Application of the Rapid Impact Compaction (RIC) technique for risk mitigation in problematic soils

C.J. SERRIDGE[1] & O. SYNAC[2]

[1] *Pennine Vibropiling (UK) Limited. (e-mail: colin.serridge@pennine-group.co.uk)*
[2] *Pennine Vibropiling (UK) Limited. (e-mail: ondrej.synac@pennine-group.co.uk)*

Abstract: The Rapid Impact Compaction (RIC) technique was originally developed for the rapid repair of explosion damage to military airfield runways and comprises a modified hydraulic piling hammer acting on a 1.5 m diameter articulating foot. Over the past 15 years the technique has been developed for civilian applications. Trials and subsequent implementation of the technique in the UK have demonstrated its suitability for treating miscellaneous fills (made ground) of an essentially granular nature up to depths of about 4 m. The technique has also been used internationally for treating essentially granular problematic/geohazardous soils in countries such as North America and Canada, South Africa, Japan, China and Iran among others. A brief review of some of the applications in the UK and internationally is provided.

A more recent application of the RIC technique has been in the treatment of collapsible (loess) soils in the remote Karachaganak region of Kazakhstan in Central Asia. Loess soils are estimated to cover approximately 10% of the earth's land-mass and typically these loess regions underlie areas of high population and major infrastructure links, and are structurally metastable, such that the deposits are prone to rapid collapse settlement resulting in ground subsidence and therefore present a significant geohazard. In Kazakhstan the RIC application was used for foundations for processing and refining plants associated with a large onshore oil and gas field development. A description of the project is provided and the importance of preliminary trials and pre and post treatment testing, together with close supervision and monitoring of the RIC technique during its implementation is highlighted.

Résumé: La technique de Rapid Impact compaction (RIC) a été développée pour la réparation rapide des dommage d'impacts sur les pistes d'atterrissage / décollage de terrains d'aviation militaires. Cette technique consiste en un marteau hydraulique agissant sur un pied articulé de 1.5 mètre de diamètre et a été également développée ces 15 dernières années pour des applications civiles. Les essais de cette technique (RIC) et les implantations qui ont suivi au Royaume Uni, ont démontré qu'elle était adaptée a traiter les divers remblais de nature granuleuse d'une profondeur jusqu'à 4 mètres de profondeur. Cette méthode a été aussi utilisée dans de nombreux pays (Amérique du nord, Canada, Afrique du sud, Japon, Chine et Iran) pour traiter les sols de nature granuleuse présentant des problèmes ou des risques géologiques. Aussi cet article fera une revue de son application au Royaume Uni et dans les autres pays.

La technique RIC a été récemment utilisée pour le traitement de sols formés de lœss dans les régions éloignées de Karachaganak au Kazakhstan en Asie Centrale. Les sols lœssiques couvrent 10% (estimation) de la surface continentale de la terre. Ces lœss sont généralement présents dans les régions fortement peuplées présentant d'importantes infrastructures. Ces régions sont métastables si bien que, ces dépôts sont souvent sujets à de rapides éboulements provoquant un affaissement du sol et présentent donc un risque géologique significatif. Au Kazakhstan, la technique du RIC a été utilisée pour traiter les sols (grands terrains de gisements de pétrole et de gaz) en vue de la construction de fondations pour des usines de traitement et de raffinage. Le projet est décrit dans cet article et met en évidence l'importance des essais préliminaires, des tests pré et post traitements, du control et d'une supervision de la technique pendant son implantation.

Keywords: Compaction; loess; engineering properties; collapse; saturation; liquefaction.

INTRODUCTION

The Rapid Impact Compaction (RIC) technique was originally developed for the rapid repair of explosion damage to military airfield runways and comprises a modified hydraulic piling hammer acting on a circular articulating steel foot which remains in contact with the ground during treatment (Figures 1a & 1b, Figure 2). Over the past 15 years the technique has been developed for civilian applications and it is estimated that there are of the order of 35 No. RIC units currently operating around the world. Mounted typically as an attachment to a hydraulic excavator, the machine comes in 5t, 7t and 9t modes (with the 7t modes typically used in the UK).

Within the UK the latter half of the twentieth century saw the growth of large areas of derelict land, as a result of the decline of heavy industry and associated demolition programmes. This land typically comprises both natural ground and non engineered miscellaneous filled ground (made ground), including building, commercial and domestic waste. In urban areas these problematic soils have frequently been considered unsuitable for development for supporting structural loads, owing to their unacceptably high compressibility and heterogeneity, without the adoption of deep foundation options/piles or the removal of the unsuitable ground and replacement with material of acceptable engineering properties (dependent upon site specific circumstances). However, these options may be cost prohibitive or environmentally unacceptable. With good building land becoming increasingly scarce and as pressure to develop such sites within the urban environment increases, ground improvement techniques such as vibro stone columns and to an extent, (dynamic compaction (DC)) are being increasingly considered for the improvement of the engineering properties of the existing ground. Further guidance on the applicability of both these techniques can be found in Building Research Establishment (BRE) Reports BR391 (2000) and BR 458 (2003) respectively. In particular, it is important to recognise that within the urban environment the effectiveness of the dynamic compaction (DC) technique in improving soil stiffness to a significant depth is countered by the effects of induced ground vibrations on nearby sensitive structures and utilities, which are exacerbated as the energy per blow is increased. Because of this environmental restraint, other ground improvement techniques such as vibro stone columns are often selected.

A significant proportion of smaller sites being re-developed for low rise construction comprise shallow essentially granular non-engineered fills 2-4 m deep which are often treated with vibro stone columns. It is likely, dependent upon the juxtaposition of existing structures and services, that many of these sites could be given consideration for and effectively be treated with RIC. There is evidence of increasing application in these circumstances. Since the energy per blow is less than in conventional dynamic compaction, the consequential risk of damage to the existing infrastructure is potentially reduced. Furthermore, from an environmental standpoint, it is important to recognise that in fill materials containing hazardous substances (e.g. chemicals, asbestos etc.) the major advantage of RIC over penetrative ground improvement techniques, such as vibro stone columns, is that greater control can be exercised to avoid exposure of hazardous material to the atmosphere whilst facilitating compaction of the soil at depth.

THE RAPID IMPACT COMPACTION (RIC) TECHNIQUE

Within the UK RIC typically employs a 7 tonne weight dropped repeatedly through 1.2 m onto a 1.5 m diameter steel articulated compaction foot (Figure 1a and 1b). Whilst the energy per blow is not large (typically 8.4t.m), the equipment permits a large number of impacts to be applied at a rate of about 40 blows per minute. The operator monitors and can record the number of impacts, the total energy input applied, the foot penetration per blow and the cumulative penetration. When a specified parameter is reached, for example, foot penetration or set per blow, the equipment is moved to the next treatment/tamping point. As the foot remains in contact with the ground, the energy is applied more efficiently in compacting the ground than in conventional drop weight dynamic compaction where the weight may fall on an irregular surface in such a way that much of the energy is dissipated in deforming the irregularities of the ground. Both field trials and laboratory simulations of RIC have shown that the manner in which the ground responds to treatment is a “top-down” process, compared to DC which is a “bottom-up” process. The first few blows in rapid impact compaction create a dense plug of soil immediately beneath the compaction foot. Further blows advance this plug deeper, which compacts soil in a deeper layer. This process progresses until little further penetration of the compaction foot can be achieved with increasing blows. The effect of the compaction process is confined largely to the ground vertically below the compaction point and treatment is therefore carried out on a closely spaced square or triangular pattern or sequenced on an arc about the centre of rotation of the base machine for the RIC equipment. Additional passes are typically offset from the primary pass to ensure effective treatment coverage. The carrier vehicle is typically a hydraulic excavator (Figure 1a). RIC has been used to treat a range of fills (made ground) of a generally granular nature in the UK (Watts & Charles 1993) and some natural sandy and silty soils, the latter principally outside the UK (Braithwaite & du Preez 1997).

