Some applications of ground improvement techniques in the urban environment

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Abstract: Within the UK, high population density and increased traffic volumes has led to the expansion of urban areas incorporating new building construction and associated infrastructure. Such developments have encroached on "brownfield" sites with a legacy of former industrial activity and "marginal sites" where weak alluvial and/or glacigenic deposits occur. Dependent upon site geological and geotechnical characterisation, this has necessitated the use of ground improvement techniques prior to construction. A brief overview is provided of one of the most widely used ground improvement techniques within the UK urban environment, namely that of (vibro) stone columns, in particular how the technique has developed in response to environmental legislation/pressure and requirements for improved performance and sustainability. The importance of detailed site investigation for stone column design in the urban environment is emphasised.

The main part of this paper then focuses on the novel application of vibro stone column (vsc) and vibro concrete column (vcc) techniques beneath new highway embankment construction over soft ground and the steps required to permit successful ground improvement implementation. This draws upon recent experiences on the M60 orbital motorway widening around south Manchester and a new relief link road construction in Kings Lynn, Norfolk (UK).

The most common types of ground related problems encountered during ground improvement relate to soil strata interfaces and boundaries (i.e. geometry not as anticipated) and the geotechnical properties of the soil profile. The usefulness of Cone Penetration Testing (CPT/CPTU) as a site investigation tool, the importance of preliminary trials (particularly for larger projects), quality control, monitoring and testing, to ensure successful implementation and performance of the treated ground is emphasised.

Résumé: Au Royaume Uni, la densité élevée de population et une augmentation du trafic a favorisé l'expansion des zones urbaines et la construction de nouveaux bâtiments et infrastructures. Ces développements ont empiété sur les sites 'brownfield' (anciennes zones d'activité industrielles) et sur les 'marginal sites' caractérisés par de faibles dépôts alluviaux et /ou glaciaux. Les caractéristiques géotechniques du sol peuvent nécessiter l'utilisation de techniques d'amélioration des sols avant de commencer toute construction. C'est pourquoi cet article présentera succinctement la technique la plus utilisée colonnes ballastées d'amélioration des sols dans les zones urbaines du Royaume Uni. La technique colonnes ballastées a été développée pour faire face á une législation environnementale de plus en plus pressante et répondre également aux exigences d'amélioration de performance et de viabilité. Sont aussi mis en évidence l'importance d'une recherche détaillée lors de l'utilisation du colonnes ballastées modèle et de l'application de ce modèle dans un environnement urbain.

Une grande partie de cet article met en exergue les nouvelles applications des techniques < vibro stone column (vsc) > et < vibro concrete column (vcc) > dans la construction des nouvelles chaussées d'autoroutes sur sols mous. On y décrira également toutes les étapes nécessaires á la réussite de l'implantation de cette technique. Toutes ces observations ont été faites récemment lors de l'élargissement du périphérique de Manchester et de la construction d'une voie de secours a Kings Lynn dans le Norfolk (RU).

Les interfaces et extrémités des strates du sol ainsi que ces propriétés géotechniques sont les deux types de problèmes fréquemment rencontrés lors de l'amélioration des sols. Cet article souligne l'utilité des tests CPT (CPTU) pour les recherches dans les sites, l'importance des tests préliminaires (particulièrement pour les grands projets), les contrôles qualité et encore de la surveillance pour s'assurer d'une implantation réussie et des performances du sol traité / amélioré.

Keywords: Environmental urban geotechnics; site investigation; cone penetration testing; geotechnical engineering; design; risk assessment.

INTRODUCTION

Within the UK, high population density and increased traffic volumes has led to the expansion of urban areas. A legacy of industrial activity has given rise to economic and environmental pressure to redevelop land with past industrial usage and other anthropogenic processes, the so called "brownfield sites" (frequently containing deep heterogeneous/miscellaneous fills (made ground deposits) and contaminated soils and groundwater), and to build on land hitherto considered marginal for development, where soft clay soil profiles prevail. This has presented both the engineering geologist and the geotechnical engineer with the challenge of improving methods of geotechnical site characterisation (including site investigation methods), and providing satisfactory foundation solutions and performance at low cost and with minimum environmental impact. For many types of low-rise development, piling through deep fill or natural soft soil deposits may be either uneconomical or impractical and some form of ground improvement/treatment is frequently necessary.

Ground improvement techniques have therefore become a major area of geotechnical engineering and a large number of treatment methods have been developed to suit a wide range of ground conditions and foundation problems. Furthermore, this has led to existing ground improvement techniques being adapted for an increased range of ground conditions and environmental constraints. The first part of this paper focuses on vibro stone column techniques, currently one of the most commonly used ground improvement techniques within the UK urban environment. Over the last twenty years the stone column technique has developed and been modified in response to environmental legislation and pressure, and requirements for improved performance, quality control and sustainability. This has included the introduction of the dry bottom feed installation technique; *vibro concrete plug* technology; computerised monitoring systems and the increasing use of recycled aggregates in stone column construction. A brief overview of some of these developments, which fall within the developing field of "*environmental urban geotechnics*", is provided. The importance of detailed site investigation information for vibro stone column design and application/implementation in the urban environment is also emphasised.

The main part of this paper then focuses on the novel application of vibro stone column (vsc) and vibro concrete column (vcc) techniques to control both total settlements and settlement gradients (behind piled bridge abutments) beneath new highway embankment construction over soft ground, associated with urban transport infrastructure projects. The steps required/necessary to permit successful ground improvement implementation are discussed, drawing upon recent experiences on the M60 orbital motorway widening scheme around south Manchester and a new relief (link) road construction in Kings Lynn, Norfolk (UK). The most common types of ground related problems encountered during ground improvement relate to soil strata interfaces and boundaries (i.e. geometry not as anticipated), and the geotechnical properties of the soil profile. The usefulness of CPT (CPTU) as a site investigation tool to address these issues, together with the importance of preliminary trials (particularly for larger projects), quality control, monitoring and testing, is emphasised. The objective is to highlight and promote discussion on the engineering geology and geotechnical engineering of urban transport infrastructure and provoke some response to challenge the way in which we work and how they can be improved and applied through experience, to the development of tomorrow's sustainable cities. For the purposes of this paper non-engineered fill materials are referred to as "made ground".

VIBRO STONE COLUMN TECHNIQUES (INCLUDING VIBRO CONCRETE PLUGS AND COLUMNS)

Introduction

The vibro stone column technique was introduced to Great Britain and France in the 1950's and is currently one of the most commonly adopted ground improvement/treatment techniques within the UK urban environment. The objective of vibro stone column installation is to provide a composite "ground structure" of in-situ material (soil) and stone columns, which act as vertical reinforcement, and which overall has lower compressibility and increased bearing capacity. In the context of loose uncompacted granular soils the vibratory action of the vibroflot (vibrating poker), will also densify material immediately surrounding the column, thus improving its geotechnical properties. For made ground deposits the objective of the treatment should also be to reduce the heterogeneity and make its subsequent performance more predictable, in effect converting a non-engineered fill into something close to an engineered fill, Charles (2002). A further advantage of stone columns is that they provide very efficient drainage paths for pore water pressure dissipation, which in turn provides acceleration of calculated consolidation settlements within the treated depth. Clearly, this is particularly useful when considering the support of embankments over soft ground. Applications for stone columns are widespread and the technique is well suited to low-rise lightly loaded structures, including housing, light portal frame industrial units and also beneath heavier less settlement sensitive structures such as road and railway embankments. The method has also seen application in slope stabilisation and remediation works. Useful commentary and guidance on vibro stone columns and their applications is given in Greenwood & Kirsch (1983), Moseley & Priebe (1993) and Building Research Establishment (BRE) Report BR391 (2000), among others.

