GROUND TREATMENT IN RECLAMATION DESIGN & CONSTRUCTION - THREE HONG KONG CASE HISTORIES

STEPHEN L. GAMBLE

Frankipile Australia Pty Limited,
Sydney Australia.

SUMMARY

Most reclamation projects involve the forming of land over soft or loose near-shore or shallow water sediments, which often require some form of ground treatment to minimise post-construction settlement. Each reclamation project has a unique set of conditions, which will determine which of the available ground treatment techniques are appropriate for achieving the required performance improvement Three case studies are presented which illustrate some of the different ground treatment techniques used, and the reasons for their choice is discussed.

INTRODUCTION

The construction of new land by reclamation is not a new process. It has been carried out throughout history where swamps have been drained, coastal lagoons filled or shorelines extended. These operations would typically be slow and the occupant of the resultant land would need to be able to tolerate the ensuing settlement. In modern times our reclamation technology allows us to construct reclaimed land quicker, and of a better finished quality, than these humble beginnings. The ability to quickly produce a good quality reclamation arises directly from the advances made in ground treatment. These include techniques to improve the condition of both cohesive and granular material. The techniques of ground treatment more commonly used in reclamation construction include pre-loading with a surcharge, inducing additional soil drainage, improvement by introducing additional material, and by compaction. These techniques are implemented using a variety of methods. For ease of discussion, the various ground improvement methods will be introduced and described under four group headings in the first part of this paper.

Nowhere is the advancement of reclamation technology more apparent than in Hong Kong. Ever since the island of Hong Kong was ceded to Great Britain in 1841, the pressure of development in the colony has demanded a continual expansion of the available building space which has continually outstripped the supply of available building sites. The first reclamation shown on the current geological mapping of the colony [1] is dated 1863, and it is seen that further reclamation projects have been carried out intermittently since that time. In recent times, spanning the lead-up period to the handing over of sovereignty from Great Britain to the Peoples Republic of China, the pace of development in Hong Kong has increased dramatically. With container port traffic growing approximately 20% every year, the construction of a replacement international airport with road and rail links, together with the requirement for space to accommodate the burgeoning commercial and residential development; the areas of reclamation recently completed, under construction, or in design stage add together to form a brobdingnagian amount of construction activity. All of this work is carried out under very tight programmes, with the occupants of the newly created land expecting to be able to build on it immediately after hand-over. To further increase the geotechnical difficulties, these reclamations are built in areas where the existing geological sequence includes a soft near to normally consolidated marine silty clay, which is highly compressible. Three case histories of recent reclamation projects in Hong Kong will be discussed in the second part of this paper. These three cases illustrate some different geotechnical problems that have occurred, and the ground treatment techniques that were adopted to address these problems.

GROUND TREATMENT METHODS

The ground treatment methods used in reclamation design and construction, generally aim to improve the strength and the load-settlement behaviour of the reclaimed land, and although it is recognised that some projects will have other special requirements, this paper shall focus on these two main aims. The various methods for ground treatment are grouped for ease of discussion under the following four main categories.

- Soil Compaction Methods
- Soil Replacement Methods
- Accelerated Consolidation Methods
- In-Situ Soil Column Improvement Methods

These are briefly discussed in turn in the following section, giving details on mode of implementation, special applications, and limitations of the techniques.

Soil Compaction Methods

The ground treatment methods included in this group includes vibratory compaction, dynamic compaction, and compaction grouting, however the latter is rarely applied to reclamation construction and hence will not be discussed further. Both the vibratory and dynamic compaction methods aim to increase the density of the soil by realigning the individual soil grains with vibration or dynamic impact energy.

