International Conference on Case Histories in Geotechnical Engineering

(2008) - Sixth International Conference on Case Histories in Geotechnical Engineering

13 Aug 2008, 5:15pm - 6:45pm

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J. D. Redgers
Soletanche Bachy France, Dubai, UAE

A. L. Moxhay
Ground Improvement Consultant, Brighton, UK

G. S. Ghataora
University of Birmingham, UK

I. Jefferson
University of Birmingham, UK

Recommended Citation

Redgers, J. D.; Moxhay, A. L.; Ghataora, G. S.; and Jefferson, I., "Case Histories of Settlement Performance Comparisons on Ground Improvement Using Soil Stiffness" (2008). *International Conference on Case Histories in Geotechnical Engineering*. 5.
https://scholarsmine.mst.edu/icchge/6icchge/session_01/5

6th International Conference on
Case Histories in Geotechnical Engineering, Arlington, VA, August 11-16, 2008

CASE HISTORIES OF SETTLEMENT PERFORMANCE COMPARISONS ON GROUND IMPROVEMENT USING SOIL STIFFNESS SEISMIC WAVE AND TRADITIONAL METHODS

Redgers J.D. Soletanche Bachy France, Dubai, UAE
Moxhay A.L. Ground Improvement Consultant, Brighton, UK.
Ghataora G.S. University of Birmingham, UK
Jefferson I. University of Birmingham, UK

ABSTRACT

Ground improvements often aim to reduce settlement risks for foundations and this requires reliable methods of prediction. Current approaches are based on empirical procedures and methods developed over 30 years ago. This has resulted historically in designs and installations of unnecessarily sophisticated foundations. In addition many developments now encountered by ground improvement contractors involve previously developed or ‘brownfield’ sites made up of heterogeneous and variable made ground. Methods to predict settlements traditionally use destructive and invasive approaches such as SPT or CPT that can be insensitive to time dependent changes, which often occur when brownfield sites are improved. By comparison geophysical methods are both non-invasive and non-destructive. One such technique that has demonstrated considerable promise is that of continuous surface wave determinations, which allows stiffness depth profiles to be obtained in a cost effective way. A recently developed method to determine settlements from these data has shown through four case studies presented in this paper to accurately predict settlements measured from zone tests. Thus offers a potentially more reliable way to predict settlement profiles than traditionally used methods.

INTRODUCTION

The use of ground improvement has been around for over 80 years, although anecdotal reports, for example, from Roman times indicate that compaction and the use of lime and cement were used to form building aggregates. However it was not until the early 1920’s that techniques such as vibro-compaction became more commonplace. These early attempts were based upon the tried and trusted methods of construction with contractor knowledge leading the designs that aimed to ensure buildings would not suffer undue settlements.

Over the years, empirical design methods have been produced, with the ground improvements seen as a black box approach with unsubstantiated claims by contractors’ for treatment and strengthening of the ground. However, it is freely acknowledge by many authors that ground improvements offer a cost effective method to treat weak often marginal ground condition negating the need for more costly (both economically and environmental speaking) deep foundation solutions such as piling (e.g. Mitchell 1981; Mitchell & Jardine, 2002).

It was not until the 1970s that designs began to become more formalized, e.g. Hughes and Whithers (1974), Priebe (1976) and others see Barksdale & Bachus (1983). In more recent times, ground improvement techniques have become more commonplace, especially the use of vibro-replacement for building foundations and ground bearing floor slabs, but again the lead is seemingly contractor driven with consultants content to specify pile designs but leaving clients “see the expertise of specialist sub contractors” for ground improvement works. Ultimately, the aim is to strengthen the ground, but more often than not the primary aim is to reduce settlements to an acceptable level.