Vibro stone column installation techniques in the UK

Within the UK, stone column installation, (with a few exceptions), is now principally carried out using the dry technique. The specific circumstances of bore stability (particularly with regard to fine-grained soils) and groundwater regime, determine whether a top feed (Figure 1a) or bottom feed (Figure 1b) technique is carried out. Charges of stone are introduced (from the surface, in the case of the top feed technique, and by way of a tremie pipe in the case of the bottom feed technique), and compacted in stages by the vibroflot (vibrating poker) until a dense stone column is constructed to the surface. The dry bottom feed technique (Figure 1b), which was introduced into the UK in the mid 1980's, has largely superseded the wet top feed technique on geo-environmental grounds, due to issues surrounding water supply and effluent disposal, especially on potentially contaminated sites. Other advantages of the technique are that it permits construction of clean continuous stone columns (i.e. the vibroflot acts as a stabilising element within the bore, preventing introduction of unwanted inclusions). There is also additional benefit from the pull down facility from the leader mounted rigs employed (typically up to 150 kN downforce). The method therefore provides productivity gains as well as providing a clean, water and effluent-free approach. The method has also provided a basis for achieving improved quality control as regards to column installation and introduction of "real time" computerised monitoring of installation parameters.

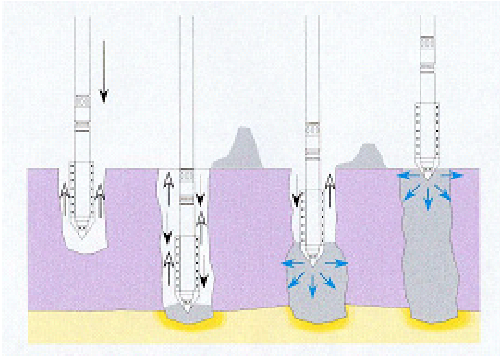


Figure 1a. Dry top feed vibro stone column technique

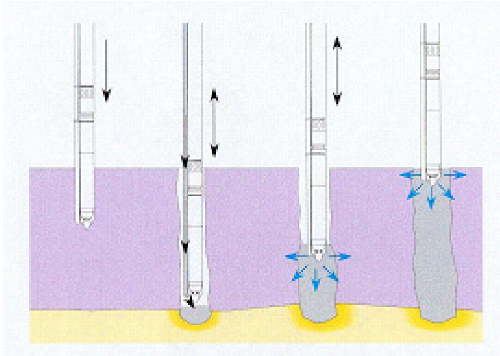


Figure 1b. Dry bottom feed vibro stone column technique

Soil applications and limitations of vibro stone columns

The range of soils suitable for the different vibro stone column techniques and their suitability is covered in Greenwood & Kirsch (1987), Moseley & Priebe (1993) and BRE Report BR391 (2000), among others. It is important to recognise, however, that whilst stone column techniques provide an economic and adaptable solution for many foundation requirements, the geotechnical background and potential problems with the ground must first be correctly diagnosed and the technical possibilities and limitations of stone column techniques must be clearly understood before attempting implementation. Whilst applicable to a wide range of soils there are restrictions to their use and certain ground conditions may prevent the proper construction of stone columns or specified minimum performance requirements being met. Whilst it is not possible, within the scope of this paper, to discuss the specific soil circumstances which may either preclude the use of stone columns, or require special measures to be taken before implementation, suitable guidance is given in BRE Report BR391 (2000), which addresses the following aspects: *obstructions in the ground; very low shear strength cohesive soils; high shrinkage clay soils above the water table; peat and highly organic clays; filled ground* (more detailed information on the behaviour of fills, including reference to inundation/collapse compression and treatment by stone columns is given in BRE Report BR 424; Building on fill: geotechnical aspects (2001)); *major changes in soil conditions over short lateral distances* (e.g. within the vicinity of a buried quarry high wall or buried quarry edge) *and contaminated land.*

It is also important to highlight that recently placed clay fills, (due to increasing use/on-site retention of site won materials, attributed principally to the cost of off-site disposal of materials and the landfill tax , and also increasingly-sustainability issues), can pose a hazard if not satisfactorily engineered in place, due to self weight settlement issues within the body of the fill. The situation will not be significantly improved by introduction of stone columns and significant depths of clay fill material should not be considered suitable for treatment particularly if it is less than 7-10 years old, (although each site should be judged geotechnically on its own merits and dependent upon the specific application, as longer periods may be required, for example). Where engineering of suitable clay fill soils are being considered, the structural applications (and limitations on settlement), will influence the effectiveness of the engineering (i.e. achieving 95% of maximum dry density with a UK Highways based specification may not be adequate for a particularly settlement sensitive structure) even with stone columns. However, there are stabilisation techniques, which can be applied to some of these soils such as lime-stabilisation with potential for improving the situation.

Where the made ground is stiff or dense, particularly where these overlie deeper, weaker soil layers, which require improvement/treatment, use of pre-boring techniques may be required to assist vibroflot insertion to the required depth. Conscious of the arisings, which can be associated with pre-boring, current research, includes looking at the development of more powerful vibroflots (vibrating pokers), which are better, able to penetrate a wider range of more competent heterogeneous made ground. Within the urban environment in particular, there are situations in which ground improvement is used not so much to address a clearly identified deficiency in the ground, as to reduce the risk posed by heterogeneous ground conditions such as non-engineered fills. It is sensible to invest in risk mitigation measures rather than refine the calculation risk. For example, for (inert) heterogeneous granular fill it may be preferable to improve the ground by vibro stone column techniques rather than carry out further site investigation in an attempt to prove treatment is not necessary, Charles, (2002). In this situation, treatment may be considered to be a form of insurance. Nevertheless, effective treatment requires some knowledge of the likely hazards. It is perhaps also important to highlight that insertion of the vibroflot into the ground and monitoring of ground response, can also act as a site investigatory tool during treatment and any unforeseen conditions can be appropriately identified and addressed.