With the vibratory method, a probe is vibrated into the soil, sometimes aided by water jets (depending on the probe type). Upon reaching the required depth the probe is vibrated and lifted with series of cyclic lifts and re-insertions that ensure that each level of the sub-surface profile is sequentially compacted. The compaction probing is usually carried out on a regular grid, with spacing chosen on the basis of site trials that match the probe system being used, to the soil type. The various systems are usually crane mounted and depending on site conditions, produce results which are both fast and economical. The plant used for vibratory compaction generally falls into one of two categories: horizontal amplitude (immersion) probes which have the vibrator at the tip of the probe, or vertical amplitude probes where the vibrator is mounted at the top of a probe which is often fitted with fins or wings. The noise and vibration levels associated with vibratory compaction are generally low but will obviously vary according to a combination of vibration energy, frequency, soil conditions, and the sensitivity of the nearby structures. Experience [2] has shown that vibrating plant of current day energy levels can be safely used 15m from sound structures, with some instances of vibroflots used significantly closer.

To be successful, vibratory compaction requires the soil to be predominantly sandy, with a fines content of less than about 15%. If the fines content of the soil is too high, the increase in pore pressure resulting from the re-arrangement of the grains cannot dissipate quickly and there is a tendency for liquefaction of the soil. Several authors [3 & 4] have published criteria based on the particle size distribution of the soil for judging the suitability of the soil for vibratory compaction.

Dynamic compaction employs impact energy to cause the re-alignment of soil grains. This impact is achieved by dropping a heavy weight, usually from a crane, onto the ground surface. The dynamic compaction is usually carried out in 3 phases, consisting of the primary phase which compacts the deeper layers in the soil, the secondary phase which compacts those upper layers missed in the primary, and lastly the ironing phase where material is added and compacted in the depressions created in the first two phases and as the name implies, the surface is ironed out by a general pounding. As with vibratory compaction dynamic compaction is carried out on a regular grid with the spacing defined by site trials, which are also used to determine the appropriate size of pounder to be used. Most soil types other than soft silts and clays can be successfully compacted using this technique and the results achieved are quick and cheap. The compactive effort penetrates beneath the water table and in layered soil conditions. Fills contaminated with boulders or rubble can be successfully compacted using dynamic compaction.

The dynamic nature of this compaction technique gives rise to its main disadvantage, in that the shock-waves from the dropped pounder, have the potential for causing problems on site. As with other construction activities that cause ground vibrations, the public perception of the vibrations are often more serious than any physical damage to nearby structures, either way the problem is a real one. The depth of penetration of the dynamic compaction effort depends on the size of the pounder and the height of the drop, and the size of available cranes is often the limiting factor. The effectivness of this treatment as well as the vibro compaction, can be confirmed by before and after CPT soundings.

Soil Replacement Methods

The methods for ground treatment bracketed in this group include vibratory replacement, dynamic replacement and driven stone columns. Each method involves the construction of a column of granular material, usually gravel sized, using either vibration or dynamic impact energy. The construction of the stone column aims to improve the bearing capacity and the drainage characteristics of the soil. The performance of each of the three methods can be checked by conducting load tests, and by monitoring settlements in the treatment area.

Vibratory replacement uses an immersion type vibrating probe already briefly described in the above section on vibratory compaction. The probe is advanced into the ground to the desired depth, and then successive charges of gravel (usually crushed rock) are added around the probe as it is lifted and re-inserted. This operation is continued cyclically, so that a column of compacted stone is built up to the surface. The introduced gravel displaces the in situ soil horizontally; and the size of the column, which largely depends on the strength of the in situ soil, is calculated from the volume of gravel used. The compactive effort is measured by monitoring the current drawn by the electric motor, or in the case of a hydraulic system the oil pressure in the vibrator. Vibratory replacement is usually carried out where an increased surface bearing capacity is required, usually in soft clays and silts where compaction methods are not appropriate. The installation of stone columns using vibratory replacement, is usually carried out on a regular grid, depending on the extent of the structural load on the ground surface. If the area of treatment is large, the stability of the stone columns is generally very good. If however the treated area is narrow or small in size, or the columns are constructed in very soft layers of significant thickness, some checking of column stability is required, since they have little shear capacity.

