Centrifuge modelling of ground improvement for double porosity clay

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Veröffentlichungen des Instituts für Geotechnik (IGT) der ETH Zürich
Band 246, November 2015
Foreword

Waste materials of heterogeneous, overconsolidated clay lumps, which exhibit double porosity through inter-granular voids between the lumps and intra-granular voids within them, are produced by excavation for large scale opencast mining. These are deposited in deep open pits, and left to settle and consolidate with time. Subsequent use of the scarred landscape for construction of infrastructure leads to major challenges in terms of being able to characterise these 'lumpy clays' and to limit excessive settlements. Ground improvement is required to ensure serviceability. Various techniques have been used in the past to reduce the porosity, by means of embankment preloading, columnar insertions of sand or gravel, or dynamic compaction.

Previous investigations have confirmed that the height of the groundwater table has played a major part in how the double porosity clay deposits have responded to treatment. Various processes such as abrasion, fragmentation, saturation and loading change both the structure and the behaviour of these fills. The rate of settlement has been found to be affected by the degree of saturation of the lumps, which has strongly influenced their individual and collective stiffness and strength. The double porosity structure has usually been maintained at shallow depths above the water table, whereas ductile yielding has been known to occur at higher effective stresses, and below the water table. However, the boundaries to these two extremes of behaviour and the transition between them have not been quantified in detail through parametric studies, either due to self-weight loading or when undergoing ground improvement.

Dr Emma Pooley has investigated and quantified the response of representative, scaled deposits of double porosity clay, borrowed from a site in the Czech Republic, through an EU FP7 project funded under the Marie Curie programme. She conducted an extensive range of small-scale centrifuge model tests under enhanced gravity to investigate various modes of ground improvement and to confirm performance of the improved ground through vertically loaded footing tests.

The general characteristics and behaviour of double porosity soil were introduced in the context of one-dimensional compression of the structured soil. These reduced to the intrinsic state with increasing compression, accompanied by breakdown of the macro grains (lumps). The transitions between both states were quantified using Burland’s void index, combined with the critical effective stress required to initiate destruction of the fabric and bonding of the lumpy soil.

Scoping tests were carried out in a mini centrifuge on scaled lumps to develop model-making techniques to represent the prototype landfills, by varying sizes, grading, modes of saturation and consolidation in-flight. Subsequently, large-scale oedometer tests were carried out on scaled lump distributions for the subsequent centrifuge model tests. This gave an early hint about the importance of the effect of groundwater and saturation on the compressibility of the structured deposit. Consistent one-dimensional loading curves of the void index against log
effective vertical stress emerged, from which the breakdown critical vertical effective stress could be plotted as a function of the initial saturation ratio. A unique power curve describes this relationship.

Three different types of ground improvement were investigated subsequently in the drum centrifuge at 50g: embankment construction (preloading: 3 tests), sand compaction piles (SCPs; 10 tests) and dynamic compaction (6 tests). The first approach was found to be unsatisfactory, since the double porosity structure below the embankment was destroyed, accompanied by a significant reduction in macro permeability, which also decelerated the rate of consolidation.

Various arrangements of SCPs, in terms of installation mode, number and spacing as well as water table height were tested, and new experimental methods were developed for the tests using dynamic impact compaction. In the latter case, fracture, crushing and movement of the lumps contributed to loss of the double porosity structure and a reduction in the inter-granular porosity. Dynamic loading was transmitted onto the water phase and excess pore pressures were generated, measured by pore pressure transducers installed in the clay. Subsequent pore pressure dissipation was hampered by the reduced permeability. However, substantial volume loss under the compactor over the top 2 to 3 m of the deposit was very effective in reducing the voids in the surface layer and offers promise for practical application.

The effect of ground improvement methods on stiffness and strength was investigated by carrying out vertically loaded foundation tests on an axisymmetric footing fitted with a tactile pressure sensor. Whereas dynamic compaction was found to be highly effective at limiting settlements for vertical effective stresses of less than 25 kPa, the array of SCPs also reduced settlements, largely due to the displacements caused by the vertical and radial compaction during installation. Interestingly, the impact of installing SCPs in the passive zone outside the footing enhanced the stiffness and strength further, although this was not as efficient as placing the SCPs directly under the footing.