The selection of the compaction method (DC or RIC) and plant type for a particular project, will depend on ground and groundwater conditions, and requirements for design and execution. Each system has merits and limitations (BRE Report BR458, 2003). It is important that these are understood and considered in the design and application of DC/RIC on a particular site and in the context of the prevailing ground conditions. Indeed, it may be necessary for more than one technique to be employed at a particular site to gain maximum benefit.

a)

b)

Figure 1. RIC treatment **a)** within proximity to existing structure and **b)** showing imprints produced by repeated blows of a 7t piling hammer on the circular steel compaction foot which remains in contact with the ground.

In the urban environment, the RIC technique has a number of specific advantages compared to the conventional drop weight dynamic compaction (DC) technique. These can be summarised as follows:

- The dedicated plant used is relatively small, with moderate mobilisation and operating costs compared with conventional drop weight dynamic compaction. Thus, smaller sites may be economically treated. Rigging and de-rigging times are also quite rapid.
- Treatment can be carried out in closer proximity to existing structures and services vulnerable to vibration damage. There is generally no danger from flying debris.
- Discrete, relatively small foundation areas can be treated without compromising production.
- Energy is more efficiently transferred through the compaction foot which remains in contact with the ground.

It is important to recognise that those specifying RIC ground treatment understand the nature of the particular treatment process employed and its potential benefits for the ground conditions being considered. BRE Report BR 458 (2003), provides a technically prescriptive specification for the process, including design issues, which is based on accepted best practice and is structured in such a way as to encourage clear definition of a rationale for treatment, namely "the geotechnical principle of improvement" and the technical means ("method of compaction") by which this improvement will be achieved.

Treatment depth and design

Typically, the RIC method in the UK is used for the treatment of essentially granular fills in order to improve their geotechnical properties (stiffness and bearing capacity) and to reduce settlement. RIC design in the UK firstly involves geotechnical characterisation of the soils to be treated, with emphasis placed on quantifying in-situ relative density and grading characteristics. Groundwater level is an important factor for consideration of suitability of the RIC method as shallow groundwater level can act as a hydraulic barrier reducing effective energy transfer to the fill materials. However, it is the "compaction trial" (discussed under testing and quality control), which provides the designer with the necessary information to permit refinement of the design. With ground improvement techniques involving surface impact such as RIC there cannot be direct control of treatment depth, as would be the case with vibro stone columns. A critical element of RIC design therefore is the depth to which a particular treatment is effective.

With RIC the total energy input will have a major influence on the depth of compaction. With the rapid impact compactor the energy per blow is very much smaller than conventional DC and the fixed energy per blow of typically 8.4 t.m is not the major influence on the depth of compaction due to the progressive top down improvement of the treated ground. Of much greater significance to the effective depth of compaction is the number of blows at a compaction point or the energy applied overall to the ground surface. For typical impact spacing, 35 blows will impart about 170 tonne.m/m^2 of energy. This level of energy input has produced significant compaction to depths between 3 and 4 m in non-engineered generally granular fill (Watts & Charles 1993) and up to about 3 m in natural sand and silty soils using a 7 t hammer (Braithwaite & du Preez 1997). Table 1 gives some typical examples of the range of ground type and depths of compaction associated with RIC application in the UK. Outside the UK greater depths are being quoted in natural granular soils and is referred to in one of the brief case histories presented later in the paper. The technique is generally not very effective in low permeability saturated soils.

Table 1. Typical depths of compaction using RIC (after BRE BR Report 458, 2003)

Ground type	**Total energy applied (tonne.m/m^2)**	**Depth of compaction (m)**
Loose building waste	150	4.0
Ash fill	150	3.5
Select granular fill	150	4.0
Sandy silt and silty sand	80 and 190	2.0 and 3.0

The most common and serious risk to buildings on fill is the potential of most non-engineered fills to suffer collapse settlement on wetting. The phenomenon and its causes are well understood and comprehensively documented, as is the degree of compaction of a fill required to minimise, or preferably eliminate, that potential. Careful consideration of the applicability of either DC or RIC in these circumstances is therefore required. Outside the UK this problem occurs in many natural soil deposits, notably loess soils, and DC amongst other ground improvement techniques, have been applied to the treatment of susceptible soils in locations around the world. The application of RIC to collapsible loess soils in Kazakhstan (central Asia) is discussed later in this paper.

TESTING AND QUALITY CONTROL

Preliminary trials are an important pre-requisite to any extensive RIC works. Furthermore, as the main RIC works are proceeding, ongoing monitoring and testing is necessary to ensure that the appropriate amount of energy is being applied to the soil profile and that performance requirements are being met. The compaction trial, in particular, is important for the evaluation of ground response. The optimal number of blows per pass is typically taken as the value beyond which continued blows produce negligible further penetration of the compaction foot.

During the trials or works, the degree of compaction can also be monitored by comparison of pre and post treatment dynamic penetrometer tests (DPT's), static cone penetration tests (CPT's) or standard penetration tests (SPT's). In Canada, Becker Penetration Tests have been used in coarser soils. Unfortunately, due to the heterogeneous nature of some of the fills, which all of the above mentioned tests would reflect, it is sometimes very difficult to evaluate the improvement with accuracy. It is considered (where safe and practical), that plate bearing tests (PBT's) carried out at different levels during the trials / after treatment may enable more accurate appraisal of the treated fills bearing characteristics. Moreover, use of some form of in-situ geophysical testing also has an important application and can potentially overcome some of the limitations of in-situ penetration tests.

APPLICATION OF THE RIC TECHNIQUE TO NON ENGINEERED GRANULAR FILLS (MADE GROUND) – SOME BRIEF CASE HISTORIES FROM THE UK

Introduction

Increasingly, RIC treatment is being applied at geotechnically complex sites in the UK and a commensurate degree of process control and data feedback is therefore essential. Introduction of ground improvement techniques such as RIC has led to the increasing use of in-cab instrumentation and on-board computers. Automatic in-cab recording has clear advantages for process control and contract purposes and can also provide valuable feedback to the design process and confirm assumptions about pre-treatment ground conditions made from the original site investigation or in some cases, provide additional information. The RIC technique generally covers a significant area, if not all of a site, and data related to the execution of the compaction process can be used to "map" the treated area. This can provide information about in-situ ground conditions and the response to treatment. Particular zones may be highlighted in which conditions are significantly different from those anticipated in the original design. The information can be made available rapidly to the ground improvement designer and modifications made to the treatment design and specification where necessary. Figure 3 shows information reported by Watts & Charles (1993) for rapid impact compaction application on an old ash fill site in Sheffield (UK). Both the rate and total penetration of the compaction foot was recorded for a given number of blows**.** Total penetration for 50 blows is shown on a scale of shading that has highlighted a diagonal feature across the trial area. Measurements also indicated little or no reduction in penetration rate with increasing blow count, indicating that the compactor had identified an area of particularly poor fill ("soft" zone). Subsequent site investigation with trial pits and boreholes revealed a layer of soft cohesive fill between 1.2 m and 2.4 m below original ground level, within the main body of granular ash fill on the line of the inferred "soft" zone.

Figure 2. Rapid impact compaction (RIC) technique.

