropriate since the efficiency factor is relatable to the soil, the construction technique and to the fixed length used, and not to the mode of representation of soil strength. The limited number of $f_{10}$ values are illustrated in Fig 13.

Fig 14 provides a guide to the design method that could be utilised at Newcastle Stage 2 to determine the length and distribution of the unit fixed anchors when controlled by the available SPT information.

c) ANCHORS IN FINE SANDS

A number of trial SBM anchors and normal anchors have been installed using end of casing grouting techniques into medium to fine sand with variable content of silts and clays. The test data has not yet been fully analysed to allow presentation of reasonably precise efficiency factor versus fixed length relationship as portrayed in Fig 11. However, the presence of a similar trend is apparent and accepted.

BS8081 recommends the use of the following equation:
\[ T_f = L \ n \ \tan \ \varphi \quad (7) \]

where \( L \) = fixed anchor length
\( n \) = load capacity factor ranging from 135 to 165kN/m in fine to medium sand
\( \varphi \) = shearing angle of soil

This equation makes no allowance for the occurrence of progressive debonding or fall off in load/m length as fixed length increases. In the absence of a Fig 11 applicable to fine sands, initial studies have arrived at an appropriate mathematical expression for the efficiency factor to be applied to equation 7:

\[ T_f = L \ n \ \tan \ \varphi \cdot f_s \quad (8) \]

where \( f_s = (0.91)^{L \ \tan \ \varphi} \)

Graphical representation of this relationship presents curves very similar to those of Ostermayer. In the author’s experience the capacities of anchors achieved by end of casing grouting techniques in fine sands are normally quite compatible with capacities that Ostermeyer achieved using post grouting techniques. It must be fully appreciated however, that in equation 8 the load capacity value ‘\( n \)’ is heavily influenced by construction technique, and grout pressures must at least be in the 5 to 10 bar range. Specialist contractors may have their own appropriate proven values of \( n \) but the application of an efficiency factor is still appropriate.

d) OVERALL SUMMARY

During the 7 years since inception, the single bore multiple anchor system has attained loads in straight shafted anchor holes in soils, mixed ground and weak rocks that could not have previously been considered attainable:

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Load Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>London Clay</td>
<td>2150kN</td>
</tr>
<tr>
<td>Glacial Till</td>
<td>3000kN without failure</td>
</tr>
<tr>
<td>Medium dense medium to fine sand</td>
<td>2400kN without failure</td>
</tr>
<tr>
<td>Highly weathered Chalk</td>
<td>1280kN without failure</td>
</tr>
</tbody>
</table>

Working loads in the range of 750kN to 1500kN or possibly more, are now available in soils. Some 10,000 unit anchors have now been installed and tested, the majority being for permanent usage, and a small number with special fully removable tendon facilities. Failure of only a handful of unit anchors has occurred due to ground conditions, but with the sound performance of other unit anchors in the bore, no redrilling or remedial works have been necessary as a result of the inbuilt safety system.

The considerable amount of data provided in trial SBM anchors with differing unit fixed lengths has allowed the development of efficiency factors for anchors founded in clays, and, although not finalised, also in fine silty clayey sands. This information provides a better understanding of the influence of progressive debonding on anchor capacity and for the first time accurately quantifies its effect.

e) ACKNOWLEDGEMENT

The Author would like to thank Keller Colcrete of the Keller Group for continual support in the research and development of this completely new (now patented) anchor system. Combined research and studies in conjunction with the University of Surrey has allowed development of spread sheets for portraying the distribution of bond stress along the length of the tendon (Mr R Woods) and the development of a mathematical expression for the efficiency factor applied to sand anchors (Mr K Barkhordari).

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Fig.1  a) Progressive debonding along a normal anchor fixed length
     a) Progressiver Spannungsverlauf entlang einer Haftstrecke

     b) Single bore multiple anchor simultaneously loads a number of short fixed lengths
     b) Single Bore Multiple Anchor Spannungsverlauf mehrerer kurzer Haftstrecken

Fig.7 Normal and SBM anchors in London Clay
Fig.7 Normale und "SBM-Anker" in London Clay

Fig.8 Exhibited failure bond stresses of SBMA and normal 20m anchors
Fig.8 Dargestellte Bruchspannungen eines "SBM-Ankers" und eines normalen Ankers von 20m

Fig.9 Exhibited failure bond stresses of SBMA and normal 30m anchors
Fig.9 Dargestellte Bruchspannungen eines "SBM-Ankers" und eines normalen Ankers von 30m

Fig.12 Design of SBMA in clay.
Fig.12 Konstruktion eines SBMA in Clay

Fig.14 Design of SBMA in glacial till
Fig.14 Konstruktion eines SBMA in glazialem Ton
Fig 1 a) Progressive debonding along a normal anchor fixed length.

Fig 1 b) Single bore multiple anchor simultaneously loads a number of short fixed lengths.
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Anchors</th>
<th>Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>370KN</td>
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<tr>
<td>6.5</td>
<td>6m enc.</td>
<td>165kN</td>
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<tr>
<td></td>
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<td>122kN</td>
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<td></td>
<td></td>
<td>145kN</td>
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<td></td>
<td></td>
<td>220kN</td>
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<tr>
<td></td>
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<td>250k+ kN</td>
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<tr>
<td>20.0</td>
<td>105m²</td>
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<td></td>
<td></td>
<td>7.5m</td>
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<td>300+kN</td>
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<tr>
<td></td>
<td></td>
<td>300+kN</td>
</tr>
</tbody>
</table>

**Single Bore Multiple Anchors compared directly with normal anchors in London Clay**

Fig 7 Normal and SBM anchors in London Clay
Fig 11 Efficiency ($f_s$) vs Length of Fixed Anchor.
Fig 12  Design of SBMA in clay

Fig 13  Design of Bond Stress/N Factor ($f_{10}$) vs Length of Fixed Anchor
Fig 14  Design of SBMA in Glacial Till