Three zones identified as fragmentary (F), transition (T), and continuous (C) describe the structured sedimentary deposit as it transitions to the intrinsic state and are delineated in sketches of the three different ground improvement methods. The processes exhibited by each phase / zone during loading, and the resulting stiffness, strength and permeability have been characterised for behaviour under self-weight consolidation.

Dr Emma Pooley has successfully combined a mechanistic appreciation of the processes that contribute to breaking down the structured soil, with evidence from a range of laboratory tests and physical models, to ensure that settlements can be induced to occur in a controlled fashion during the process of ground improvement, rather than during subsequent performance service in practice.

Prof. Sarah Springman CBE FREng
Acknowledgments

Foremost, I would like to thank Professor Dr. Sarah Springman for her supervision of this research and for originally accepting me as a PhD student. Her contribution to this thesis was invaluable in many aspects: the execution of centrifuge tests, scientific discussion, and her exacting standards for the written work. In addition, I am immensely grateful to her for allowing me the flexibility to pursue a profession in cycling alongside my doctoral studies. Without her support and encouragement in that other side of my life, I would never have had the opportunity to take part in an Olympic Games. I owe Professor Springman a huge debt of gratitude for her enthusiasm and understanding, without which I could not have completed the work documented here. She is an inspiring role model for me, an example that I aspire to emulate, and I am proud to have been associated with her.

My sincere thanks also to Dr. Jan Laue for his supervision and encouragement, especially during the long (and sometimes difficult) periods of centrifuge testing, and the writing of this thesis. His support has been very valuable and I am grateful for the time he has invested. I am also grateful to the independent examiners Dr. Jan Boháč and Professor Dr. Ivo Herle, for their interesting feedback and valuable corrections.

The work presented was carried out as part of a Marie Curie Research Training Network “Advanced Modelling of Ground Improvement on Soft Soils (AMGISS)” (Contract No. MRTN-CT-2004-512120) supported by the European Community through the programme “Human Resources and Mobility”. I am particularly grateful to the AMGISS network director, Professor Dr. Minna Karstunen, for her support and for helping me to negotiate a flexible contract with Dr. Patricia Arsene of the European Commission.

I wish to thank Ernst Bleiker, Heinz Buschor, Rouvan Mühlethaler, and Dr. Thomas Weber for their generous assistance during centrifuge testing. I am most especially grateful to Markus Iten for his mastery of the centrifuge and also his superhuman patience. Some of the experimental work documented here was carried out in collaboration with Nitin Aggarwal and Dr. Jan Najser; my thanks to them for their help and interest. The assistance of many other staff at IGT has been invaluable for this research, among them: Mengia Amberg, Ralf Herzog, Gabriela Laios, Michael Plötze, Marco Sperl, Felix Wietlisbach, Sonja Zwahlen, and Adrian Zweidler.

My thanks to the other doctoral students at IGT, for their good company over the years. I am lucky to have had truly delightful office colleagues, and I am grateful to them for their advice, for helping me to learn German, and for their tolerance of my cycling shoes and incessant tea-drinking: Dr. Bernd Imre, Dr. Andrea Thielen, Dr. Yuko Yamamoto, and Thomas Buchli, thank you!

Without the camaraderie and encouragement of many dear friends, I would never have finished this thesis. I cannot name them all but I’d especially like to thank Abi, Benjamin, Chauncey, Dani, Dave, Esther, Forrest, Georgette, Jenny, Mona, Tim, and particularly Nick, for their friendship and tolerance. I am also grateful to Dr. Steve Peters for his timely chats,
Acknowledgments

and for reminding me that most things can be helped by a sense of humour (Munroe, 2006). I’m thankful for the opportunity I’ve had to get to know some truly extraordinary people through cycling, running, and triathlon, and the sense of perspective their friendship has given me.

My heartfelt thanks to my family for their tolerance and support over the many years I have tested their patience. I’m grateful for the encouragement, gentle rivalry, and humour of my brother and sister – I did not expect to be overtaken in the doctoral race, but it has only increased my (already great) admiration for my siblings. I would like to thank Veronica and Jan, for their understanding and help in different ways. My thanks to my father for not minding whether I ever finished this thesis or not, but helping me to be the kind of person who wanted to. I am deeply grateful to my mother, who set the best example of dedication, hard work, and determination that a daughter could hope for – as well as always being there for me with a hug when things were difficult.