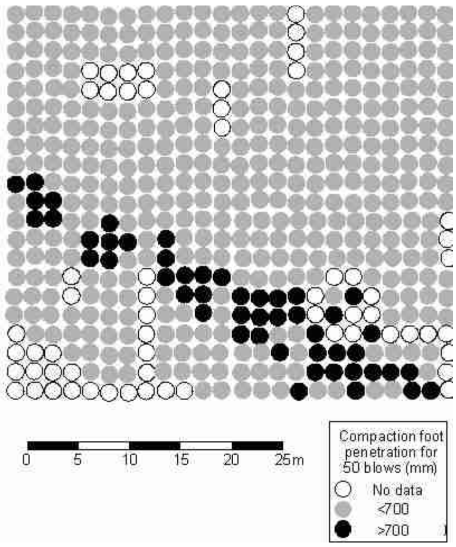


Figure 3. Rapid impact compaction (RIC) data used to "map" a treated area in Sheffield, (after Watts & Charles 1993)

Waterbeach (UK) – Inert building waste.

Watts & Charles (1993) reported on field trials undertaken in 1990 using the RIC technique in a loose inert building waste at Waterbeach, UK. The made ground had been end tipped and spread with a dozer in 1m lifts without systematic compaction in 1987 to a total depth of 6.5 m and overlying a natural clay deposit. Typical constituents of the made ground included brick, concrete, wood, glass and rag with some soil (principally sand sized particles). Dynamic probing demonstrated large variations in blow count over short depths, indicating the significant variability of the building waste. The groundwater table was at around 4.5 m below the upper surface of the fill.

An area of the site was treated with RIC using a 7 tonne hammer falling through 1.0 m onto a 1.5 m diameter compacting foot. Abutting treatment points were used spaced at 1.5 m centres, and each treatment point received 50 blows. The average energy input was 150 t.m/m^2. Surface settlement was measured at generally greater than 0.3 m. Vertical compression in the upper 2 m of the fill was of the order of 10% and significant compression was measured to a depth of 4m. The measurement of Rayleigh wave velocity was one of the methods used to assess the properties of the made ground before and after RIC treatment. Dynamic shear modulus was calculated from these results and which demonstrated significant improvement (Watts & Charles 1993).

Sheffield (UK) – Improvement of an old ash fill site.

Watts & Charles (1993) also reported on trials at the eastern end of a former steelworks site in Sheffield and which had formerly been occupied by railway sidings. Non-engineered fill (made ground) consisting mainly of ash, clinker and slag had been deposited historically over the natural alluvial valley deposits to a depth of about 3.5 m. Pre- RIC treatment penetrometer tests showed the fill materials to be in a loose condition (Figure 4). A 40 m x 35 m area was designated for the trial and prior to commencement of RIC the area was covered with a 0.5 m thick granular working blanket of demolition waste (comprising mostly broken brick and crushed concrete), to safely support the weight of the RIC rig and act as a source of granular material to doze into imprints formed during the RIC treatment. A grid of levels was also taken within the trial area before and after RIC treatment to permit monitoring of enforced settlement resulting from the treatment. Settlement with depth was measured by a specially installed magnet extensometer. A treatment pattern of almost abutting compaction points (approx 1.68 m grid), was adopted, with each compaction point receiving 50 blows of a 7 tonne hammer dropped through a height of 1.2m giving a total applied energy input of around 150 t.m/m^2. The loose essentially granular fill underwent significant compression and densification during treatment as demonstrated by the magnet extensometer readings and post treatment dynamic probe results (Figure 4). In common with dynamic compaction (DC), the lack of compaction close to the ground surface demonstrated the need for proof rolling of the treated surface following RIC completion. The trials provide a useful insight into the capabilities of the RIC technique in essentially granular fills within the UK.

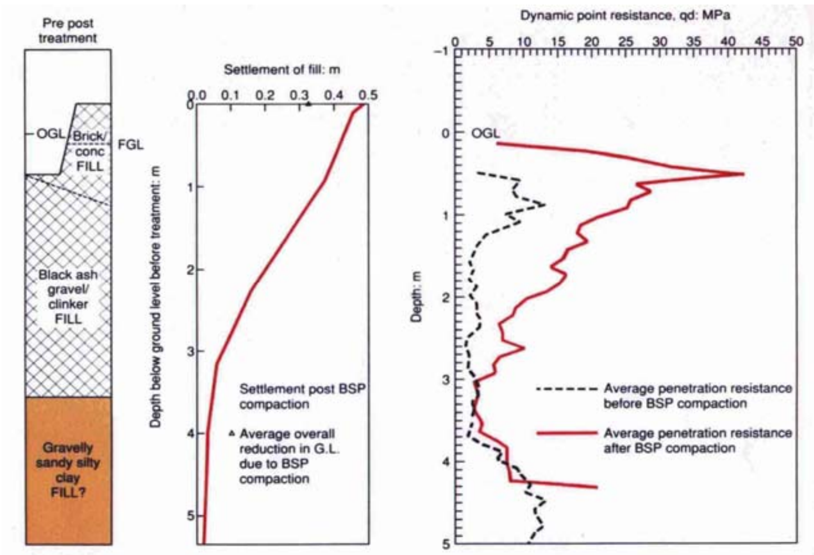


Figure 4. Results of RIC trials (including dynamic probing) in miscellaneous granular fill, Sheffield (UK) after Watts & Charles (1993).

Thurrock, Essex (UK) – Extension to existing building.

A Swedish furniture retailer wanted to extend their existing outlet at Thurrock, Essex (UK). The development was over an abandoned chalk quarry (a legacy of the cement industry in the area), which had been backfilled with around 5-6 m of contaminated, essentially granular fill in an uncontrolled manner. Site investigation had shown the relative density of the made ground to be essentially loose. However, there were areas of soil which were locally cemented due to the use of the quarry as a raw material supply for cement production in the 1950's and 60's. Floor loads of up to 50 kN/m^2 were required for the extension to accommodate warehouse storage. Traditional drop weight dynamic compaction (DC), whilst having been adopted for the existing structure was precluded for the extension due to the inherent risk of vibration damage. Vibro stone column techniques would not penetrate the cemented bands of fill without the use of pre-boring and would have produced a significant amount of contaminated spoil if undertaken beneath the entire building footprint.

RIC treatment was applied in two main (offset) grid passes. Use of vibration monitoring allowed the RIC technique to encroach to within 10-12 metres of the existing structure (Figure 1a). Vibro stone columns were used to treat the remaining area, thus significantly reducing the amount of pre-boring and contaminated arisings which had to be dealt with using this composite ground improvement approach. Imprints formed during each treatment pass were infilled with granular material, with final proof rolling of the treated slab area taking place prior to construction of the ground bearing floor slab. Use of both large plate load and zone load tests demonstrated that the bearing capacity had been satisfactorily achieved. The main building foundations were constructed on a vibro concrete column (VCC) system end bearing in competent natural Chalk strata.

Dagenham, Essex (UK) – Lorry park at Ford motor company site – improvement in CBR.

Continual on-going improvements at the Ford Motor Company site in Dagenham, Essex (UK) necessitated the construction of a new lorry park at the jetty transfer area, within a zone of waste ground which had been reclaimed with essentially granular materials comprising sand, gravel, ash, foundry waste and demolition rubble placed in an uncontrolled manner. The design requirement for the new lorry park was for achievement of a CBR of 20% following RIC treatment and proof rolling, prior to constructing the surfacing / hardstanding. Treatment was carried out over an area of some 37,000 m^2, employing two main treatment passes (on offset grids) with between 20 and 30 blows at each compaction point. Compaction trials/checks and plate load tests were used to verify the efficiency of the treatment technique during and after its execution respectively.

West Midlands, West Bromwich (UK)– Potentially combustible ground & proximity working to existing structure.