The information that is available on ground improvements and used by the civil engineering industry comes from ground treatment specialists. Since details of recent advances made are not in the public domain consultants and specifiers have to rely on design texts base on site specific trials often taken from several decades ago. Whilst these are suitable for gaining a basic understanding of soil improvement techniques, they are not entirely applicable to the design problems of energy inputs and settlement control required in today’s marketplace. To try and fill these knowledge gaps, many laboratory studies have been undertaken. However, most of this work is undertaken on uniform or well graded sands and gravels, or ideal clays. None of which readily replicates actual site conditions, which need to be addressed. Engineers have been forced to be over cautious in their designs due to the constraints imposed by indemnities and insurance-backed warranties. This has led to excessive cost and wasteful use of limited resources, which is increasingly going against the grain of greater sustainability within construction, driven by many international and national agendas. Moreover, the lack of a reliable means of predicting ground settlements has historically led to the design and installation of unnecessarily sophisticated foundations. Whilst predictions of settlement grossly in excess of actual building performance might in some ways satisfy the requirements of our modern litigious society, it is the responsibility of the engineer to pursue the path closest to the truth and reality in terms of live constructions to minimize these impacts.

The vast majority of data that are available tend to suffer from bias associated with either their source or their end use. Generally, summaries are written by contractors using successful projects only, due to these being targeted at sales information. This often is focused on techniques favored by specific contractors. Other sources of information are: results of laboratory based investigations and numerical analysis. Both tend to relate to empirical procedures and methods developed in the 1960s and 1970s. By definition, site based studies tend to relate to specific ground conditions. Thus general application of site based studies should be viewed with much caution. In addition no brownfield site data (sites previously developed) as such are in the public domain, certainly in the UK, which given that most developments often occur on brownfield sites in countries like the UK, severely limits the lessons that can be learnt. Some guidance does exist for techniques such as vibro-stone columns (VSC) (Barksdale & Bachus, 1983) and for dynamic compaction (DC) (Lukas, 1995). But still much of this relates to sands and clays rather than the commonly encountered materials such as fills and made ground.

To determine whether improvements actually achieved have been effective a suite of assessments should be undertaken both pre and post treatment for quality assurance (QA) purposes and to ensure a satisfactory level of improvement has been achieved. Such assessments can be physical typically invasive and often destructive or geophysical methods which are typically both non-invasive and non-destructive. Previous examples of the use of geophysical methods include assessments of improvements achieved by rapid impact compaction (Butcher & McElmeel, 1993) and for examination of VSC (Moxhay et al., 2001). However, geophysical techniques currently are not used to any significant degree. This is possibly due to lack of understanding of the techniques, in particular their limitations and possible lack of confidence in their use. This could be in due in part to poor planning of geophysical surveys and over-optimism on the part of the geophysicists on what is achievable (Clayton et al., 1995). Charles & Watts (2002) highlighted that when undertaking geophysical assessments of ground improvement careful planning is essential. Thus, any geophysical assessment of any treated ground must incorporate physical soundings to ensure proper calibration. If undertaken, then such approaches have considerable scope. Jefferson et al. (2008) demonstrated this in relation to the assessment of VSC used to improve a brownfield site for a housing development.

In this paper, data have been collected from a number of sites over the last 10 years, where ground improvement has been undertaken, are presented. This includes prediction of settlement based upon the currently widely accepted principles as well actual settlements recorded, and these are compared to a seismic wave profile of ground stiffness predictions. To assist in this process a computerized method has been developed for predicting settlement from the minimum-strain stiffness data obtained in Continuous Surface Wave (CSW) surveys (see Moxhay et al 2001 & 2008, for details).

CURRENT APPROACHES

Modern-day developers now issue specifications and criteria for settlements particularly floor slab settlements for industrial buildings as a matter of course, quoting permissible levels of total and differential settlements frequently with a very small tolerance. Ground improvement when used in the form of stone columns or dynamic compaction does, in the vast majority of recorded cases, achieve the desired specification although, very often, the actual performance of the slab or structure varies significantly from predictions. Whilst this condition can be considered as satisfying in itself, it does pose the question of ultimate capacity, i.e. how much benefit has been achieved by the ground improvement work and as a consequence where does the point of maximum permissible loading exist.