Looking back, it is clear how much this work relied on the assistance of others and I am very thankful for their help. Even though my name may stand as the author of this thesis, it was necessarily the result of collaboration and teamwork. I would like to thank all those who have helped me over the past years and whose names I could not list here.
Kurzfassung


Kurzfassung

wurde eine Technik entwickelt, welche Tonklumpen aus typischen tschechischen Bergbau-
Deponien im Ofen trocknet und danach durch mechanisches Brechen zerkleinert.

Die Auswertung der Zentrifugemodellierung und Ödometerversuche ermöglichte die
Einstufung des Verhaltens eines Tons mit Doppelporosität unter eindimensionaler Belastung
in drei Stress-Phasen, entsprechend des Umfangs der Zerstörung der Bodenstruktur:
grobstückig, übergängig und kontinuierlich. Die Übergangsphase beginnt bei einer totalen
Spannung, $\sigma_{\text{crit}}$, welche als „Breakdown Stress“ (sprich Zerstörungsspannung) bezeichnet
wird, bei welcher die Zerstörung der klumpigen Struktur weit verbreitet beginnt und sich die
intergranularen Porenräume schnell reduzieren. Es wurde beobachtet, dass eine höhere
Sättigung einer tieferen Zerstörungsspannung entspricht. Die kontinuierliche Phase wird
erreicht, wenn die intergranulare Porenräume verschwunden sind und die Gesamtporosität
die intragranulare Porosität erreicht.

Die Zentrifugemodellierung bestätigte, dass der Grossteil der Setzung eines Bodens mit
Doppelporosität während des Aufbaus der Deponien entsteht. Kleine Abweichungen in der
Höhe des Grundwasserspiegels, möglicherweise aufgrund der Inhomogenität des Bodens,
erursachten grosse Unterschiede in der ersten Kompressibilität. In den Bereichen, wo ein
optimiertes Bodenverhalten erforderlich ist, sollten Bodenverbesserungsmethoden die
Doppelporosität gezielt zerstören und die Bodeneigenschaften damit verbessern. Der
Übergang von der grobstückigen zur kontinuierlichen Phase wird durch die vollständige
Sättigung der Tonklumpen erleichtert.

Die Evaluierung der Bodenverbesserungsmethoden zeigte, dass die dynamische
Intensivverdichtung sehr effektiv zur Begrenzung der Setzung im Bereich der Schlagstelle ist
und deswegen wertvoll für die Anforderungen des Zustands der Gebrauchstauglichkeit. Die
Reaktion des Porenwasserdrucks wies darauf hin, dass dynamische Verdichtung mittels
Wellen von erhöhtem Porenwasserdruck auch einen Effekt weit entfernt von der Schlagstelle
haben. Eine grosse Gruppe von Schottersäulen ist zwar zur Begrenzung der Setzung
effektiv, jedoch ist die Wirkung eher lokal. Im Fall einer grossflächigen Belastung muss die
Entwässerung der Bodenschicht ebenfalls betrachtet werden, weil der Verlust intergranulärer
Porenräume zu einer deutlichen Verringerung der Durchlässigkeit führt. Die Anforderungen
des beabsichtigten Gebrauchs müssen in jedem Fall für die Entwicklung einer
Bodenverbesserungsstrategie betrachtet werden.
Abstract

Double porosity soil is characterised by a soil continuum containing two distinct porosities. Typically, this consists of macro-grains (lumps) of soil that have an internal porosity defined as the intragranular porosity. The spaces between lumps are identified as intergranular voids that give rise to the intergranular porosity. Human activities such as land reclamation or mining can give rise to large areas of land with subsoil that exhibits double porosity. The need to build in, or on, these areas is increasing, due to demand for land for industrial usage, infrastructure, and residence. However, the engineering properties of such soils are challenging, and often difficult to predict due to their inhomogeneity and a lack of information about the initial or current parameters.

Double porosity mining waste landfills in Northern Bohemia in the Czech Republic were studied in this project. There, decades of open-cast mining of brown coal have left vast areas of land affected by the waste overburden that has been removed and dumped in old mining pits. Redevelopment of areas affected by mining sometimes requires construction on old overburden waste spoil heaps, which consist primarily of lumps of overconsolidated clay and are therefore characterised by a double porosity soil structure. The loading response on these clayfills entails large absolute and relative deformations, which means that ground improvement is normally needed before construction begins, to ensure that both stability and service limit state requirements are met.