Construction of a new warehouse and offices adjacent to an existing warehouse construction at Great Bridge, West Bromwich, (UK) involved the use of a combination of RIC and vibro stone column ground improvement techniques. In the 19th century the site had formed part of a colliery for coal extraction with subsequent significant filling and re-contouring of the site and its immediate surrounds having taken place. The site was re-developed in the 1940’s for the production of welded steel tubing and an underground fire within the colliery spoil was reported to have occurred on the site in the 1960’s. The predominant made ground deposits across the site, particularly at shallow depth, comprised gravely (sometimes silty) sand of ash, clinker, slag, coal, mudstone and sandstone. Within this matrix and generally within 3m bgl, brick and concrete rubble had also been proven. The made ground deposits were typically black in appearance with coal inclusions and considered to be indicative of the potential presence of incomplete combustion products. Deposits (pockets and lenses) of lime were evident in some of the trial pits witnessed and it was thought that this may represent lime injected into the ground to extinguish the underground fires or alternatively spent lime from a former gasworks to the east of the site. The made ground was fairly uniform and had been in place for some time, and was predominantly granular in nature with a loose relative density. Some representative grading analyses confirmed the typical particle size proportions detailed in Table 2. The made ground extended to depths of up to between 8 and 10 m beneath the development site and was underlain by competent glacial deposits in turn resting on Carboniferous Etruria Formation Mudstone.

Table 2. Grading characteristics of made ground at Great Bridge, West Bromwich (UK)

Soil constituent	Range of proportions %
Clay/silt	5-13
Sand	33-40
Gravel	50-54
Cobbles	0-4

Despite the potential applicability of vibro stone columns to the improvement of the made ground deposits encountered on the site, calorific values in a number of made ground samples were high and introduction of high permeability stone columns (combined with friction between the vibro equipment and surrounding soil during stone column installation) could have significantly exacerbated the potential for any underground combustion by allowing ready access for oxygen. This therefore precluded the use of vibro stone columns. The presence of an existing adjacent relatively new warehouse unit also precluded the use of conventional drop weight dynamic compaction (DC) with the result that RIC was proposed as the main ground improvement solution for the site to permit construction of a new warehouse with integral offices, constructed on shallow pad and strip foundations with a ground bearing floor slab. Up to three main treatment passes were undertaken with a total energy input of around 200 t.m/m^2 applied to provide a bearing pressure of 150 kPa beneath main foundations and with 90 t.m/m^2 applied beneath ground bearing floor slab areas to provide a bearing pressure of 35 kPa. Imprint depths under the earlier treatment passes were of the order of 450-500 mm (for a total of 40 blows at each imprint position), reducing to around 100-200 mm (for a total of 30 blows at each imprint position) on the later treatment passes.

To minimise any increase in stress below the level of effective ground improvement, foundation depths were kept as shallow as possible. It was recognised that the presence of the existing warehouse would preclude the use of RIC closer than 10 m (based upon experience and subsequently confirmed by vibration monitoring).Whilst the use of stone columns would have been precluded due to the risks highlighted above for the soils underlying the majority of the site, historic remediation prior to construction of the adjacent existing warehouse had been such that the soils encountered within around 10-15 m of the existing building were more cohesive and non-combustible, therefore permitting stone columns to be used beneath that part of the building footprint, thus providing a composite ground improvement solution for what were difficult site conditions.

Other potential applications of the RIC technique in the UK

Increasingly in the UK the RIC technique is being given consideration for further improvement of soil stiffness, particularly beneath high specification ground bearing floor slab areas where, for example, stone columns have already been installed. This method has been loosely described as “energizing” the stone columns thereby further improving competent stiffness. Additionally, consideration has been given to the application of the RIC technique to landfill sites, for example to improve landfill space in older landfills, and to improve the integrity of the final cover systems. However, this warrants further research accompanied by appropriate risk assessment.

APPLICATION OF THE RIC TECHNIQUE INTERNATIONALLY

Japan, Hokkaido –liquefaction mitigation

The use of RIC is reported (Anon 1996) for a 750 m^2 (5000 kl) oil tank foundation in Hokkaido, Japan, to mitigate liquefaction potential in loose to medium dense natural sand and gravel deposits. Groundwater level was very shallow, typically at around 1.0m depth, which made it necessary to excavate and dewater the site so that ground water level was about 3.5 m below the proposed treatment level, located at 6.0 m below existing surrounding ground level. A total of 5 passes with 50 blows per footprint was specified (equating to a very high total energy input of up to around 650 t.m/m^2). Passes 1, 3 and 5 were undertaken on the same 1.8 m square grid, with passes 2 and 4 undertaken on a 1.8 m offset grid from passes 1,3, and 5. Following each treatment pass imprints were dozed in using surrounding granular material from entirely within the treatment area and a level survey undertaken. Pre and post treatment penetration tests using SPT's showed significant improvement in the upper 5m (improvement in SPT value of between 20 and 30) and with some improvement in relative density reported to depths of up to around 10.0 m below initial treatment commencement level. The recorded enforced settlement was of the order of 400 mm.

Other applications of the technique reported in Japan include major urban highway projects to compact granular fill materials adjacent to bridge structures, and retaining walls to eliminate differential settlement (with, for example, number of blows restricted to around 5 at about 1m from an abutment wall (subject to vibration monitoring), increasing to around 30 with increasing distance from the wall, to preclude any vibration damage, (Anon,1996).

Iran, Assalouyeh, coastal reclamation project

Construction of a 20 km coastal petrochemical refinery on reclaimed land approximately 0.8 km in width protected by a rock armour defence wall associated with the South Pars gasfield, straddling the Iranian and Qatari sectors of the Persian Gulf has seen the use of RIC. Fill used in the land reclamation for the refinery comprised crushed rock quarried from coastal mountains and typically ranged in depth from 3 m (landward end) to 14 m (seaward end). Following initial trials (with pre and post treatment SPT testing), RIC treatment was carried out using two main treatment passes to provide effective compaction of the granular fill deposits to depths of up to 6m utilising two 9t BSP RIC compactors. For greater depths conventional drop weight dynamic compaction (DC) using tampers/weights in the range 10-30 tonnes dropped from heights of up to 30 m is reported to have been adopted, (Anon, 2004).

Canada – liquefaction mitigation

Several projects have been carried out in British Columbia using the RIC technique in deposits of sand and gravels (both natural deposits and made ground) for applications such as low rise structures and areas of hardstanding. Depths of influence of the RIC treatment in the range 3.00-6.00 m have been reported, for silt contents ranging from about 1-10% (Cooper 2005). There is increasing evidence of the technique being used to mitigate liquefaction potential in such soils for low-rise structures.

APPLICATION OF THE RIC TECHNIQUE TO LOESS SOILS IN KAZAKHSTAN CENTRAL ASIA

Introduction

The RIC technique has been recently applied on what is regarded as probably one of the largest onshore oil and gas field developments currently taking place, located in the remote Karachaganak region of north west Kazakhstan in Central Asia, where a very large gas condensate and oilfield was discovered in 1979. Within the region a 3000 ha site was being developed as a refinery for Karachaganak POBV.

Central Asia constitutes one of five major recognised loess regions (which also include North America, South America, Europe (including western Russia) and China. These loess regions underlie highly populated areas and major infrastructure links, and are structurally metastable, that is, the deposits are prone to rapid collapse settlement leading to ground subsidence. The areas of most widespread concern are concentrated in eastern Europe and Russia and to a growing extent in China (Derbyshire, Dijkstra & Smalley,1995) and also central Asia (due to exploitation of oil and gas reserves described above). The Karachaganak region is a largely featureless windswept plain underlain by loess soils of low bearing capacity and prone to sudden collapse. Variable climatic conditions lead to flash storms and rapid inundation causes immediate soil collapse.