Doubtless, where ground conditions are essentially granular it would be conceivable to relate theory and performance much closer given a relatively small amount of post-treatment study. But what happens when such techniques are used to improve soft and largely fine grained soils, i.e. those that would be typically classified as non-responsive soils to energy input. Throughout the UK such conditions predominate and the largest market for ground improvement typically involves shallow compaction of up to 6m of weak and mainly fine grained fill, often with coarse inclusions of more granular material e.g. brick, concrete, stone and/or gravel. Below this, more competent soils typically exist.

This paper focuses on the relationship between stiffened soils and soil rafts and long term settlement performance of supported structures. This is because, this is an area that case studies detailed below have revealed that actual settlements recorded in all cases are significantly less than those generated by predictive techniques commonly used.

PREDICTIVE METHODS COMMONLY USED IN INDUSTRY

One of the most frequently used calculations used to determine settlements of stone columns particularly when installed in large groups, follows the work of Priebe (1976) later reported in English with enhanced understanding in Priebe (1995) This approach produces a relationship between the expected stone column cross-sectional area (Ac) and the grid area between (A). The resulting Settlement Reduction Factor (SRF) can be set against the settlement that could be expected from the structure under consideration when built on untreated ground.

$$SRF = 1 + \frac{A_c}{A_o}\left[\left(\frac{0.5+F}{K_{ac} x F}\right) - 1\right] \qquad (1)$$

where, $K_{ac} = \tan\left(45 - \frac{\phi'_c}{2}\right)$ (2)

and, $F = \frac{\left(1-v^2\right)\left(1-2v\right)\left(1-A_c/A_o\right)}{\left(1-v-2v^2\right)\left(1-2v+A_c/A_o\right)}$ (3)

It is noteworthy that Greenwood and Kirsch (1983) are more cautious and advises that the upper limits of SRF to be no more than 1/ (3 + K_{ac}) or 1/6 of total settlement potential.

However, there are several basis of calculation that exist to establish settlement predictions for structures supported on mechanically improved ground and not surprisingly the range of answers obtained can be wide. In addition a more global approach is used were variability across a site has to be ignored. Even so, this variation cannot explain the huge difference between calculation and actual recorded performance.

The example of VSC in Manatee County, Sarasota, Florida is a particularly interesting case that illustrates this. The site consisted of successive layers of fine sandy silty sands and clays all with low standard penetration test (SPT) N values, providing a continuous overburden. Generally in Florida, a blow count of 15 is considered satisfactory threshold for ground improvement and so stone columns were installed to support isolated footings. Concerns were raised one year after their completion as further dynamic probe testing revealed a decrease in the relative density greater than expected.

To dispel concerns about the quality of the stone columns a further full scale static load test was undertaken to 240 kN/m^2 from which the recorded settlement at maximum load was less than 3mm. Calculations undertaken in accordance with Burland and Burbridge (1985) using post SPT blow count revealed a predicted settlement of 31mm, with other predictions ranging up to 55mm using Priebe (1995) and 91mm with no treatment.

It is most unlikely that the established theory is flawed and it can also not be assumed that the specified live loading conditions are consistently over-stated. Equally there could be some which are under-stated or, where the imposed dead load is an earth embankment and thus loading is accurately known. This suggests that a detailed examination of the methods of sampling and testing are required asking if they are sufficiently accurate, especially in the cases of fine grained or “soft” soils, if a reasonable prediction of likely settlements is to be established.

Frequently stone columns alone would be unable to generate the required increase in ground stiffness but they do provide a platform for further compaction. They produce regular points of high permeability and this allows additional energy, in the form of DC to be employed without risking liquefaction of ground heave. Again, traditional ‘flat-plate’ style of DC even when carried out from low drop heights can often be too severe and therefore, specially shaped tamper weights have been developed to produce true three-dimensional ground distortion from very low energy inputs. This technology is not new and was first commented upon by Menard and Broise (1975) where dynamic consolidation was introduced and then by Varaksin (1981), but it is only recently that further work into the shape of the tamper weight and required energy input developed this technique (e.g. Feng et al., 2000) who reported on sand trials under laboratory conditions.