The primary aim of this research was a comparison, through physical modelling, of ground improvement techniques on double porosity clay landfills. A secondary objective was to contribute to the understanding of the material behaviour governing response to loading and other processes on double porosity soil. Preliminary oedometer and mini-centrifuge tests informed the design of centrifuge models. Modelling was carried out in a geotechnical drum centrifuge at g-levels of 20-200 times earth’s gravity, with the majority at 50 times earth’s gravity. Several series of centrifuge tests were carried out to model the field situation and self-weight consolidation of the landfills, behaviour under embankment loading, and to compare the effects of sand compaction piles (SCPs) and dynamic impact compaction. Processes were carried out in-flight and the soil settlement and pore water pressure changes were measured to monitor the model behaviour. Soil response to cone penetrometer testing and vertically loaded footing tests was compared.

A new classification of “lump size distribution” (LSD) was defined, analogous to particle size distribution on the intragranular scale, and used to compare the field scale soil structure with that of laboratory specimens and centrifuge models. A repeatable method was developed to produce a large quantity of scaled-down clay lumps from material excavated from typical landfills, by oven drying and mechanical crushing, allowing the stress history of the soil and some angularity of the lumps to be retained.

Evaluation of centrifuge modelling and oedometer tests led to the classification of the response of double porosity clay to one-dimensional loading into three stress-dependent
phases. These correspond to the degree of destructuration of the lumps: fragmentary, transitional, and continuous. The transitional phase was defined as starting at a total stress designated as the breakdown stress, $\sigma_{\text{crit}}$, when destructuration of the clay lumps starts to become widespread and intergranular voids are reduced rapidly throughout the soil stratum. It was observed that a higher saturation degree correlates with lower breakdown stress. The continuous phase is reached when the double porosity is destructured and intergranular voids have closed up, so that total porosity is equal to the intragranular porosity.

Centrifuge model tests confirmed that the largest settlement of double porosity clayfills occurs during landfill construction. Small variations in phreatic surface height, due in some cases to the soil's inhomogeneity, caused large differences in initial compressibility. The destructuration of double porosity in the subsoil is desirable for improved soil characteristics. Ground improvement should aim for destructuration of the double porosity structure in those areas where an optimised soil response is required. The lumps should be fully saturated for the most rapid transition of double porosity clay from the fragmentary to the continuous phase.

An evaluation of ground improvement techniques indicated that dynamic impact compaction is highly effective at limiting deformation for service limit state (SLS) requirements under loading at the impact site. Pore water pressure response indicated that dynamic impacting caused compaction far from the impact site, due to transmission of waves of high pore pressure. A large array of SCPs is also effective for reduction of SLS deformations, but the benefits are more localised. Drainage of the double porosity clay stratum should be considered for loading distributed over a large area, since loss of intergranular voids also causes a major reduction in permeability of the clay waste. The ground improvement strategy for double porosity soil must be designed taking into account the usage requirements in each case.
1 Introduction

1.0 Motivation

In the North-West Bohemia region of the Czech Republic, the Most Basin contains a vast brown coal seam. This natural resource has been essential in modern history to meet energy requirements of the people and industry of the Czech Republic. Sadly, decades of exploitation through open-cast mining left behind a landscape scarred beyond recognition. The coal is excavated from enormous pits and the overburden waste dumped in old mines, which resulted in a moonscape of barren craters and spoil heaps (Figure 1.1). Concerted attempts to reclaim the wasteland left by old mines and restore it both environmentally and aesthetically have resulted in impressive amelioration, with large areas transformed into forests, lakes, parks, orchards and vineyards (Štýs, 1995). The achievement, in this regard, can be regarded as a definite contribution of the Czech Republic to environmental improvement in Europe.