Stable foundations were required for two different processing plants approximately 3 km apart, referred to as KPC and Unit 2 (U2) for refinery structures; pipelines, tanks and separation towers, all being settlement sensitive. Russian Foundation Codes did not permit adoption of spread foundations within the potentially collapsible soils without ground improvement techniques being applied. Ground improvement was therefore implemented to reduce the collapse potential in the loess soils, to improve the bearing capacity of the ground for the foundations to oil and gas processing plants, and associated structures. Various methods of compaction have been used to densify collapsible soils such as dynamic compaction, use of compaction piles, vibro stone columns etc.. However, the remote location, the fact that treatment of a number of isolated pipe rack foundations was necessary (together with auxiliary plant/s) scattered across an area of one square kilometre and the proximity of existing structures, dictated the use of RIC. Piling would have been extremely costly and would have restricted plant layout options. Traditional piling was necessary, however, for larger more heavily loaded structures.

Location of ground improvement and site geotechnical characterisation

The KPC and U2 areas are both essentially flat plateau areas, but with the U2 area occupying the watershed between the Berezovka river and its west flowing tributary.

The soil profile at Karachaganak comprises Lower to Middle Pleistocene (macroporous) loess soils and are described in the region as having alluvial/proluvial –deluvial genesis. These are historic terms, introduced by A.P. Pavlov more than a hundred years ago, but still appear to be used by Central Asian region researchers. Deluvial loess is essentially loess on slopes (from deluo – washing down) and proluvial loess is loess on plains, deposited by water. Reconciliation of aeolian deposition with the Pavlov scheme has received much discussion but it is evident that more progress is required on these aspects. The loess soils, which are widely distributed in the Karachaganak area, extend to depths of up to around 17 m. A distinct desiccated crust is present typically extending to depths of up to 2.0m.

From Russian translation the main body of loess soils are typically described as yellowish-brown sandy silts (Figure 5a), and also "silty sandy loam" and having a "lumpy" texture, with generally low salinity. Small lenses and some interbedded layers of fine silty sand are also present. The upper part of the "crust" (below topsoil level), is a fissured stiff-hard brown silty to very silty clay (described locally as a "lumpy loam") with gypsum inclusions and occasional small silty sand pockets, and with evidence of sub-vertical columnar jointing (Figure 5b). Its characteristics, which include swelling potential, having been influenced by the climatic extremes experienced in this part of Central Asia (including freeze-thaw and capillarity). The underlying bedrock is described as Upper Cretaceous Turonian and Coniacian fractured limestone-clayey marl (semi-weak rock), with interlayers and lenses of clay and sand.

a) b)

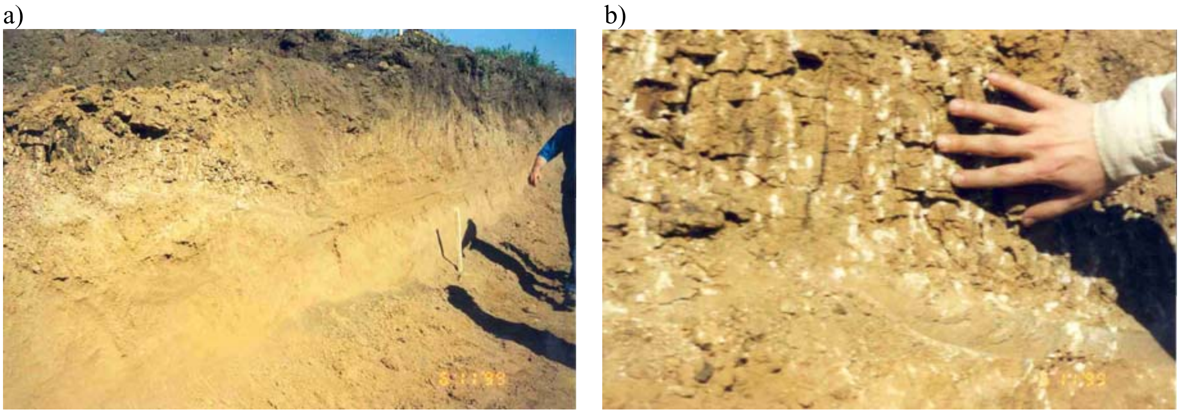


Figure 5. a) Section through upper 2.0 m of the loess soil profile at Karachaganak and **b)** detail of the upper desiccated crust immediately below topsoil level.

Geotechnical characterisation of the loess soils (based on Russian and Western Standards), is summarised in Table 3. Near-surface strengths are highest, reflecting the desiccated "crust" like nature of the loess at the ground surface. This high apparent strength is reflected in the average deformation modulus for the crust for the U2 area, for example, where 15 MPa was reported at natural low moisture content, reducing to around 8 MPa for water saturated soil. Below the crust the average deformation modulus for the loess is reported at around 10 MPa at natural moisture content reducing to 6 MPa for water saturated soil.

The groundwater level in the KPC was deep seated, typically at a depth of around 30 m at the time of ground improvement. Groundwater level in the U2 area however, is influenced by the Berezovka river and its tributary. Whilst the stable groundwater level is at around 6-7 m in the summer months, significant groundwater recharge occurs as a result of precipitation and the spring snow melting period and has been shown to rise to within 1.5 m of ground level. At the time of investigation the soils within the U2 area were shown to be saturated typically below a depth of around 3.0 - 4.2m from ground level. The KPC area consisted of principally the same soil as the U2 area but with a lesser degree of saturation, lower natural moisture content and a lower clay but higher sand fraction.

Table 3. Representative basic soil properties of Loess soils for KPC & Unit 2 (U2) areas (average values)

Location	Depth (m)	ρ_b (Mg/m^3)	ρ_d (Mg/m^3)	n %	m %	S_r %	LL %	PL %	PI %	Clay %	Silt %	Sand %
KPC	0-2 m	1.76	1.61	46.8	10.2	37	35.3	17.1	18.2	24.1	55.6	20.3
KPC	2-7 m	1.88	1.67	42.2	13.4	59	35.5	17.8	17.7			
UNIT 2	0-2 m	1.75	1.71	42.3	11.9	49	34.5	17.3	17.2	29.3	56.6	14.5
UNIT 2	2-7 m	1.95	1.66	39.7	19.3	79	31.9	16.1	15.8			

ρ_b ,bulk density; ρ_d, dry density; n, porosity; m, natural moisture content; S_r, degree of saturation; LL, liquid limit; PL, plastic limit; PI, plasticity index.

Silt is the most important size fraction in the loess (Table 3, Figure 6), in terms of soil behaviour and ground response). In the U2 area, carbonate content values were typically in the range 12.5-18.5% for the "crust" and 12.6-23.9% in the loess soil profile below the "crust". Gypsum content was typically in the range 0.07-3.17% in the "crust" and 0.16-1.10% in the loess soil profile below. Soils from both sites (KPC & U2) have high porosities (39.7-46.8%) indicative of an open microstructure. As such they are potentially metastable, that is the soil microstructure is susceptible to collapse, when flooded under loads exceeding their natural overburden pressure. Jefferson, Tye & Northmore (2001), suggest that there are a number of ways to examine the collapse and to assess the severity of the collapse. The most common, and currently the most reliable procedure is identified as double oedometer or modified single oedometer collapse testing using carefully recovered undisturbed test samples. It is further indicated that "although this will not accurately give the absolute amount of collapse in all field conditions, these index tests are extremely effective at indicating the potential risk of collapse and as such can provide a useful tool when engineering loess soils. Collapse criteria based on soil index properties such as natural moisture content, void ratio and consistency limits, although useful, may only be locally applicable and provide a rough indication of whether or not a particular loess soil may be collapsible. In any case, such criteria can only be derived by correlation with oedometer collapse tests in the first instance".