Site investigation for vibro stone column techniques

Ground improvement design is reliant upon good quality site investigation data to permit appropriate geological and geotechnical site characterisation and satisfactory risk assessment. Historically, within the urban environment, site investigations have identified and characterised the geotechnical properties of the natural more competent soil or rock strata, in anticipation of a deep foundation/pile design solution, with the overlying softer or looser natural soils and/or made ground deposits largely ignored. Historically, this has restricted the potential use of ground improvement techniques, as appraisal for suitability has been limited by the lack of geotechnical parameters. Unlike piles, vibro stone columns rely, (at least in part), for their support on the passive resistance afforded by the soils through which they are installed, so that geotechnical characterisation of these soils is essential. Furthermore the requirement for and/or supervision by suitably qualified and experienced engineering geologists/geotechnical engineers during site investigation and geotechnical site characterisation cannot be emphasised enough. Investigation and test methods should, in addition to identifying geotechnical properties, also focus on revealing the variability of the ground. Whilst shallow soil layers can effectively be examined with trial pits and trial trenches, and are of particular benefit in characterising the shallow made ground and its penetrability for standard vibro equipment, deeper layers will typically require boreholes with appropriate SPT profiling and sampling (disturbed and undisturbed). These are usefully supplemented by CPT (particularly where borehole investigation is limited and/or in the absence of sophisticated and expensive undisturbed sampling and laboratory testing in softer ground), or Dynamic probing (DP). In urban areas especially, in addition to establishing an engineering geological ground model for the site, the investigation should also focus on the history of the site, through appropriate desk studies, site walkover and reconnaissance surveys (and any additional requirements for intrusive and non-intrusive investigations). The former use of the site is very important, for example there may be remnant foundations; obstructions; voids, (e.g. basements, culverts, tunnels, mine shafts, old workings), waste materials, contamination etc., present within the soil profile which impact significantly on the choice, application and performance of certain ground improvement techniques. Even relatively small sites can yield quite complex subsurface conditions due to past anthropogenic activity. Samples are required for conventional laboratory testing to ascertain the properties of the soils concerned (undrained shear strength and consolidation testing; plasticity indices etc). This not only assists the selection of the most appropriate ground improvement / treatment process but is also required for the design of the ground improvement and assessment/prediction of its performance. Whilst Rosenbaum *et al*. (2003) have attempted a classification of made ground deposits, it should be perhaps recognised that further research on the subject is required, (dependent upon, for example, - provenance; age; or whether essentially cohesive, granular or intermediate), in order to permit more accurate assessment/designation of geotechnical design parameters and prediction of engineering performance. Further useful guidance on site investigation is included in Uff & Clayton (1986), Institute of Civil Engineers (ICE's) Steering Group document – Part 1 (1993), (parts 1- 4 are currently under review and revision, with the objective of widening awareness of the site investigation industry and reflecting developments in the industry over the last 12 years and hopefully reducing the number of ineffective site investigations that are undertaken), BRE Digest 427 (1998), BS5930: Code of Practice for site investigations (1999), Simons & Menzies (2000) among others, and more specifically for stone column treatment – BRE Report BR 391 (2000).

Vibro concrete plug technology

Penetrative ground improvement techniques such as vibro stone columns can generate potential pathways for contaminant migration. This raises environmental concerns, particularly if sensitive groundwater or underlying aquifers are present on potentially contaminated sites, due to potential pollutant linkages being created (i.e. source-pathway-receptor linkages). Some guidance on pollution prevention in this context is given in the UK Environment Agency Report NC/99/73 (2001). An innovative approach to address this issue has been the development of "*vibro concrete plug*" technology, incorporating the introduction of lean mix concrete into the basal section (toe) of the stone column, thereby isolating any pathways for downward migration of contamination via the stone columns. The technique has been implemented successfully for a vibro stone column ground improvement project in Kidderminster, UK (Figure 2). Below potentially contaminated made ground, essentially cohesive alluvial strata was present, but containing significant granular soil horizons/lenses, with potential for hydraulic continuity with sensitive groundwater in the underlying Triassic sandstone aquifer. Adopting "vibro concrete plug" technology in this way avoids pollutant linkages being formed from contamination/pollutants in the soils through which the stone columns are installed. The technique has also been used to bridge thin creep-prone organic horizons such as peat.

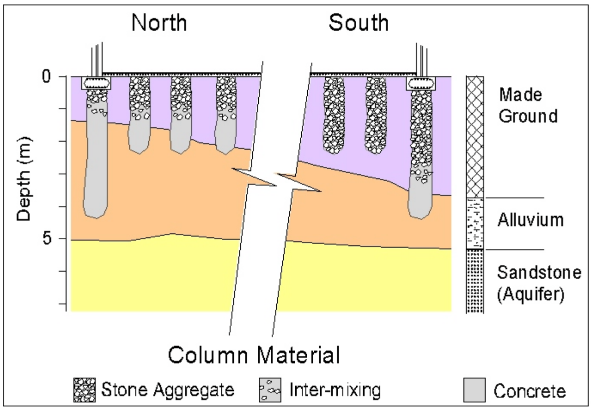


Figure 2. Vibro concrete plug technology application at a site in Kidderminster (UK)

Sustainability in the context of vibro stone column techniques

Increasing awareness for sustainable development and construction is leading to a greater desire for use of recycled aggregates/materials in vibro stone column techniques (with utilisation in this sector currently estimated at around 25-30%). Recycling is of benefit through both reducing demand on natural (primary) aggregate resources (including associated environmental impact) and disposal of material to landfill. This contributes to the sustainability objectives of protection of the environment and prudent use of natural resources. Apart from recycled (spent) railway ballast, crushed concrete has perhaps the greatest potential of all recycled aggregates for use in vibro stone columns, (Table 1) particularly in view of its availability, notably in urban/industrialised areas where, as a consequence of re-development , concrete structures are being demolished and floor slabs and concrete pavements broken up. Crushed concrete can be slightly weaker than primary aggregates used in vibro stone column construction. Therefore, in applications such as stone columns it is important that designers/specifiers do consider these issues/aspects and ensure that crushed concrete aggregate selected is subject to appropriate quality control, "fit-for-purpose" and not contaminated with fines (silt/clay size particles), which impact on the angle of internal friction and therefore bearing capacity of the column material. Further more detailed discussion on these aspects can be found in Serridge (2005).

Table 1. Modulus (E) values determined from plate load tests for stone columns constructed using recycled crushed concrete aggregate, for a site in Coatbridge, Scotland, UK.

Test Ref	Stone column length m	Test level m	Load kN/m²	Poisson's Ratio µ	Settle-ment mm	Modulus (E) MN/m²
1	5.0	-0.55	318.3	0.3	2.94	46
2	3.8	-0.55	318.3	0.3	2.91	47
3	4.5	-0.55	176.8	0.3	1.58	48
4	3.6	-0.55	176.8	0.3	1.37	55
5	5.0	-0.55	318.3	0.3	3.30	41
6	3.6	-0.55	176.8	0.3	1.71	44
7	5.7	-0.55	176.8	0.3	1.56	49
8	6.0	-0.55	318.3	0.3	3.17	43
9	3.0	-0.55	176.8	0.3	2.15	35

Vibro concrete columns

Vibro concrete columns (vcc's) were originally developed in Germany and introduced into the UK around 1991. Vcc design typically uses standard pile design methods, but taking account of the enhanced end bearing capacity associated with an enlarged toe (and densification effects in granular soils attributed to the vibratory action of the vibroflot (vibrating poker)). In the context of widespread loads from embankment structures (Figure 3a), greater emphasis is placed on stiffness-settlement behaviour and serviceability state, rather than the traditional approach of using allowable bearing capacities and factor of safety. Vcc supported embankments typically rely on the use of geogrid in the form of geogrid reinforced granular load transfer platforms to facilitate arching and transfer of embankment loads onto the vcc's. The detailed optimised design of the vcc supported embankment focuses on determining optimum vcc head size and spacing to support the embankment load (including any live load surcharge due to highway loading, for example), which in turn influences the optimum design of the geogrid reinforced granular load transfer platform. The vcc's are installed using bottom feed vibro equipment with stone aggregate replaced with high slump concrete. The vibroflot, charged with concrete, penetrates down to a suitable end bearing stratum. Upon reaching this stratum the vibroflot is withdrawn a short distance from the base of the bore and concrete allowed to flow out under pressure. The vibroflot then re-penetrates this zone of concrete (typically two to three times) to form an enlarged end bulb typically of the order of 600 mm in diameter. When suitable resistance has been reached the vibroflot is slowly withdrawn to the surface with continued pumping of concrete to form the main shaft of the vcc (typically of the order of 450 mm equivalent diameter). Upon completion of the vcc column to the surface, the vibroflot can be used to re-penetrate the uppermost section of the vcc to form an enlarged/flared head, (Figures 3b). Introduction of the technique has increased the range of weaker soils that can be treated with vibro techniques.