Figure 1.1: Large-scale mining waste areas in North-West Bohemia (photo S. Štýs, 1995).
1.1 Context of research

The redevelopment of areas affected by mining in this region also entails construction on old mining pits and waste dumps. For example, a car race track at the former Vrbenský mine, an airport near Strimice, a horse-racing stadium at Velebudice, and the D8 motorway connecting Prague and Dresden. This is associated with particular geotechnical problems due to the way in which waste material is dealt with during mining operations. The overburden soil, consisting of claystones and lumps of clay gouged out with excavators, is dumped in spoil heaps in old exploited mine pits, in depths up to 100 m (Figure 1.2). The landfills thus created have high total porosity and a “lumpy” structure, which is characterised by double porosity: the porosity within clay lumps, and the porosity of the macro-structure. These landfills experience large settlements under self-weight loading. Even after 20-30 years’ self-weight consolidation, large differential and absolute deformations are caused by surcharge loading. Ground improvement has to be carried out before construction, to ensure the future stability of the structures to be built, and to ensure that deformations do not exceed serviceability limit state (SLS) requirements.

Figure 1.2: Filling of old mines with overburden clay waste (photo S. Štýs, 1995).

1.1 Context of research

Geotechnical techniques used to improve the compression characteristics of mining waste landfills in North-West Bohemia comprise embankment preloading, installation of sand or gravel columns, and dynamic surface compaction. The design of these ground improvement regimes is largely empirical. However, the soil behaviour is complicated by the lumpy structure remaining within landfills, and the inhomogeneity of lumps makes the stiffness of the fill highly variable. This makes a prediction of soil response highly challenging, while
simultaneously requiring an approach to ground improvement that is suited to the specific soil conditions.

Mayne et al. (2009) describe the difficulty of comprehensively characterising the intricate and complex response of geomaterials. The challenge requires careful in-situ sampling, laboratory testing, and in-situ tests that are all directed at defining soil parameters within the framework of critical state soil mechanics. Non-textbook geomaterials, such as the double porosity soil described above, require an even higher level of testing and investigative effort in order to understand their anomalous behaviour. Physical modelling in the geotechnical centrifuge is a useful tool to contribute to the characterisation of complex soil conditions, and to understand the boundary value problems and mechanisms of soil response to applications such as ground improvement.

1.2 Aims, methodology, and structure of the study

The primary aim of this research was an examination of ground improvement techniques on the double porosity landfills left by deposition of mining waste in the manner described. This was necessarily combined with the objective of contributing to the understanding of the material behaviour and mechanisms governing response to loading and other processes on double porosity soil.

The IGT geotechnical drum centrifuge at ETH Zürich was employed as a tool to model double porosity landfills and examine their overall and macro-structural response to ground improvement. This entails the construction of small-scale, structured centrifuge models, which is itself an innovation in terms of developing inhomogeneous small-scale physical models. Ground improvement techniques modelled in the centrifuge comprised embankment preloading, compacted sand columns, and dynamic compaction.

In Chapter 2, a review of the previous literature relevant to ground improvement on landfills, double porosity soil, and the specific case in North-West Bohemia provides the background to the study. Preliminary laboratory testing in Chapter 3 describes oedometer tests, material preparation methods, and mini-centrifuge modelling. This informs the design of a comprehensive centrifuge modelling programme to compare ground improvement methods, the results of which are presented in Chapter 4. Innovations in material preparation and centrifuge modelling techniques are necessary in order to model the double porosity structure and the case of dynamic compaction. In Chapter 5, centrifuge modelling findings and oedometer test results are discussed in the light of the available literature, to assess the behaviour of double porosity soil, and make recommendations for practice accordingly.
2 Literature review

In this chapter, the existing research relevant to this study is reviewed in order to set out the starting point for investigation, and to provide the background knowledge necessary for understanding the results.

The geotechnical challenges posed by landfills and reclaimed land are first introduced, and the ground improvement techniques used to deal with them in current practice. Within this context, the focus is then turned to double porosity soil. The current state of research in terms of characterisation, behaviour, and physical and numerical modelling of double porosity soil is described, along with the relevant soft soil behaviour.

The specific case of mining waste landfills in the Czech Republic is described in detail, including the state of the art research in terms of laboratory testing, soil structure considerations, site investigation, and field tests. Finally, the background knowledge needed to understand and plan centrifuge modelling for this soil type is discussed.