Recently stiffened soil rafts are created using VSC and DC have been used successfully in the UK, particularly in areas of very soft ground (for example see Moxhay et al., 2001). This produces a means of permanent structural support, offering significant commercial advantage. However, their assessment must be based on successful test information with results from related to established soil strengths and density values, overcoming some of the difficulties highlighted above. Hence, the effectiveness of these improvements can be reliably demonstrated. A number of case histories illustrating soil raft creation from stiffened soil are examined below (see Case Histories section). In particular the potential power of CSW measurement is highlighted.

USE OF CSW IN SETTLEMENT PREDICTIONS

The CSW measurements use the seismic surface waves known as Rayleigh waves to measure soil stiffness. A range of frequencies is selected and a vibrator, under computer control, automatically shakes the ground at each frequency through this range. For each frequency, the surface waves are detected by the geophones placed at regular intervals. A computer measures the phase angles between the signals sent and received, from which the surface wave velocity and hence the shear modulus (stiffness) can be determined. As the frequency of the vibrator determines the depth to which the surface waves penetrate, thus by recording over a range of frequencies, a stiffness/depth profile to be built up.

There are a number of advantages over conventional methods of soil stiffness measurement and these include:

- The system is non-invasive. No drilling or sampling is required;
- Measurements are made in situ. Stiffness values close to those found operationally are determined;
- The system is rapid. A profile consisting of 30 - 40 separate measurements to depths of 10-30m (depending on ground type) can be obtained in under an hour.

The stiffness measured by the system is the maximum shear modulus, G_{max} or G_0. The method of measurement averages the values of G_{max} over a depth of about one wavelength. Each value of G_{max} is assigned to a depth of one third of the wavelength where the energy of the Rayleigh wave is a maximum – this is called the factored wavelength method of assigning a stiffness value to depth. It has been shown to be a good approach where stiffness increases uniformly with depth. From this settlements can be determined using procedures discussed in detail by Moxhay et al (2008). Further details of the use of CSW measurements and the determinations of G_{max} have been discussed by Matthews et al (2000) and Moxhay et al (2001).

CASE HISTORIES

Several case histories have been presented to illustrated the use of CSW to predict post treatment improvements in soil profiles where stiffened soil rafts have been produced, highlighting the advantages with CSW generated settlements predictions over more traditional approaches.

Site 1: Belverdere, London

This site was a previously unused area adjacent to the River Thames in East London. Other buildings (mainly warehouses and a power station) in the area had been constructed on driven or augered piles, through the stiff surface crust and the alluvial deposits into the terrace gravels at 10-12m depth (see the CPT trace shown in Fig.1.). The aim here was to generate a sufficient stiffness within the responsive soils in the upper 4m of the site, in effect creating a large stiffened soil raft permitting the use of a ground bearing slab.