Figure 3a. Vibro concrete column (vcc) installation for embankment approach to piled bridge abutment.

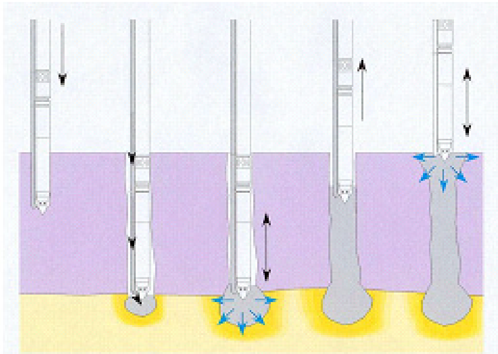


Figure 3b. Vibro concrete column (vcc) installation sequence.

GROUND IMPROVEMENT SOLUTIONS FOR NEW (URBAN) HIGHWAY EMBANKMENT CONSTRUCTION OVER MADE GROUND AND SOFT SOILS

Introduction

Over recent years both motorway/highway widening and new highway embankment construction schemes have become increasingly fast track and complex within the UK, with many phases of traffic management. Consequently, it is not always possible to permit sufficient time within the construction programme to allow settlement to occur for new embankments, particularly over weak/soft ground, without some form of ground improvement. Fast track construction programmes hence require an innovative and flexible (design) approach. For highway schemes, the approaches to bridges or the transition between rigid bridge abutments and the consolidating soil behind the abutment, is a challenge for the engineering geologist/geotechnical engineer exploring cost effective ground improvement solutions to ensure smooth vehicle ride quality and to reduce maintenance and more significantly, to substantially remove lateral loads on existing or new bridge pier/abutment piles (resulting from lateral displacement of soft ground under embankment loads, bringing lateral pressures onto piles). Similarly, the engineering challenge also exists at the approach to drainage culverts crossing an urban highway. Drawing upon recent experiences on two highway embankment projects in the UK – on a motorway widening scheme around south Manchester (M60 orbital motorway) and a new link road construction in Kings Lynn, Norfolk, where such an approach has been required, the following key aspects, which all form important steps in achieving successful ground improvement implementation, (Figure 4), are discussed: *geotechnical site investigation for highway projects ; the design process and review; interfacing of different ground improvement techniques (including transition zones); preliminary trials; practical issues (including dealing with the unknown); monitoring, testing and quality control.*

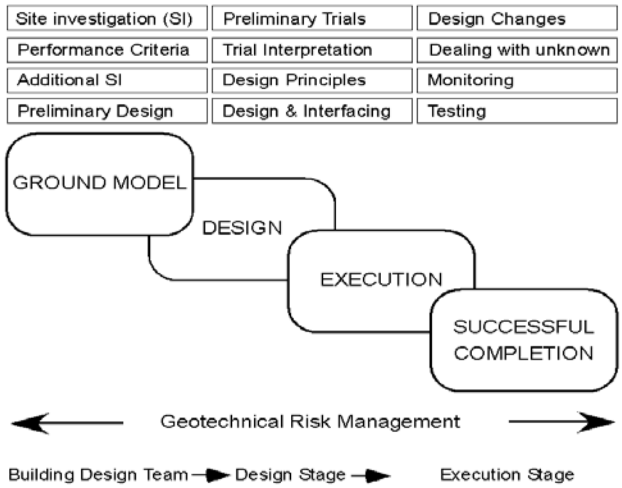


Figure 4. Steps for achieving successful ground improvement implementation

Geotechnical site investigation for highway projects

For highway projects in the UK there can be a significant period between the initial site investigation and the actual commencement of either new highway or widening schemes (due to public inquiries, change in government policy and funding/financing mechanisms, or in the case of new highway projects in particular, - change in route alignment). Boreholes and trial pits, for example, can be quite widely spaced and may not be adequate for the more localised particular ground improvement technique/s being considered or anticipated. Therefore, most initial design is likely to be based on limited site investigation and the likely shortcomings of this must be recognised by the designer/s. Once an optimum design concept has been identified, further ground investigation should normally take place (together with any further necessary desk study and field reconnaissance/walkover surveys), to provide the information required to allow more detailed design to proceed and development of the pre-construction ground model. Ground improvement design requires a knowledge of the ground conditions, particularly the likely geometry of the ground, its geotechnical properties (including anticipated ground response to the particular or intended ground improvement technique) and ground water regime, together with estimates of how they might vary, or how they might be improved by the particular ground improvement technique. Ground investigation (boreholes, trial pits (Figure 5a), CPT 's (Figure 5b), other field testing and also laboratory testing), should typically be planned to test the conceptual ground model to provide further information on perceived hazards or risks (including geo-environmental issues) and to provide the engineering geological/geotechnical parameters required for more detailed analysis and design. Further information relating to these issues is given in Clayton (2001). As indicated earlier in this paper, the most common types of ground-related problems encountered during ground improvement relate to soil strata interfaces/boundaries (i.e. geometry of soil body not as anticipated), and the geotechnical properties of the soil. Whilst it is recognised that only in cases where there are significant geotechnical risks, or where benefits can be obtained from adoption of a sophisticated geotechnical approach, will it be advisable to carry out very detailed ground investigation, Clayton

(2001), it should be reiterated that the likely shortcomings of this must be recognised by the designer/design team. It is perhaps also important to recognise that the site investigation technique/s selected should be sensitive to the anticipated (or prevailing) ground conditions and ground improvement techniques being considered.

Figure 5a. Trial pit investigation.

Figure 5b. Cone penetration test truck

M60 motorway widening scheme

The M60 forms an orbital motorway around Manchester and is referred to as the Manchester Outer Ring Road (Figure 6a). A 7.4 kilometre section of the motorway, which experiences high daily traffic volumes and congestion, is being improved between Junctions 5 and 8 by the widening of the existing motorway, with the associated construction of new embankments, on and off slip roads and new bridges/abutments. Apart from the bridge crossings, the motorway runs on embankment (reaching maximum heights of 10 m near junctions), constructed on the western edge of the Mersey Valley floodplain over most of its length between junctions 6 and 7, where widening is principally concentrated on the clockwise side of the motorway (Figure 6b). As this section of motorway around junctions 6 and 7 traverses the floodplain of the river Mersey, the underlying soil profile typically comprises a sequence of weak alluvial deposits. These are underlain by generally competent glacigenic deposits (including glacial till (cohesive) and both glacial and fluvio-glacial sands and gravels), presumed to be mainly of late Devensian age, *c.* 20 000 to 14 500 BP. These in turn overlie bedrock of Triassic age, (*c.* 298-205 Ma) including either Sherwood Sandstone Group sandstone or Mercia Mudstone Group siltstone or mudstone, constituting the north-eastern edge of the Permo-Triassic Cheshire Basin. Ground conditions in the river valley have also been influenced by human/anthropogenic processes and the weak alluvial soils in the ground improvement areas are frequently blanketed by a veneer of fill (made ground), representing waste materials (including ash), from historic tipping and landfilling, including potentially contaminated fill, inert fill and also embankment fill (associated with the construction of the existing motorway in the 1970’s). In addition to the current channel of the river Mersey which meanders through the Mersey valley, a former (infilled) course of the river channel was also identified between junctions 6 and 7. Whilst the glacigenic deposits are generally competent the nature of the overlying alluviual deposits and heterogeneous/miscellaneous made ground presented the major challenge in terms of developing a ground improvement design solution that mitigated slope instability, substantially removed lateral loads (due to lateral displacement (“squeezing”) of the soft soils upon embankment construction), on bridge pier piles and minimised post construction total and differential settlements, whilst maintaining the desired construction programme for new embankments and reduce/preclude future maintenance. Within the designated ground improvement areas (Figure 6b), the alluvial deposits are generally encountered between 1.5 m and 5.0 m below basal embankment level, and are typically around 4-5 m in thickness (range 2-6 m), comprising predominantly very soft to soft silty clays (with undrained shear strengths in the range 15-20 kN/m^2) and organic clayey silts, (with the presence of some sand laminae and fine gravel layers). Standing water level variations, as determined from piezometer readings, are typically within the range 2.5-5.0 m below basal embankment level. Whilst there is not scope within this paper to provide detailed descriptions of the geological ground model for the M60 widening project it is important to recognise, for example, that the nature of some of the made ground generated potential geo-environmental risks which were also important considerations.