The results of oedometer testing confirmed that the loess soil profile had collapse potential that was diminishing with depth. From the hydroconsolidation (Rogers, Dijkstra & Smalley, 1994), behaviour investigated in the laboratory the upper 3.2-4.0 m of the loess soil profile at Karachaganak was assessed as having collapse potential. In accordance with Russian Standards (Foundation Beds, 1997) the soil was classified as (Type 1) settling/collapsing soil. Figure 7 shows results for soil samples from different depths (1.5 m and 7.5m) which were subjected to a compression under saturation to develop the inundated compression curve (initiated at 100 kPa), and demonstrated by the shallower depth (1.5 m) sample, the maximum test load being 400 kPa.

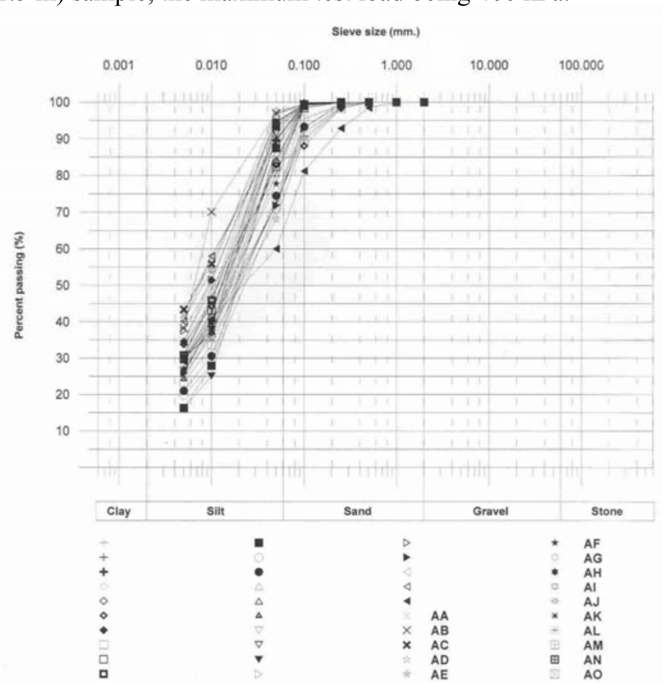


Figure 6. Average of all particle size distribution data for KPC area loess.

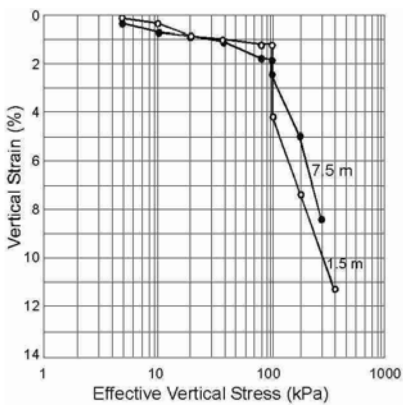


Figure 7. Vertical strain-log stress curve of loess tested in an oedometer to determine inundation compression curves for soil at 1.5 m and 7.5 m depth.

Design/Performance requirements

The design requirement for the project was to provide a bearing capacity of 150 kN/m^2 with a long-term settlement requirement of less than 25 mm for foundations not exceeding 10 m in width.

Rapid Impact Compaction (RIC) trials

Prior to commencement of the main works, preliminary trials (Figure 8) were undertaken at the KPC and U2 areas, to assess the suitability and effectiveness of the RIC method, including the most appropriate treatment regime and both depth and degree of improvement. The RIC equipment utilised a 7 t BSP piling hammer dropped through a height of 1.2 m onto a 1.5 m diameter steel compaction foot. Initially treatment trials were undertaken within the upper desiccated "crust" close to natural ground level to investigate the effect of the crust on ground response and the depth of improvement. Improvement was significant (Figure 9a & 9b) and demonstrated that the crust provides an efficient energy transfer mechanism. Imprint depth at 50 blows was 150 mm (increasing to 350 mm at 200 blows) and at 50 blows was 500 mm (increasing to 1200 mm at 200 blows) for the KPC and U2 areas respectively. However, in view of the anticipated construction sequence and founding depth below the desiccated crust, excavation below the crust was carried to permit execution of further more representative trials in the KPC and U2 areas. Two passes from this reduced level were carried out with pre and post treatment dynamic probe testing (DPT/DP's) both on and between imprints (Figure 8), together with pre and post treatment plate bearing tests (PBT's).

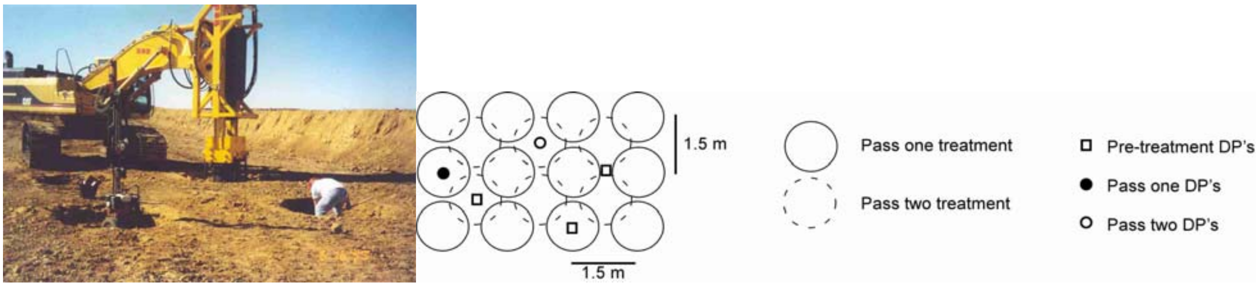


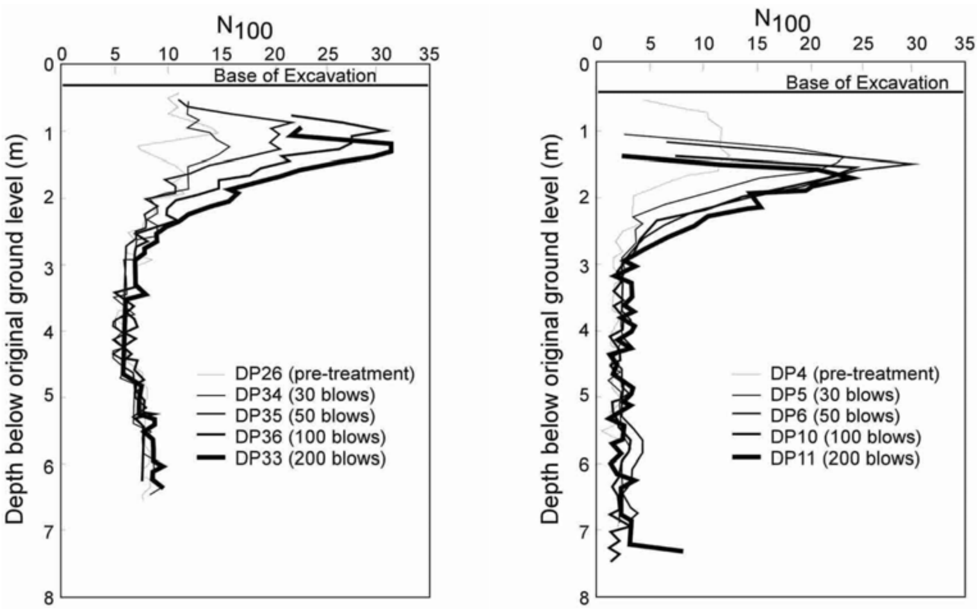
Figure 8. Details of layout of trials and testing undertaken in KPC and U2 areas at Karachaganak.