Dynamic replacement employs the same equipment as the dynamic compaction described above. The stone columns constructed by dynamic replacement are formed by pounding successive charges of crushed rock into the soft ground. The ideal conditions for dynamic replacement are for a surface layer of sandy soil overlying a soft silt or clay, which in turn overlies a firm/dense founding layer. The stone column is constructed through the soft layer and is founded on the firm/dense layer. This method of ground treatment is only effective for a limited thickness of the soft layer, which depends on the size of pounder and the height of its drop (thus by the size of crane available). If the capacity of the crane/pounder is reached, there is a risk that the stone column will not fully penetrate the soft layer. This may be overcome by pre-drilling, however this would markedly increase the cost of the ground treatment.

Driven stone columns have a final result similar to the two preceding soil replacement methods, however their mode of construction is markedly different. They are installed using a rig usually used for installing driven cast-in-place (Franki) piles. The stone column is constructed by a driving a temporary liner into the ground using a bottom drive drop hammer. When the liner has reached the required level, which can be checked by the blow-count of the hammer, successive charges of crushed rock are driven out of the bottom of the temporary liner as it is withdrawn. This forms a column of compacted stone similar to those described above. The distinct advantage this system offers is one of confidence. With the ability to monitor the penetration rate of the diving tube, and also the energy imparted to each charge of gravel as the tube is withdrawn, this method of installation gives greater reliability to the quality of the resultant stone column. It must be recognised that the method is slower, and also requires the mobilisation of a specialist piling rig, which as a consequence makes this method marginally more expensive.

Accelerated Consolidation Methods

Accelerated consolidation treatment aims to speed up the settlement due to soil consolidation by increasing the overburden pressure and/or reducing the length of the drainage path within the soil. These methods are applied to reclamations with clayey and silty layers, where the inherent impermeability of these gives rise to consolidation settlements.

Pre-loading using some form of surcharge increases the overburden pressure acting on the consolidating soft layer, thereby causing early consolidation of the soil during the construction period. The surcharge is usually a temporary fill embankment placed on the ground surface, however the surcharge load can also be achieved by de-watering or by some other form of temporary load. Pre-loading is mostly used in conjunction with other ground treatment, but in suitable conditions it is used by itself. Ground treatment with surcharge is expensive, and extra resources of earthmoving plant and fill must be included in the construction programme, as well as the time required for sourcing, placing, removal and disposal of the surcharge material itself.

The method for accelerating the consolidation by reducing the length of drainage paths involves the introduction of drains into the soil, and thus decreases the time taken for consolidation of the soil layer. This well established method of treatment is particularly applicable to reclamation construction, which often involves thick layers of soft impermeable sediments being buried under the reclamation fill. The drains are generally installed vertically into the soil and are usually made from a free draining material such as sand or a synthetic drain fabric. The sand drains are simply a column of suitably sized free draining sand placed in a hole that is drilled or driven into the soil. The size of sand drain is usually 150-250mm diameter, which balances the installation cost against the ability of the drain to resist necking, clogging or some other mode of failure. The alternative, more modern form of vertical drain is the band or wick drain. These are usually made from a geotextile wrapped, shaped strip that allows free draining along grooves, dimples or similar relief in the strip's surface. The drain itself is usually between 2 to 10mm thick and 100mm wide. These drains have the advantage of a longer service life which is attributed to their ability to remain free draining after considerable compression of the surrounding soil, and their resistance to clogging. The band drain is usually installed within a hollow mandrel which is pushed into the ground by a hydraulically operated installation rig, the mandrel is withdrawn leaving the drain behind in the soil. Both types of drain are relatively inexpensive, however they require purpose-built crane or excavator based installation equipment. The treatment method is time consuming, because an extended period of typically 12 to 18 months consolidation time is required on top of the time for the drain installation, which in itself comparatively rapid. The alternative however, is to leave the ground untreated which may entail consolidation periods extending for perhaps decades. Usually vertical drain treatment is used in conjunction with surcharge treatment. Geotechnical instrumentation plays an important part in carrying out this treatment, since it is only by monitoring the settlement behaviour of the reclamation can a judgement be made on its effectiveness. This would usually require the monitoring of settlement with buried plates and magnetic extensometers, together with pore pressure monitoring using standpipes and piezometers.