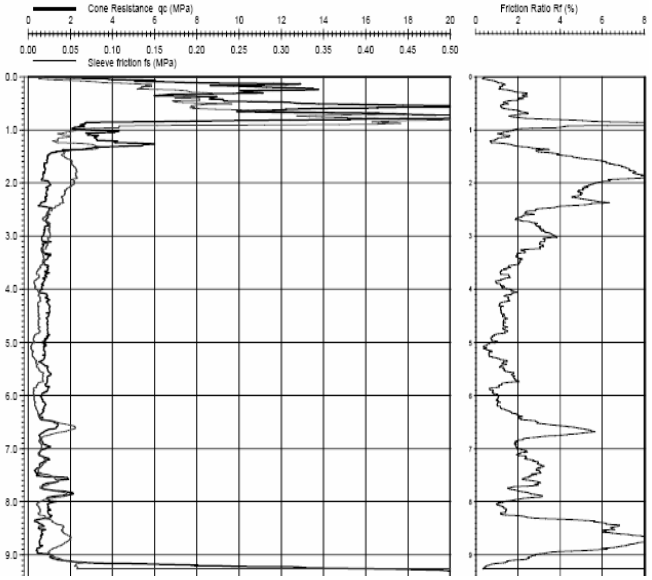

Fig. 1. Pre-treatment CPT at Belverdere

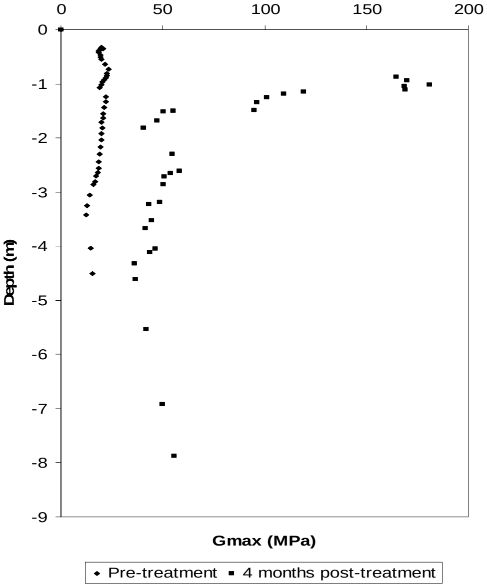

Fig. 2. Pre and post treatment G_{max} at Belverdere

Whilst all foundation footings were piled, the cost benefit to the client in savings offered over a piled and suspended floor slab was the main motivator in the project. Numerous zone tests were undertaken in excess of that normally recommended using the Specification for Ground Treatment (ICE 1987), to give the client are more onerous testing regime to demonstrate the improvement was successful based on the provided specification. Figure 2 shows the extent of post treatment, with stiffness increase demonstrated to some significant depth. Prediction of settlements showed that using traditional approaches gave values of 55mm compared to values of 8mm determined using the CSW method discussed above. This latter prediction compares extremely well with those measured by zone tests, which gave settlements of 7mm.

<u>Site 2: Devon</u>

This site was a redevelopment of an industrial warehouse, for a residential housing community and associated access roads. The aim of the treatment was to increase the bearing capacity and reduce settlement potential for a raft foundation as well as improved California Bearing Ratio for pavement construction. The National House Building Council (NHBC) required a full depth treatment of fill, which corresponded to 18m at this site. Figure 3 shows the CPT trace for this site.

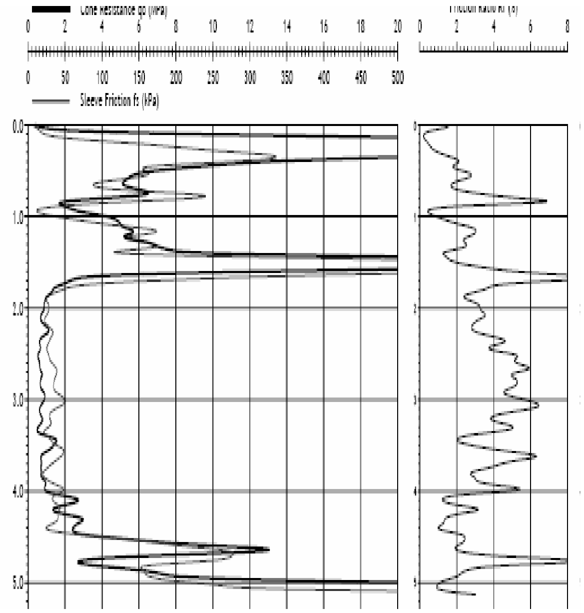

Fig. 3. Pre treatment CPT at Devon

Despite numerous meetings the local authority would not approve any scheme other than piling for the roads and residences. However, the developer progressed with a scheme of piling for the residences and ground improvement for the road scheme with an extended defects liability period to satisfy the local authority. Since completion in 2004 no problems have been reported.

The improvement works undertaken at this site consisted of dynamic compaction utilizing an 8 tonne tamper and 12m drop height to give an effective depth of treatment of approximately 5m. Figure 4 shows variation of G_{max} before and 4 week after treatment. Consistent with Moxhay et al (2001) further improvements have been observed with time.