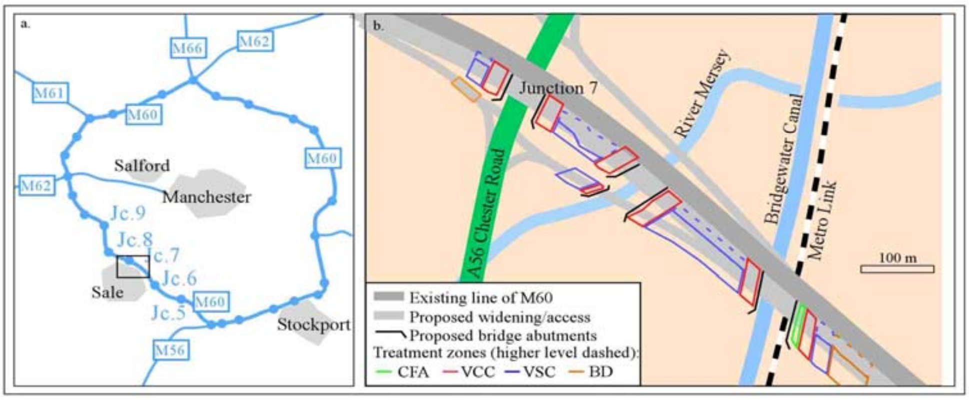


Figure 6a. Location of M60 widening. **6b.** Detail of M60 widening around junction 7 and juxtaposition of ground-improvement techniques. (CFA – continuous flight auger piles, VCC- vibro concrete columns, VSC- vibro stone columns and BD – band drains).

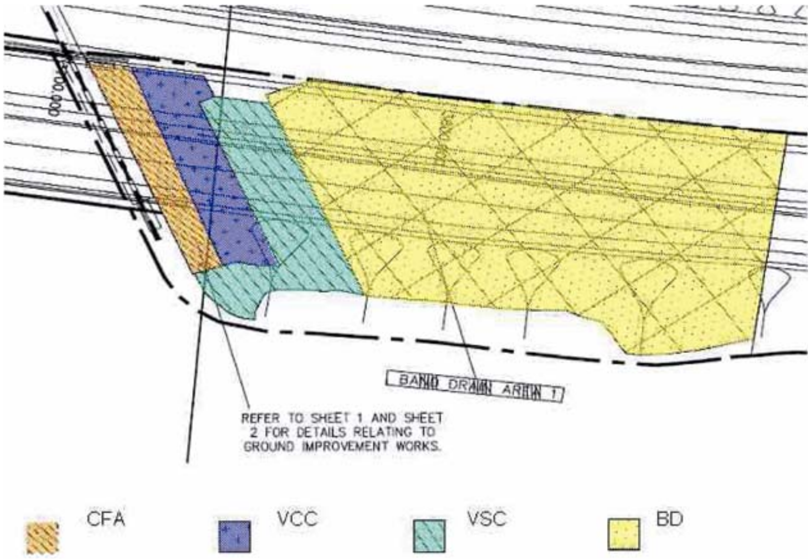


Figure 7. Interfacing of different ground improvement techniques on M60 motorway widening embankment approaches to the Metro-link tram line and Bridgewater canal bridge crossing. (CFA – continuous flight auger piles, VCC – vibro concrete columns, VSC – vibro stone columns and BD – band drains). (Distance between chainages = 100 m).

Cone penetration testing (CPT)

Methods are now available for interpreting CPT using the piezocone (CPTU), for engineering purposes in clay soils with regard to soil type and stratification and also parameters such as stress history, undrained shear strength, small strain shear modulus and coefficient of consolidation. The latter parameter, for example, can be assessed by measuring the dissipation or decay of pore pressure with time after a pause in penetration of the piezocone. An increase in our knowledge and understanding of the factors affecting or influencing the results of CPT/CPTU data is allowing more consistent results to be obtained. More recently the continued development of high quality databases of CPTU results and soil properties is enabling a new or improved set of correlation to be developed, Powell & Lunne (2005).

Much appears to have been written with regard to the interpretation of coefficient of consolidation and permeability. Cone penetration test (CPT) equipment (with some representative reference boreholes and laboratory testing), can provide a very useful compromise when compared to the cost of an extensive detailed borehole investigation comprising sophisticated undisturbed sampling techniques and subsequent laboratory testing, by providing a lot of high quality data quickly and economically, particularly for soft alluvial soils and soft sensitive clays. In order to provide/have confidence in the interpretation of CPTU results in clay soils it is vital that test results are both accurate and representative of the in situ soil conditions. This can be achieved by using equipment and procedures in accordance with the new International Reference Test Procedure (IRTP), (1999). The use of 10 cm^2 cones is typically recommended and a particular feature of the IRTP is the *Accuracy Classes* according to what the results are to be used for. The most strict accuracy class is applicable when the CPTU results are required to be used to derive soil design parameters in soft clay soils. It is a requirement to measure inclination in addition to cone resistance, sleeve friction and pore pressure. This allows consistency in test data and interpretation and estimation of soil type, together with greater resolution and data quality. Sensitive cones should be considered where very soft-to-soft "sensitive" soils are anticipated. CPT and its variants such as CPTU, (piezocone test), provide a very versatile investigation tool and can be readily adapted for/to the specific ground improvement application, whether they are utilised for pore pressure dissipation tests in soft alluvial soils, or for further investigating the level, thickness and load carrying potential of the soils (e.g. competent glacigenic sand and gravels), that are required to support vcc columns loads in end bearing. Both these applications were recently employed on the M60 motorway widening scheme around south Manchester to supplement additional borehole investigation. This enabled the geological/ground model to be refined and to feed into the risk management strategy, which in turn added confidence to verification of the design. Furthermore, the availability of CPT data in AGS (Association of Geotechnical & Geoenvironmental Specialists) format within the UK, allows rapid processing and review of data and incorporation into the design process.

For a recent highway embankment project associated with a new link road in Kings Lynn, Norfolk, where vibro ground improvement techniques were adopted to support new embankments over soft ground, original percussion boring borehole investigation techniques had not accurately recorded/identified strata boundaries (including the basal marine sand deposit above the Kimmeridge Clay) or the presence, level and thickness of thin peaty soils (Nordelph Peat) within the soft soil profile. The use of less intrusive cone penetration test equipment (CPT), (which is capable of indentifying features as thin as 20 mm if a piezocone (CPTU) is used), at 50 m longitudinal intervals along the anticipated road alignment, provided more accurate information on the geometry of the soft clay body and impersistent peaty/peat horizons, together with sand lenses and layers. This again permitted the geological/ground model (Figure 8) to be refined and to feed into the risk management strategy and design verification. It is important that new information on ground conditions is communicated to all relevant parties involved in the project, as part of the design and risk management process. The spacing of vertical band drains and stone columns will have a significant influence on cost. For example, 1m c/c spacing vertical drains will cost 300% more than 2 m c/c spacing vertical drains. In view of this cost sensitive nature, it is therefore very important to acquire sufficient information on the geotechnical properties of the soil profile so that a cost effective design can be carried out.