Although both trial areas showed no significant heave even for up to 100 blows, the trials revealed apparently different behaviour for the KPC and U2 areas. The improvement at the KPC area for up to 2.5 m below the base of the "crust" was significant and clearly visible from DPT results (Figure 10a). Furthermore, comparison of pre-treatment and post-treatment plate bearing tests (PBT's) for the KPC area showed an increase of the Young Modulus from 4 MN/m^2 to 18 MN/m^2 at 500 mm below finished treatment level. Some PBT's on top of completed pass 2 treatment compaction points recorded negligible settlement even for applied pressure of up to 900 kPa.

The U2 area did not show any immediate improvement and the soil exhibited a weaker plastic type of behaviour associated with excessive pore pressure elevation (and possibly temporary liquefaction). The DPT results (Figure 10b) were ambiguous and with PBT's indicating highly plastic soil behaviour with reduced Young's modulus values compared to the natural undisturbed state. Unfortunately, due to time and programme constraints on the project, it was not possible to investigate any improvement attributed to any potential time/ageing effects following pore pressure dissipation, a process which has been observed in the Emirate of Dubai (UAE), in response to conventional drop weight dynamic compaction (DC) within coastal sabkha deposits, where locally higher plasticity values have been present (Serridge 2002). The mechanism has been tentatively described as "thixotropic" recovery. The lower clay content (and marginally lower silt content), together with the lesser degree of saturation appears to have resulted in this effect having not been observed in the KPC area, (i.e. the ground response was more favourable). It clearly indicates how sensitive the ground response to dynamic loads is, depending upon clay/silt fraction and degree of saturation.

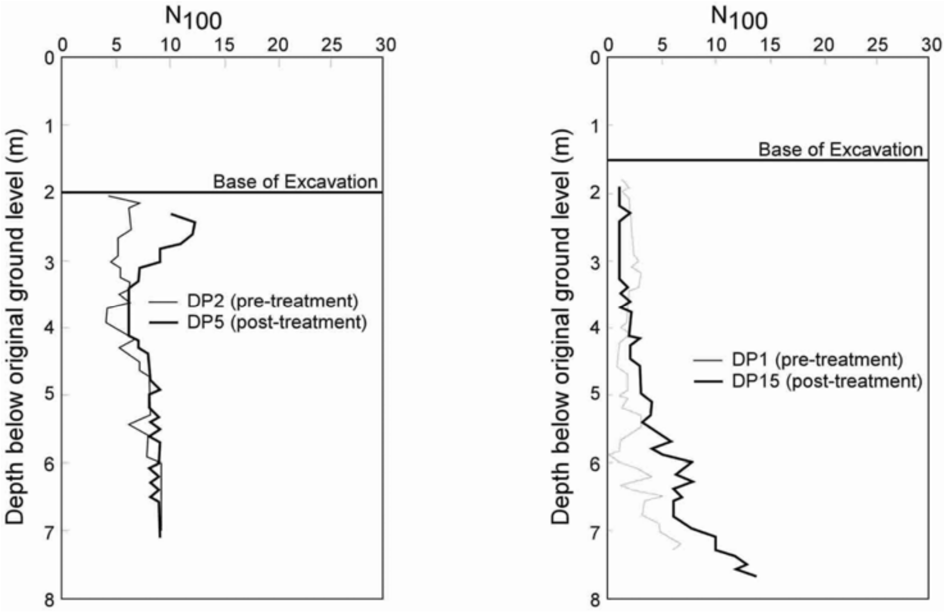
It is also clear that compaction trials were most favourable in the KPC area, (Figure 10 a), demonstrating that the technique was successful in achieving improvement to depths of around 3.0 m below the "crust" and therefore successful in reducing collapse potential in the loess soil. The depth of improvement for up to 3 m is a function of number of blows applied per treatment location, with improvement diminishing with depth. The soil saturation and the moisture content relative to its plastic limit/ plasticity are governing criteria for suitability of the RIC technique.

Due to the proximity of existing gas production wells it was necessary to investigate and limit vibration levels caused by the RIC. Vibration monitoring trials demonstrated that in order to restrict vibration levels to less than the maximum permitted value of 30 mm/sec peak particle velocity at wellhead locations, the RIC treatment would not be able to encroach closer than around10-15m.



a. b.

Figure 9. RIC treatment trials undertaken from original ground level (i.e. within the desiccated crust) in **a)** the KPC area and **b)** the Unit 2 (U2) area.



a. b.

Figure 10. RIC treatment trials undertaken below the desiccated crust at a) KPC area and b) Unit 2 (U2) area.

Main RIC works

Based upon the results of the trials and time constraints on programme, full RIC ground improvement was conducted at the KPC site only (Figure 11a &11b). The U2 area was improved by excavation of up to 2m below anticipated founding levels and controlled placement and re-compaction of soil in layers. Traditional piling was used to support the more heavily loaded structures at the U2 site. Some six RIC rigs (Figure 11a) were employed in the KPC area carrying out treatment over a total area of 60,000 m^2. The RIC improvement regime and testing for the KPC area is summarised in Table 4, based upon optimum production performance for maximum improvement depth.

a) b)

Figure 11. RIC treatment within KPC area at Karachaganak showing **a)** First treatment pass showing use of six RIC units and **b)** close up of second treatment pass.

Table 4. Main works treatment & testing regime (KPC area)

RIC TREATMENT REGIME (7t hammer; 1.2 m drop)		**THE RIC TESTING REGIME**			
1st Pass (70 blows)	**2nd Pass (50 blows)**	**DPT (DPH* 50 Kg)**		**PBT (600 mm Ø)**	
1.7 m grid	1.7 m grid (offset)	Pre-treatment	Post -treatment	at 0.5 m bGL	at 1.0 m bGL
203 t.m/m^2	145 t.m/m^2	1/200 m^2	1/100 m^2	1/2000m^2	1/2000m^2

* Dynamic probe (heavy)

Compared with UK applications and practice, the number of blows per pass and therefore total energy input was significantly larger. This was attributed to the fact that the trials did not exhibit a limiting energy for which a significant heave takes place and beyond which soil is displaced rather than compacted. The sequence of works involved the following:

- *Stage 1* - Excavation to foundation level, levelling and rolling.
- *Stage 2* - Pre-treatment DPT testing.
- *Stage 3* - First pass by RIC rig (70 blows), levelling and rolling.
- *Stage 4* - Level survey and DPT testing.
- *Stage 5* - Second pass by RIC rig (50 blows), levelling and rolling.
- *Stage 6* - Level survey, post treatment DPT testing and PBT at 0.5 m and 1.0 m below final treatment level.
- *Stage 7*- Restoration of levels to underside of foundation level using selected granular material placed and compacted in layers.

Whilst ground improvement works were suspended during the harsh winter when heavy snowfall and subzero temperatures (-15 ^{o}C) hampered the construction process, outwith this period, (with the exception of the periods after the heavy rains when it was necessary to wait for the uppermost soil layers to dry out), the RIC equipment and method proved very reliable (with temperatures approaching + 40 ^{o}C in the summer months). As part of the quality control and on-going monitoring of the effectiveness of the treatment, dynamic probe testing (DPT) and plate bearing tests (PBT) were undertaken. This included execution of some 3,600 linear metres of pre and post treatment dynamic probe testing and some 60 No. plate load tests.