In Situ Soil Column Improvement

The technique of in situ column improvement involves the injection or mixing of additives to the soil to improve its performance under load. The two main methods in this group are jet grouting, and lime columns. These techniques are less frequently used in reclamation construction, because of their specialist requirements.

Jet grouting involves the mixing and partial replacement of the in situ soil with cement slurry injected under very high pressure. A grout tube is installed into a hole either pre-drilled, or self bored to the required depth. The jetting operation involves the grout being pumped under high pressure through jets at the base of the grout tube which are aimed in a horizontal direction into the soil layer. Where a cylindrical grout body is required, the grout tube is rotated during the grouting and withdrawal. Tabular shaped bodies can also be formed by halting the rotation. Jet grouting is ideally suited to granular soils, but can be successfully used in a fairly wide range of soil types however cobbles and larger sized particles significantly effect the shape of the grout body, and purely cohesive soils tend to substantially reduce the jet penetration and hence the size of the grout body. Jet grouting is a relatively expensive ground treatment method that is not often applied in reclamation construction, it is used more frequently in other specialised applications.

Lime columns are constructed by deep mixing unslaked lime (CaO) with soft clay or silt layers. The effect of this mixing is to cause a change in the soil structure and chemistry, giving it increased strength and permeability. The lime column is constructed using a powerful top-drive drill rig or auger rig, on which is mounted a hollow kelly with a mixing head. After a hole is drilled to the required depth, lime is blown down the kelly and is well mixed with the soft clay/silt while the head is gradually withdrawn. A column of lime improved soil is constructed through the soft layer, which will have (depending on initial condition) an improvement in shear strength of 10 to 50 times [5], and significantly improved drainage characteristics. The treatment is not applicable to all clay types, and soils with a high organic content are unsuitable. This technique has not seen wide application in reclamation construction, but with more exposure it may see an increased utilisation

THREE HONG KONG CASE HISTORIES

Three case histories of recent reclamation projects are briefly presented in the following section. Each case offers some insight into the way the ground treatment techniques have been used in reclamation construction in Hong Kong, and a few key features are noted for each.

The Third Industrial Estate - Tseung Kwan O

With available building sites at a premium, the Hong Kong Industrial Estates Corporation was allocated an area in the planning of Tseung Kwan O (Junk Bay) development on which to establish Hong Kong's 3rd industrial estate. The area of approximately 40ha, was to be reclaimed adjacent to the eastern side of Tseung Kwan O. The soil profile beneath the seabed was found to be fairly typical of the near shore sequence in Hong Kong, and can be characterised as a very soft to soft, near normally consolidated marine silty clay ("marine mud") of 7 to 15m thickness, underlain by a firm to stiff overconsolidated alluvial clay of approximately 5m thick, over a weathered granite profile grading to solid rock.

Several key conditions were set as part of the design for the reclamation construction as follows:

- The soft marine silty clay was to be treated in situ as part of the reclamation construction.
- The consolidation settlements should be substantially complete on hand-over
- The tight programme for construction was to include an early completion of part of the site.
- A resource of suitable sand fill sourced from the seabed in nearby Tathong Channel had been identified, and would be allocated by the Hong Kong Government to the project.

The soft marine mud was found to have a coefficient of compressibility of approximately $C_c = 0.6$, and a coefficient of consolidation for vertical drainage of approximately $c_v = 1.2$ m^2/year. These properties indicated that the marine mud layer would undergo a large amount of compression, which would take a long time to complete. Clearly treatment with vertical drains was required. These were assumed in the design to be the synthetic type band drain and would be installed as soon as possible after the reclamation fill rose above sea level. The design specified drains installed on a triangular grid with a spacing of 1.5m. In order to provide time for roads and drains construction in the early hand-over area, the allowable time for consolidation was restricted to 12 months, and surcharge embankments placed over these services areas were included in the construction programme. Since a further 6 months was scheduled for the roads and drains work, the consolidation in the remaining part of the early hand-over area was able to catch up to the surcharged areas. The rest of the reclamation which had a scheduled completion at the end of the contract, was treated with vertical drains but not surcharged. The justification for not pre-loading the building areas was the design assumption that all buildings would be piled and hence not increase the overburden pressure on the marine mud.