3D modelling of the shallow subsurface

Within the wider context of site investigation (S.I.), the advent of sophisticated 3D modelling of the shallow subsurface is potentially a very welcome development in this field. However, according to Culshaw (2005a) "creation of these attributed 3D models requires large quantities of the data which is collected during the thousands of site investigations carried out each year within the UK and therefore if readily available and useable 3D attributed models are to be built, then the information held in site investigation reports needs to be stored, validated, managed and made available from a single location…". This concept of centralisation of geotechnical data is not an entirely new concept however, particular if one looks at practice in countries such as the Czech Republic, for example. The main barrier to implementation of such a concept is cited as "generators of S.I. hiding behind client confidentiality". As Culshaw (2005a), implies, national databasing of S.I. may only be a practical proposition with introduction of appropriate legislation. More detailed discussion on 3D modelling of the shallow subsurface is presented by Culshaw (2005b), in the seventh Glossop lecture.

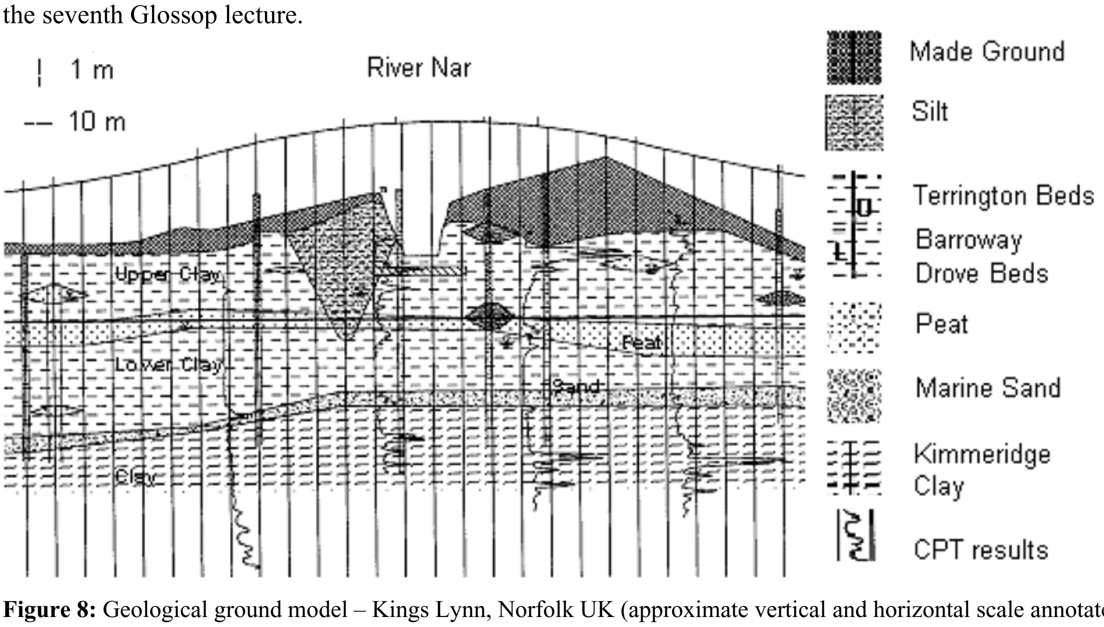


Figure 8: Geological ground model – Kings Lynn, Norfolk UK (approximate vertical and horizontal scale annotated)

The design process and review

Typically, the objective of ground improvement for highway projects is to provide stability and settlement control beneath newly constructed embankments over weak/soft soils (natural and/or made ground). However, provision of appropriate transitions and interfacing with piled abutments (and any existing motorway embankments) is also an important consideration in order to avoid significant lateral loading on abutment piles and provide a satisfactory settlement profile behind piled bridge abutments and smooth vehicle ride quality. Dependent upon the soil profile and geometry, this can be achieved in critical zones using, for example, (though not exclusively), a combination of vibro concrete columns (vcc's); vibro stone columns (vsc's) and vertical band drains (vbd), (Figures 6b; 7 & 9b).

The properties of the treated/improved soil that are to be achieved and at what time need to be clearly defined. It is important that the Specialist Contractors ground improvement design is reviewed by the project consultant, to ensure that critical elements are not overlooked, that ground properties adopted are realistic and that calculations are executed competently and correctly using recognised design procedures. The ground improvement design should demonstrate that the predicted behaviour is compatible with specified performance criteria (including, for example, minimum bearing capacity or load carrying capacity, maximum total and differential settlement under load and long term behaviour). Equally important is the observation and monitoring of ground conditions (including ground response to ground improvement installation), to ensure that geotechnical design assumptions are representative and will perform satisfactorily in the ground. Furthermore, where there is an element of design flexibility, the observational method or approach can also be implemented/adopted to ensure economic engineering of difficult ground. Reassessment of the design should be carried out as necessary throughout the construction (Figure 4). Good communication between all interested parties (design team and client), is a pre-requisite to successful design implementation. A good design needs to provide a robust defence against geotechnical risks, while being cost effective, state-of –the-art and relatively simple to install. The overall geotechnical design on the M60 orbital motorway widening scheme, for example, (of which vibro ground improvement techniques formed just one aspect), was subject to technical approval, based on the requirements of the Highways Agency HD22/02 document – Managing geotechnical risk (2002). This covers the desk study, geotechnical site investigation and interpretation as well as the development of the geotechnical design solution(s).

Bell (2004) refers to the term "construction technique" which is described as an often neglected element in the application of deep ground improvement. The term is defined as "the effective deployment of site resources to meet the design and other project objectives in an optimum manner. It normally includes: The employment of trained and experienced supervisors and operatives; purpose-designed plant and equipment; materials that are carefully specified, stored and used in correct quantities and the application of the most appropriate construction method for the site and ground conditions". It is therefore advocated by the author that the specialist contractors experience; equipment and materials intended for use should also form part of the design and review process.

Interfacing of different ground improvement techniques (including "transition zones")

When two or more ground improvement techniques are used in combination, and which interface with each other, (for example, to smooth out the settlement profile for an embankment construction behind a piled bridge abutment using vibro concrete columns (vcc's) and vibro stone columns (vsc's)), it is important that the settlements and rates of settlement associated with the different techniques are understood and accommodated within the design, including the provision of granular drainage blankets and geogrid reinforced granular load transfer platforms, to ensure compatability of the different techniques and achievement of a smooth settlement gradient/profile. It is also necessary to evaluate both the magnitude and rate of settlement of the subsoil supporting the embankment (when designing the embankment) so that the settlement in the long term will not influence the serviceability and safety of the embankment. Figure 7 shows a typical interfacing detail of ground improvement techniques behind a new bridge across the Metro-link tram line and Bridgewater canal on the M60 motorway widening scheme, Manchester (Figure 8b). These included installation of CFA piles down to rockhead for the new bridge abutment, to minimise impact on existing piled abutments, the development of a vibro concrete column (vcc) solution (within a 10 m zone behind the proposed new bridge abutment), including an integral load transfer platform to transmit loads to the underlying competent granular glacigenic deposits (with lateral load on bridge pier piles substantially removed). Installation of a zone of vibro stone columns was carried out immediately behind the vcc's to reinforce the weak soils and improve composite soil stiffness and reduce any lateral soil displacement and stresses on to the installed vcc's, upon embankment construction. Zones of stone columns and of band drains permitted stage construction (in conjunction with monitoring of installed instrumentation: piezometers; extensometers; inclinometers etc). The short term stability for embankment construction over soft clay (in the context of stone columns or band drains), is likely to be more critical than the long term simply because the subsoil consolidates with time under loading and the strength increases. The unique interfacing of these ground improvement techniques result in a gradual, rather than abrupt change in ground stiffness behind the piled bridge abutment and therefore provide a smoother settlement gradient and vehicle ride quality and reduced long term maintenance.