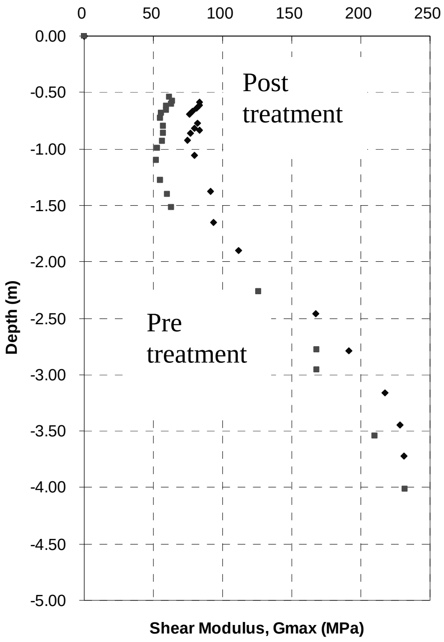

Fig. 4. Site 3 Devon – Pre and Post (4 weeks post treatment) G_{max} Values

Again as with the previous case study in London, settlement predictions using CSW methods very closely agreed with those observed during zones tests, details of which are illustrated in Fig. 5.

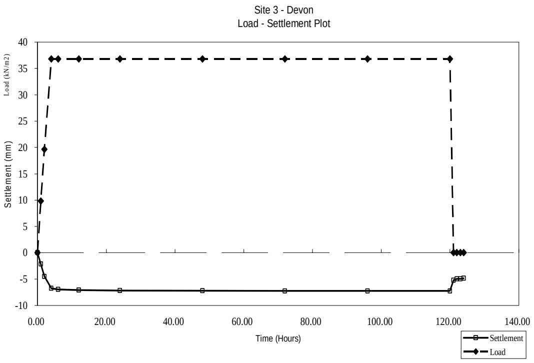

Fig. 5. Load Settlement Plot (2m x 3m to working load)

<u>Site 3: Heathrow, near London</u>

This site was a redevelopment of an industrial warehouse into a mixed retail / hotel development. The aim of the treatment was two fold, improve the bearing capacity and settlement control for a ground bearing slab, as well as enhancement to remove negative skin friction load component from piles. Both items were accomplished. There have been subsequently no reported concerns.

Figure 6 shows the initial stiffness and changes that occured with time corresponding to CSW taken at immediately after treatment and then at 11, 21 and 40 days after treatment had taken place. The corresponding SPT and CPT undertaken in conjunction with the CSW testing did not show the trend shown in Fig. 5. Importantly, Fig. 5. shows that immediately after treatment a detrimental effect occurs due to the improvement process. However, the subsequent stiffness increase coincided with a decrease in pore water pressure from the drainage effects of the stone columns, entirely consistent with observations made on other sites (see Moxhay et al., 2001).

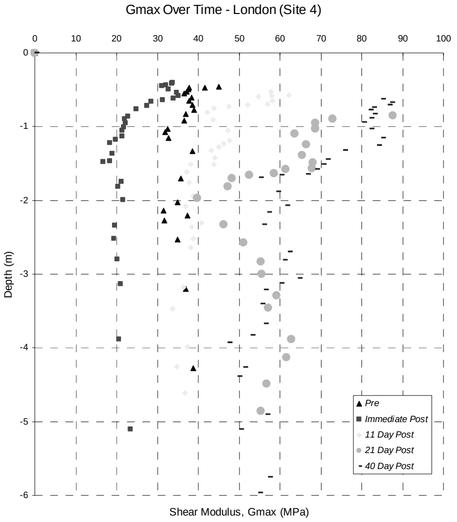

Fig. 6. Increases of G_{max} over time

As with previous case study sites settlement predictions from CSW data compared extremely well with measurements made from zone load tests. However, for this site the differences between traditional approaches and the CSW method of settlement predictions were less marked. It is important to note that the settlements before treatment were not predicted to be particularly high and this is attributed to the relatively high initial strength of the ground conditions found at this site compare to the other case study sites presented in this paper.