Discussion

Both the compaction trials and the main works verification testing showed that the RIC technique was successful in reducing collapse potential in loess soil in the KPC area. The recorded / observed depth of improvement was typically of the order of 3 m from the treatment commencement level, (i.e. from the base of the "crust", with level of improvement diminishing with depth). The degree of saturation and moisture content relative to its plastic limit are governing/limiting criteria for the suitability and effectiveness of RIC in these loess soils. This was demonstrated during compaction trials at the U2 area, where it was possible to improve the desiccated crust but not possible to achieve any apparent/significant immediate improvement within the loess soil below this level. The soil below the desiccated zone in the U2 area possessed a higher degree of saturation (and associated higher moisture content above its plastic limit, Table 3), which did not facilitate any improvement by the RIC technique and gave rise to a weaker plastic type of soil behaviour under elevated pore pressures, with no apparent decrease in void ratio or increase in density. The possibility of improvement with time following the pore pressure dissipation requires further investigation and research. The results also revealed a 1-1.5 m thick layer below the surface of the improvement zone where DPT values were lower than pre-treatment values. This is consistent with the findings of others (e.g. Zakharenkov & Marchuk, 1967) and it is considered that these lower values are attributed to poor ground response to the RIC process, with the dynamic probe testing results showing a decrease of blows due to a disturbed soil fabric. However it was evident, based upon DPT results, that some improvement in soil properties occurred below the disturbed zone (below the zone of laboratory assessed metastable soil). The mechanisms associated with this also warrant further research.

CONCLUSIONS

- The RIC technique is finding increasing application within the UK urban environment and has demonstrated its ability to improve the engineering properties of a range of essentially granular heterogeneous made ground deposits to depths of up to between 3 and 4 metres. The technique is generally not effective in low permeability saturated soils. A significant proportion of small sites which are being re-developed for low rise construction, comprise shallow essentially granular fills which are often treated with vibro stone columns. It is likely, dependent upon site specific circumstances, that many of these sites could also be given consideration for RIC treatment, in particular where there might be issues with spontaneous combustion in certain colliery type spoils or risk of exposure of contaminants such as asbestos to the atmosphere, as might be the case with use of penetrative ground improvement techniques such as vibro stone columns.
- Depth of influence of RIC treatment is a function of soil grading characteristics and groundwater regime, and also significantly, applied energy. There is some evidence to suggest that the higher the energy input in particular soil gradings, the greater the depth of influence. However, this warrants further research.
- Within the UK, and more significantly, internationally, the RIC technique has also demonstrated its effectiveness in natural sandy and gravely soils and also improvement to greater depths dependent upon specific site geotechnical characteristics (with some evidence emerging in Japan and Canada, for example, of the technique being used for mitigation of liquefaction potential for low-rise structures). A desirable objective would be to establish a centralised data base for gathering of experience and case histories on RIC experiences both in the UK and internationally, to increase understanding of the range of soil types and profiles which the technique can be applied to and assist in further development of the RIC system as a whole, including the use of GPS in "mapping" of the RIC technique.
- Apart from monitoring of enforced settlements as the treatment progresses and ground response tests (compaction trials), to ascertain the optimum amount of energy which can be applied in a particular treatment

pass, site control measures to assess the effectiveness of the treatment should be selected to suit the particular ground conditions. This might include load tests, dynamic probing; CPT or SPT profiling carried out at discrete locations or some form of geophysical testing, the latter of which can potentially overcome some of the limitations of in-situ tests in heterogeneous made ground, for example. As has been highlighted in this paper for a site in Sheffield, UK, data recorded during the execution of RIC as regards to ground response, can highlight anomalous or unexpected ground conditions which may not have been identified in the original site investigation and allowing appropriate actions to be taken.
- Loess is a worldwide problematic soil and gives rise to a geohazard in the context of the built environment. This provides the engineering geologist with the challenge of achieving satisfactory site characterisation and prediction of engineering behaviour, and the geotechnical engineer with the challenge of providing practical and satisfactory ground improvement solutions and therefore foundation behaviour. The RIC technique has been utilised successfully for reduction of collapse potential in loess soils in the KPC site at Karachaganak in western Kazakhstan to a depth of up to around 2.5-3.0 m (from the commencement level of 2.0 m below general existing ground levels). The soil response to RIC is dependent on soil properties, principally degree of saturation; moisture content and plasticity. These aspects warrant further investigation and research in respect of any time dependent improvements in higher plasticity, more saturated loess soils. The particular advantages of the RIC technique compared to conventional "drop weight" dynamic compaction (DC) have been highlighted. The RIC technique therefore potentially provides a ground improvement option, which dependent upon site specific circumstances (particularly geotechnical properties and site characterisation), could potentially be given consideration for reducing risk in these problematic soils in loess regions in the context of low-rise structures (concurrent with further investigation and field trials to facilitate improved understanding of the mechanisms of loess metastability and subsequent collapse through appropriately defined and specified research).

Acknowledgements: The authors acknowledge the assistance and encouragement of colleagues in Pennine Vibropiling (UK) in the preparation of this paper.

Corresponding author: Mr Colin J. Serridge, Pennine Vibropiling (UK) Limited, New Line, Bacup, Lancashire, OL13 9RW, United Kingdom. Tel: +44 1706 877555. Email: colin.serridge@pennine-group.co.uk.

REFERENCES

ANON.1996. BSP International RIC Project Report sheet – Hokkaido Oil Tank Foundation, Japan.

ANON.2004. Ground Consolidation – BSP in ground consolidation work in Iran, *Geo Drilling International,* 20, December, 2004.

BRAITHWAITE, E.J. & DU PREEZ, R.W. 1997. Rapid impact compaction in southern Africa. *Proceedings of the Conference on Geology for Engineering, Urban Planning and the Environment.* South African Institute of Engineering Geologists, 13-14 November 1997.

BUILDING RESEARCH ESTABLISHMENT. 2000. Specifying vibro stone columns. *BRE Report BR391, Garston, BRE Bookshop, UK.*

BUILDING RESEARCH ESTABLISHMENT. 2003. Specifying dynamic compaction. *BRE Report BR458, Garston, BRE Bookshop, UK.*

COOPER, A. 2005. BSP International. *Pers. Comm..*

DERBYSHIRE, E., DIJKSTRA, T.A. & SMALLEY, I.J. (eds) 1995. Genesis and Properties of Collapsible Soils.
Series C: Mathematical and Physical Sciences – Vol. 468. Kluwer Academic Publishers, Dordrecht.

FOUNDATION BEDS. 1997. SNIP 2.02.01-87, *Building Codes of Russia,* SNIP Register Ltd, 1997, Chicago.

JEFFERSON, I., TYE, C. & NORTHMORE, K.J. 2001. Behaviour of silt: the engineering characteristics of loess in the UK. In Problematic Soils (Jefferson. I., Murray. E.J., Faragher. E. & Fleming, P.R. eds) pp 37-52 Thomas Telford Publishing, London.

ROGERS, C.D.F., DIJKSTRA, T.A. & SMALLEY, I.J. 1994. Hydroconsolidation and subsidence of loess: studies from China, Russia, North America and Europe, *Engineering Geology,* **37**, pp 83-113.

SERRIDGE, C.J. 2002. Dynamic compaction of loose Sabkha deposits for airport runway and taxiways. *Proceedings of the 4th International Conference on Ground Improvement Techniques,* March 2002, Kuala Lumpur, pp 649-656.

WATTS, K.S. & CHARLES, J.A. 1993. Initial assessment of a new rapid impact ground compactor. *Proceedings of the Conference on Engineered Fills,* pp 399-412. London, Thomas Telford.

ZAKHARENKOV, M.M. & MARCHUK, A.I. 1967. Experimental radiometric investigation of compaction of settled ground by means of heavy-duty tamping equipment, *Osnovaniya, Fundamenty i Mekhanika gruntov,* No.4, pp 21-23, July/August, Kiev.