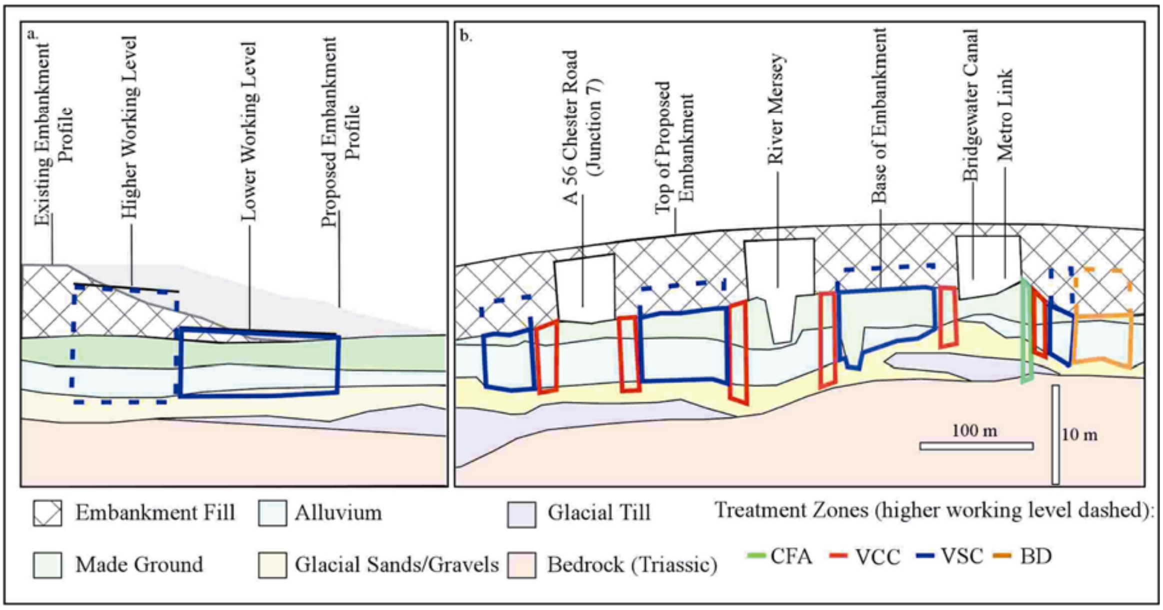


Figure 9a. Transverse and **9b.** Longitudinal schematic sections across the M60 near junction 7 (refer to fig 6a) showing typical soil profiles, treatment zones and treatment levels. (CFA – continuous flight auger, VCC – vibro concrete columns, VSC – vibro stone columns and BD – band drains).

Preliminary trials

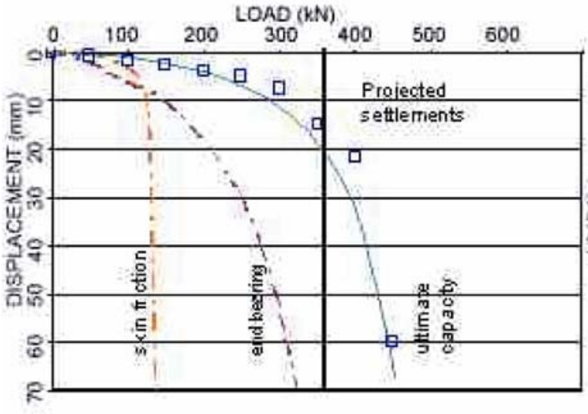
Vibro ground improvement techniques by virtue of their flexibility and reliability have proven suitable for a wide range of soils and highway embankment structures. However, preliminary trials (where programme and contractual constraints permit), are an important consideration/pre-requisite to any large scale ground improvement proposals for highway projects, particularly where new applications or systems (innovative techniques) are being proposed and/or ground conditions are complex/difficult. They also permit assessment of ground response, refinement of design and more accurate prediction of long term settlement performance. Ground improvement is potentially set at “high risk” in difficult ground until trials are successfully implemented.

Preliminary trials at Kings Lynn

Such an approach was adopted for a new relief (link) road construction, on embankment, in Kings Lynn, Norfolk (UK), where vcc’s were required to be end bearing in stiff Upper Jurassic Kimmeridge Clay (which had not been previously attempted in the UK), and stone columns were required to be installed through Flandrian (and Recent) very soft to soft marine alluvial and alluvial soils overlying the Kimmeridge Clay, (see Figure 8), to permit both assessment of ground response and refinement of installation procedures using the dry bottom feed stone column technique. Use of the wet top feed (vibroreplacement) technique was not permitted on environmental grounds.

One of the main issues with vcc design is in selection of criteria for settlement and factors of safety that are compatible and which allow for the likely variability of the ground, yet limit the differential settlement/s between piled bridge structures and vibro stone column zones beneath the adjoining embankment/s. This can only be realistically achieved by making a prediction of vcc behaviour based on preliminary tests with large head displacements (Figure 10b) and on the best estimate of the soil parameters from available geotechnical data. Preliminary vcc tests undertaken on the Kings Lynn project were analysed using curve fitting hyperbolic functions as described by Fleming (1992), with asymptotic definition of the ultimate load (Figure 10a). Ultimate skin friction and end bearing values of 150 kN and 300 kN respectively, were derived from the analysis. Vibro concrete column (vcc) design parameters were back analysed using standard bearing capacity calculations and known soil parameters in the test/trial area. An assumption was made on the distribution of skin friction in soft alluvial soils and in firm-stiff/stiff overconsolidated Kimmeridge Clay. To allow for the required vcc settlement criteria at serviceability states and to limit differential settlements, varying factors of safety ranging from 1.15 to 1.5 were proposed across the vcc treatment zones. The square or rectangular vcc grid spacings were determined using proposed factors of safety and combined embankment and highway (live) loading conditions.

There was also opportunity to construct a surcharge load test (vsc trials) on an array of trial stone columns installed at relatively low cost, to gain some indication of likely performance. However, monitoring of actual full embankment construction on installed stone columns (main works) yielded significantly lesser settlements. This supports arguments put forward by Greenwood (1991) & (2004), that for proving stone columns under wide loaded areas, attention (economic and technical) is best spent focussed on supervising column construction very closely to ensure that design specifications are consistently met. The reason for the better performance of the full embankment construction is attributed to loading conditions strongly influencing the stiffness and strength of stone columns. Except for columns near the edge of a loaded area that are not uniformly constrained nor wholly vertically loaded, the columns become stiffer and stronger as load is applied. In fact the applied load is described as the dominant influence on the strength and stiffness of columns. As a result columns in large arrays under wide loaded areas such as embankments perform better than those under smaller loaded areas where more columns are constrained only by unloaded ground. Such tests will always show them to be less stiff and settling/deforming more under test loads than the full embankment construction. The vcc and vsc trials became the benchmark for site controls and verification on the Kings Lynn project.