2.0 The challenge: landfills and ground improvement

There is an increasing demand for land for urban and industrial development in many countries around the world, due to increasing population and pressure on land use. This leads to the need to use marginal land, “brown field” areas such as old municipal landfills, quarries, and mining sites (Narendranathan & Sukumar, 2012). In other cases, where the available land area is severely limited and already fully exploited, such as for example Singapore, land reclamation from the sea is now an established practice (Leung, 2012). Landfill sites and dredged reclaimed land often provide difficult conditions for construction, exhibiting high total and differential settlements, and potential risk of collapse or liquefaction. This can be due to weakness of the fill used, or loose packing during filling, which leads to high total porosity of the fill. In the case of landfills and mining waste, inhomogeneity of the fill and lack of information about the parameters of the subsoil (composition and construction) contribute to the difficulties in planning construction on such sites, as described by Charles & Watts (2001).

The problems of settlement specifically in brown coal mining waste piles, and some field observations of long-term in-situ measurements, are described by Dorschner (1965). Walde & Förster (1992) divide the settlement into distinct components: self-weight compression and settlement due to a rise in ground water (primary settlements) and compression due to static or dynamic loading (secondary settlement). Diener (1999) reports on the existence of a critical water content for the occurrence of settlements, and the influence of the rate of rise in height of the water table on the magnitude of settlements.

Sondermann & Kirsch (2009) give a general description of ground improvement to meet bearing capacity and serviceability limit state requirements. They describe the desired outcomes of successful ground improvement as some, or all, of the following:
2.0 The challenge: landfills and ground improvement

- Increase in density and shear strength, to improve stability.
- Decrease in compressibility, to reduce settlements.
- Change in the permeability, in order either to reduce water flow or to increase the strain rate.
- Increase in homogeneity.

There are three general possibilities to try to achieve an improved soil layer: replacement, densification, or reinforcement. Replacement of the soil is not considered for this case of landfills, since it would be counterproductive to the aim of improving an area of land for construction purposes and would simply transfer the problem elsewhere (as well as being impractical for such huge volumes of soil). Ground improvement methods by means of densification and reinforcement are summarised in Table 2.1.

The details of design parameters and specific application techniques for the ground improvement methods shown in Table 2.1 are described in Sondermann & Kirsch (2009). Previous to this, Greenwood & Kirsch (1983) had correlated field experience and approaches to design for vibratory and dynamic ground treatment methods, concentrating on the appropriate field of application for the various processes. Furthermore, Girsch & Chropen (2006) describe the commonly exploited methods of ground improvement for landfills, as follows:

a) Dynamic impact compaction: controlled fall of a heavy weight, or explosions.
b) Sand or gravel columns, sometimes pre-bored, compacted by ramming or vibrating.
c) Vibratory compaction: application of a vibration to cause densification or temporary liquefaction, addition of more soil to replace lost volume. Used on loose sand and gravel.
d) Concrete piles: designed to reach down to underlying bedrock or stable soil, and carry the entire load of construction. The strength of the surrounding soft soil layer is irrelevant.

Vibratory compaction is effective on loose granular soils, but is unsuited to ductile soils such as those addressed here; Bergado (1996) describes vibration methods as being effective in soils consisting of < 15-20% clay-silt sized fines. Similarly, concrete piles are not suitable when the depth to the underlying stable layer is unknown since they do not actually improve the soil stiffness, instead bearing the load themselves, and they must therefore be based in an underlying stable soil layer. Current practice for industrial improvement of double porosity clay landfills is therefore to apply either dynamic impact compaction, compacted columns, pre-loading, or a combination of these methods.
Table 2.1: Methods of ground improvement (after Sondermann & Kirsch, 2009).

<table>
<thead>
<tr>
<th>Static methods</th>
<th>Dynamic methods</th>
<th>Displacement methods (densification of surrounding soil)</th>
<th>Non-displacement methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-loading</td>
<td>Vibratory compaction: Depth shaker</td>
<td>Vibro-compacted columns</td>
<td>Mechanical insertion</td>
</tr>
<tr>
<td>Pre-loading + assisted consolidation</td>
<td>Vibratory compaction: Surface shaker</td>
<td>Vibro-compacted cementation</td>
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<td>Impact compaction: Falling weight</td>
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<tr>
<td>Groundwater manipulation</td>
<td>Impact compaction: Blasting, Air-pulse method</td>
<td>Lime/cement stabilising columns</td>
<td>Freezing</td>
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McIntosh & Barthelmess (2012) describe a case study of the ground improvement needed for construction on a 17-year old municipal waste landfill in New South Wales, Australia. The ground conditions for such a landfill differ somewhat from the double porosity soils described herein, and include the challenge of managing leachate and gas emissions. However, the high total porosity and expected settlements are similar to the behaviour of the Czech landfills. The successful use of dynamic compaction to compact the loose fill, and reduce construction settlement, is described. The specific compaction regime was of a 25 tonne weight, dropped 3-4 times on each point from a height of 20 m, on a 6x6 m grid pattern. This equated to impact energy of 4.9 MJ. The craters left by compaction were backfilled with gravel and the uneven surface created was ameliorated by use of a larger compacter in a later “firming” phase. Settlements of 0.5-1.5 m were observed during compaction on the 4-12 m high landfill.