Site 4: Barnsley

This site was an old coal mining area, in an area being used for urban redevelopment, close to major motorway networks. Due to the previous work on site, numerous coal workings had left high walls and shallow fill, as well as deep fill areas from open cast activities. A development of two warehouses (each keeping away from the high wall was dropped when the client wanted one large distribution center. This meant the high wall could not be avoided. The cost of a fully piled building would have made the development uneconomic so alternative proposals were considered. The use of dynamic replacement (rock pillars) proved to be the most cost effective option and it was developed into a cost efficient and successful treatment regime.

Rock pillars are formed using a shaped tamper to create a void in the ground as well as to impart energy into the ground. The resulting void is then filled with a clean, hard, inert granular fill (crushed and recycled concrete in this case) which was again compacted before loose filled is placed on the surface. Subsequently a complete pass of traditional flat plate DC took place. Typically the masses involved were 6 – 8 tonnes, with drop heights of up to 14m. A typical rock pillar (Menard and Broise, 1975) is shown as Fig. 7.

Fig. 7. Typical “Rock Pillar” before up filling

Here the objective was to create a uniform stiffness across both the shallower and deeper fills, shown in Fig. 8., so that the foundations and ground bearing slab did not exhibit undue differential settlement.

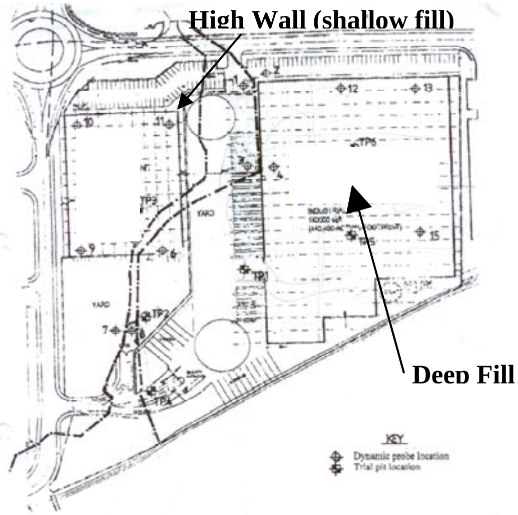

Fig. 8. Site sketch showing the high wall and deeper areas of fill to be treated.

To ease concerns over settlement performance, 3 static load tests were undertaken. Test 1 was a 1.8m x 1.8m test area loaded to 50 kPa, corresponding to the deep fill; Test 2 used the same loading arrangement as Test 1 but over the high wall fill, and Test 3 was a 1m x 1m plate loaded to 175 kPa. The resulting load settlement curves for these three tests are shown in Fig. 9.

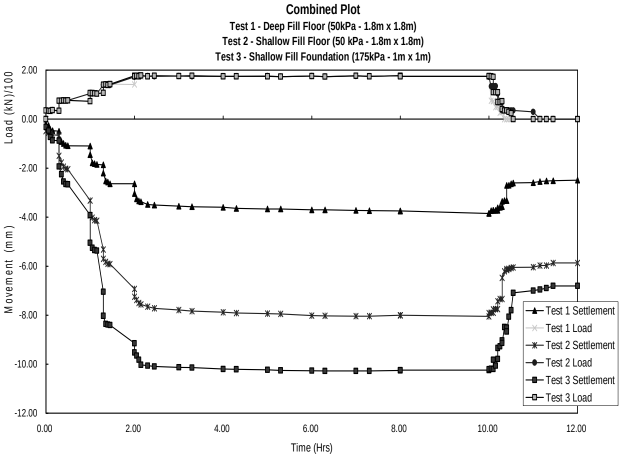

Fig. 9 . Combined plot showing the difference in settlement over the high wall and shallow fill

For illustration, Fig. 10. shows the resulting stiffness measurements using CSW for this site, corresponding to the general fill material, before and after treatment. As with all the previous case studies CSW predictions matched measured values particularly well.