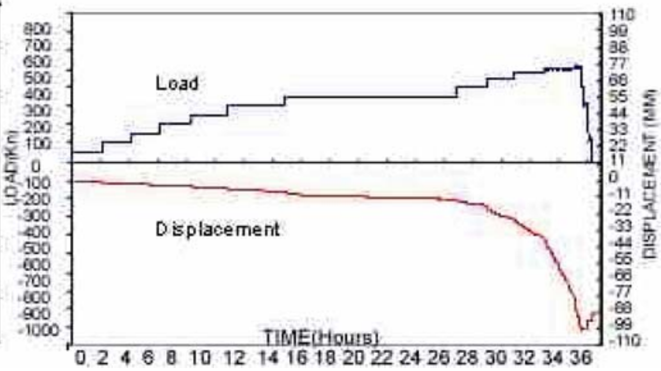


Figure 10a. Vibro concrete column (vcc) settlement analysis in Kimmeridge Clay – Kings Lynn, Norfolk, UK.(Solid vertical line = chosen Factor of Safety)

Figure 10b. Vibro concrete column (vcc) stiffness-settlement behaviour in Kimmeridge Clay – Kings Lynn, Norfolk, UK.

Practical issues

There are practical issues to consider when implementing ground improvement techniques for highway widening schemes, particularly as the existing motorway/highway/road will require to remain operational. This might involve use of sheet piling and carrying out ground improvement from one or more levels to permit access and safe working. Such matters were required to be addressed on the M60 motorway widening scheme in Manchester, for example, where new embankments extend out over the slope of the existing motorway embankments and for some distance beyond the toe. (Figure 9a). Because of the gradients of the existing embankments, it was necessary to excavate into the existing embankment side slopes, with either temporary steepening or the use of temporary slope support including sheet piling and anchored sheet piling. Stone columns had to be installed from two levels: a higher and lower working platform level (Figure 9a), which influenced both the loading conditions and in turn the stone column design (notably spacings and lengths). Some pre-boring, particularly for higher working platform levels in vibro stone column areas was needed to facilitate/assist penetration of vibroflot equipment through the existing competent embankment fill into the underlying weak alluvial soils. Localised CFA piling was required adjacent to a drainage culvert (once its location had been established), in view of concerns with regard to the vibratory effects and horizontal forces associated the vibro equipment (Figure 11).

Figure 11. CFA piling operation (foreground), in lieu of vcc's within proximity to existing drain, on alignment of motorway embankment widening approach to location of new bridge crossing over metro–link tram line and Bridgewater canal. Existing M60 motorway bridge in back ground.

Monitoring, testing and quality control

Good supervision and experienced site personnel are essential to ensure ground improvement design is implemented correctly in the field. Computerised monitoring of installation parameters during column construction (both vcc's and vsc's) is essential, including stone consumption (vsc's) and concreting pressures (vcc's). For stone columns in particular, close observation and monitoring of the diameter/cross sectional area; aggregate consumption (and compaction of the introduced aggregate), is important, to ensure the design area replacement ratio is being achieved. Site records (including computerised records) should be reviewed on a regular basis during the implementation of the ground improvement works. Whilst zone load tests and surcharge tests can be used to examine the performance of the composite stone column-soil system, applicability will depend on scale effects (i.e. size of the test relative to the extent of the final embankment structure). In this regard, for reasons described earlier, efforts should be focused more on achieving the required design parameters in the field, through close supervision, monitoring and implementation of effective quality control procedures.

Verification testing for vcc's might typically include dynamic testing on selected vcc's, to assess the elastic/immediate settlement behaviour of the column under the design loading. The integrity of the vcc can be checked randomly by sonic integrity testing. Performance testing might typically comprise zone load testing on either individual vcc's or groups of vcc's. Equally important is the monitoring of installed instrumentation, (piezometers; extensometers; inclinometers etc), particularly during and following embankment construction, (especially for stone columns and band drains). On the M60 project, for example, instrumentation was monitored by the geotechnical consultant and decisions on when it was safe to raise the embankments based on previously prepared stability charts and pore water pressure measurements. During the design process, it is very important to check the stability of the embankment/s with consideration of different potential failure surfaces namely circular and non-circular.

CONCLUSIONS

- An increasing proportion of building development takes place on poor ground, presenting the engineering geologist with the challenge of satisfactory site characterisation and the geotechnical engineer with the challenge of providing satisfactory foundation performance at low cost. Ground improvement/treatment using stone columns provides a means of modifying ground behaviour so that ground properties are improved and heterogeneity is reduced. However, the economic design of such schemes relies upon satisfactory characterisation of the geotechnical properties of the weak made ground and/or natural soil deposits overlying the competent soil layers or rock. Historically, this has restricted the potential use of ground improvement techniques, as appraisal for suitability has been limited by the lack of geotechnical parameters. This issue needs to be addressed further. Treatment of the ground prior to building can reduce uncertainty, and, consequently, ground improvement/treatment is of increasing importance within the practice of geotechnical engineering.
- Environmental constraints has seen the wet top feed stone column technique having been largely superseded by the dry bottom feed technique in the UK and concerns about stone columns generating pathways on brownfield sites, for contaminant migration into underlying sensitive groundwaters or aquifers, has seen the development of *vibro concrete plug* technology. Increasing awareness for sustainable development in construction is also leading to a greater desire for use of recycled aggregates in vibro stone column techniques. Crushed concrete has good potential as a recycled aggregate for this application, particularly in view of its availability in urban and industrialised areas where as a consequence of demolition in redevelopment areas, concrete structures are being demolished and floor slabs and concrete pavements broken up. Good quality control procedures are important to ensure 'fitness for purpose'.
- Motorway embankment and new highway embankment construction schemes in the UK urban environment have become increasingly fast track and complex and increasingly require an innovative and flexible (design) approach. For highway schemes, the approaches to piled bridges or the transition between rigid bridge abutments and the consolidating soil behind the abutment is a challenge for the engineering geologist/geotechnical engineer exploring cost effective ground improvement solutions to ensure smooth vehicle ride quality and to reduce maintenance. The important steps required to move from the initial design stage (and building the design team) through to successful ground improvement implementation include geotechnical site investigation; the design process and review; interfacing of different ground improvement techniques; preliminary trials; practical issues (including dealing with the unknown). Monitoring, testing and quality control within an appropriately defined risk management strategy have been discussed drawing upon recent experiences for two highway infrastructure projects in the UK. Schemes such as the M60 motorway widening also promote quicker journey times, better air quality and noise attenuation.
- The potential of the piezocone test (CPTU) for characterising the geotechnical properties of soft clay soils is increasing its use and application as a very effective and versatile site investigatory tool within the UK. In order to obtain test results that are accurate and representative of the in-situ soil conditions it is important that equipment and procedures used follow the International Reference Test Procedure (IRTP). In the UK, availability of CPT data in AGS (Association of Geotechnical & Geoenvironmental Specialists) format allows rapid processing and review of data and incorporation into the design process.
- With the increasing size, scope and complexity of ground improvement projects currently taking place both with the UK and throughout the world, it is important that geotechnical advisors (preferably with appropriate knowledge and experience of vibro ground improvement techniques) are involved at an early stage as regards to specifying the relevant site investigation and performance criteria for the anticipated ground improvement technique/s. The steps described in this paper as regards to a ground improvement specific risk management approach will hopefully contribute to achieving successful ground improvement implementation, both nationally and internationally.

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