2.0.0 Sand compaction piles

Sand or gravel compaction piles are used widely in practice to cause both densification and reinforcement of soft soil. Depending on how they are installed, they can be described as either a displacement or a replacement method. If inserted directly into the soil, this displacement and the ensuing compaction process cause densification of the surrounding fill. If pre-bored, the compaction process nonetheless causes column bulging and some densification of the surrounding fill. Compaction of the piles is achieved by incremental
withdrawal and re-insertion of the sand/gravel feeder. For vibro-compacted columns, the feeder is also vibrated to achieve a higher column density. As discussed by Herle et al. (2006 & 2008), the density of stone columns achieved during vibro-installation is a key factor for the load transfer and eventual bearing capacity of the columns, thus ultimately the level of reinforcement they provide to the soil. The density of compacted stone columns is difficult to determine in-situ and there is normally no routine direct control of this factor during installation. Herle et al. (2008) also point out the importance for mechanical behaviour of stone columns, of the non-uniformity, grain size, and grain shape of the sand or gravel used.

According to Priebe (1995), the degree of ground improvement due to compacted piles can be deduced from the existence of the sand or gravel columns alone, even discounting the densification of soil between them. The essential parameters for this ground improvement technique are the geometry of column layout, and the backfill material, which are easy to measure and are independent of more variable factors such as soil properties. The soil properties, equipment, and procedure play only an indirect role in design of a sand column system, and that is mainly to estimate column diameter. The determination of the improvement factor assumes that the columns are based on a rigid subsoil layer, that the column material is incompressible, and neglects the bulk density of both column and soil. Therefore the assumption is that there is no possibility of end bearing failure, so settlement only occurs through bulging of the columns, which is estimated to be constant over each column’s length. The improvement of a soft soil under such conditions by the existence of stone columns is evaluated on the assumption that the column material shears from the beginning, while the surrounding soil reacts elastically. It is also assumed that the coefficient of earth pressure for the surrounding soil $K = 1$. This gives improvement factor $n_0$ as follows:

$$n_0 = 1 + \frac{A_c}{A} \left( \frac{5 - \frac{A_c}{A}}{4 \cdot K_{sc} \cdot (1 - \frac{A_c}{A})} - 1 \right)$$

where:

$A_c$ = cross sectional area of columns, $A$ = unit area for evaluation.

$K_{sc} = \tan^2 \left( 45 - \frac{\phi_c}{2} \right)$

$\phi_c$ = internal friction angle of backfill material.

Therefore according to Equation (1), the improvement factor is determined by the area ratio $A_c/A$, and the friction angle of the backfill material. Since double porosity clay is highly compressible and inelastic (at least in the upper layers), a sand column is unlikely to bulge consistently over its length. If the surrounding soil is extremely soft and ductile, as may be the case near the surface of some double porosity landfills, radial expansion of the stone column during compaction may mean that a high density of the sand or gravel is not achieved, which can reduce the stiffness and strength of the column (Herle et al., 2006; Herle et al., 2008).

A detailed examination of design considerations for the use of stone columns as ground improvement in soft soils, taking into account both ULS and SLS, is described by Springman
et al. (2012). The expected settlements, and the interaction between stabilisation and accelerated consolidation, are considered with reference to design codes.