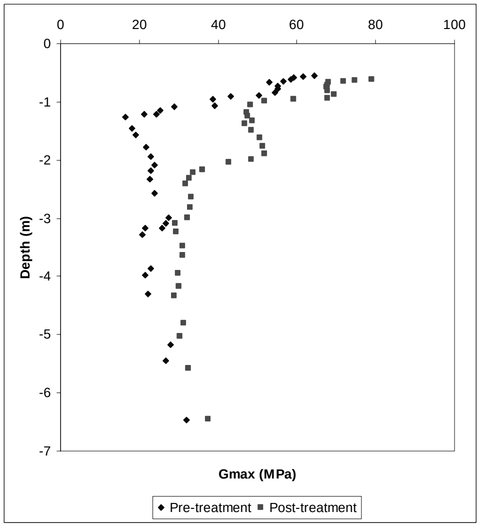

Fig. 10. Pre and post treatment G_{max} values.

DISCUSSION

It is clear from the case studies discussed above those traditionally used approaches such as Priebe (1995) for settlement predictions significantly overestimate actual behavior as demonstrated by load tests. The settlements predictions and measurements from each of the four case studies are summarized in Table 1.

Table 1. Comparison of the predicted settlements and measured settlements. All settlements are in mm.

Site	Pre - treatment Settlement	Priebe (1995)	CSW	Load test measurements
1	85	55	8	7
2	42	25	9	7
3	31	19	9	7
4	74	30	14	11

This differences from measured to predictions from traditional approaches to a large extent due to they method used that relies on site data generated from relative crude penetration tests. This is particularly true with most sites encountered that typically consist of 'made ground', which is highly heterogeneous and variable in nature. The CSW method to determine stiffness has already proved its worth as it can handle a wide range of material types (Matthews et al., 2000). This has been demonstrated by the four case studies presented in this paper, which following the work of Moxhay et al. (2008) has allowed reliable and relatively accurate predictions of settlements to be made.

Overall, predictions based on the CSW approach will improve confidence and overcome conservative estimate from standard predictions, especially when applied to composite ground. This is particularly important when dealing with ground that has be ameliorated using DC or VSC techniques. The key is the relative cost of the CSW approach, which typically takes an hour or so to assess a full treatment zone, yielding a complete picture of stiffness with depth. It is also extremely useful in assessing changes that occur with time, something Charles and Watts (2002) highlighted as key when examining improvements achieved. Typically changes occur due to excess pore pressures built up during treatment process will dissipate especially in finer grained soils. Often more traditional approaches are insensitive to changes that occur and the more sensitive CSW method can allow time related stiffness changes to be assessed. This yields a more complete picture of the treatment achieved as seen with case study number 3. Thus with these much improved settlement predictions will reduce the use of unnecessarily sophisticated foundation solutions.

It is clear from the case histories presented that further laboratory work to model a made ground to compare with earlier works is required to improve the overall understanding of how ground improvement works. This is because sites are most commonly encountered by the ground improvement industry are often not homogeneous and encompass a wide variety of artificial ground. Thus standard settlement equations may not be always valid and a means to assess the overall improvement of the soil mass rather than isolated areas will be of greater benefit.

CONCLUSIONS

CSW has proven to an effective technique in assessing the settlement of treated made grounds. It is faster to undertake and hence less costly than standard traditional methods of assessment such as large scale static load tests. It has proven to be more reliable in terms of assessment over larger areas than reliance on CPT or SPT probing.

The current state of the art design for ground improvement, in terms of settlement control is not making the best use of analytical models. This places a reliance on traditional soil mechanics, which is not always being applied correctly to model the actual conditions that exist for the site under consideration.

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ACKNOWLEDGEMENTS

The authors would like to thank Richard Tinsley and his brother Will Tinsley of Surface Wave Surveys for their help with the geophysical surveys and Roger Bullivant, Chairman of Roger Bullivant Ltd for his help with the ground improvement works.