In the field, compacted sand and gravel columns are used successfully in practice on double porosity soils. Girsch & Chropen (2006) describe the details of ground improvement carried out for a section of motorway crossing the double porosity clay landfills studied in this thesis, near Usti nad Labem in the Czech Republic. They report the serviceability limit state requirements as being post-construction settlements of $\leq 150$ mm for embankments, and $\leq 50-100$ mm for bridge footings (depending on the particular case). In that study, compacted gravel piles were chosen as ground improvement and a length of 33,000 m in total were installed within two months. Specifications were for pile diameter $\geq 0.8$ m, and the piles were pre-bored to a diameter of 0.75 m in a triangular pattern at a spacing of 1.7 m, to a depth of 3-15 m, depending on the local landfill depth. The piles were filled with gravel in the particle size range 8-32 mm, in 30-60 cm steps, using hydraulic compactors exerting a force up to 200 kN. The settlements measured following construction after ground improvement were less than 50% of the defined limits.

### 2.0.1 Dynamic compaction

Dynamic impact compaction consists of dropping a heavy falling weight repeatedly on the soil. The impact object weighs 10-200 tonnes, the fall height can be 5-40 m, and the number of impacts on each point is 5-20 (Schmidt, 2005). Compaction points are typically spaced 5-15 m apart (Bergado, 1996). The resulting impact hole is backfilled with granular material such as sand and gravel. Sometimes impact compaction will be resumed after backfilling. According to Schmidt (2005), the soil surrounding the impact point is also compacted by this method, due to the impact energy being transmitted through the soil structure by seismic waves. As described by Woods (1968), there are three kinds of seismic wave: Rayleigh waves on the surface (R-waves), and compression and shear waves below the soil surface (P-waves and S-waves, respectively).

Impact compaction is suited to soils in the range from gravel to ductile clay-silt admixtures, and both partially and fully saturated soil, though the effectiveness diminishes with increasing permeability of clayey soils. It is widely used for the improvement of waste landfills through densification. Schmidt (2005) describes the design procedure for dynamic impact compaction, for which the variables must be decided according to the parameters of the soil stratum to be compacted, and the characteristics which ground improvement is intended to attain. The effectiveness of dynamic compaction depends on the magnitude of the weight used, the fall height, the impact area, the number of impacts, and the compaction spacing. Each impact transfers an amount of energy to the soil $E$, which affects the soil to a depth in metres $d_E$, defined respectively as:

$$E = m \cdot g \cdot h \quad (2)$$

$$d_E = \alpha \cdot (m \cdot h)^{0.5} \quad (3)$$
where \( m \) = mass of falling weight (in tonnes), \( h \) = fall height (in metres), and \( \alpha \) is a coefficient defined by Bergado (1996) as being in the range from 0.3-1.0. The coefficient \( \alpha \) is smaller for fine-grained soils and larger for granular soils. With each impact, the depth to which it is effective, \( d_E \), increases. With an increasing number of impacts, this energy accumulates in the soil and causes compaction by applying stress to the soil skeleton. The magnitude of energy required for adequate compaction varies according to the soil type and amount of densification needed, but the design guideline described by Bergado (1996) is that for each cubic metre of soil to be improved, the energy needed is in the range of 10-15 \( d_E \cdot m \) (for clayey silt) and 5-10 \( d_E \cdot m \) (for backfill). Thus when the required improvement depth (\( d_E \)) is known, the required impact energy for a given surface area of soil can be calculated and this is used as a starting point to plan the impact energy, and spacing and number of impacts. During the process of dynamic impact compaction, the quantity of backfill used to fill impact holes (corresponding to the volume loss from compaction) should be monitored for quality control purposes. It is also essential to monitor pore pressure in the soil, since a series of impacts causes a build-up of excess pore water pressure in fine-grained soils with low permeability, that can lead to liquefaction. Before this occurs, the impacts should be paused so that the excess pore water pressure can dissipate and the effective stress can increase again, because liquefaction would be counter-productive.

The effect of explosive compaction has some similarities to dynamic impact compaction, in that it causes a sudden introduction of an excess pore pressure field into the soil, so that the soil skeleton is compacted and the overall porosity is reduced. The main difference from dynamic impact compaction is that the excess pore water pressure caused by explosive compaction is even more transient and therefore may not leave time for dissipation, transfer of effective stress to the soil structure, and the resulting volume loss required for improvement. Explosive compaction is described by Tamáskovics (2001), who also notes that the best conditions for effective explosive compaction are in saturated soil with high porosity.