As with most reclamations designs involving ground treatment measures and staged sectional completion of the works, the construction strategy adopted for the Third Industrial Estate had to be tailor-made to suit the specific requirements of the reclamation, and the assumptions made about the consolidation behaviour of the clay had a direct impact on the construction programme, as well as the expenditure on ground treatment. It can also be seen that the geotechnical engineer had to be aware of the site-specific construction and planning issues, and had to address these in a realistic programme of construction activities in order to arrive at a workable reclamation design.

The Island Reclamation for the HKCEC (Wanchai Reclamation Phase I)

The existing Hong Kong Convention and Exhibition Centre (HKCEC), which was built in the late 1980's, has proved to be a very successful venue for conventions and exhibitions, and within a short time after opening, a requirement for additional exhibition hall space was identified. This expansion was in line with the long-term planning for a large reclamation spanning the Central and Wanchai districts on the northern coast of Hong Kong Island, however the HKCEC's need was immediate and the Central & Wanchai Reclamation had not passed the planning stage. Therefore an island reclamation, that would be incorporated into the future Central & Wanchai scheme was proposed, and approved by the Hong Kong Government.

The island reclamation was to be located in Victoria Harbour a short distance offshore from the existing waterfront promenade in front of the HKCEC. A series of drillholes and cone penetration tests (CPT) revealed that ground conditions beneath the seabed included a varying sequence comprised of very soft marine mud (similar to that found in Tseung Kwan O, discussed above) , over marine and alluvial sands and alluvial silty clay, which in turn were underlain by a weathered granite profile grading to bedrock. The ground investigation showed that the thicknesses and lateral extents of the various surface layers in the sequence varied, and this was thought to be due to the more turbulent water currents in this fairly narrow section of the harbour. This variability of ground conditions required rather more care to be devoted to the geotechnical aspects of the reclamation design.

The reclamation was to be purpose built for a low-rise exhibition hall building of some 3 to 4 storeys, which would occupy most of the reclamation area. The only other occupant of the reclamation would be a ferry pier and its associated bus access and terminal, both with only minor infrastructure requirements. The geotechnical design assumed that the exhibition hall was to be a piled structure with a single level basement slab suspended off the structure. This configuration of building meant that no ground treatment measures were required beneath the building, however the services connections and the on-grade access road would require a careful assessment of the consolidation behaviour of the sub-reclamation silty clay layers, and also of the settlement of the reclamation fill itself.

Since by good fortune, the thickness of the soft marine mud was generally found to be less than 2m beneath the reclamation area outside the building footprint, consolidation settlements were considered unlikely to cause problems for the on-grade roads and services. Thus ground treatment to accelerate the consolidation using band drains was considered unnecessary. However the settlement of the hydraulically placed sand-fill was recognised as a potential problem for these structures. Vibratory compaction was therefore specified to be carried out on a grid to cover the whole area of reclamation not within the footprint of the future exhibition hall building. The spacing of the grid for vibratory compaction was to be defined by site trials, with the results confirmed by before and after CPT soundings. Vibratory compaction was chosen for its well demonstrated ability in improving the density of the marine sand fill, both above and below the water table.

This project illustrates that with the good communication between the geotechnical and structural engineers associated with this project, significant (and expensive) extra ground treatment was avoided. The key assumption used in the geotechnical design, which was subsequently adopted in the structural design, of a piled building structure with suspended basement slab, meant that most of the reclamation, which incidentally included the thickest layer of problem soil, was able to be left untreated.

West Kowloon Expressway/West Kowloon Reclamation

The West Kowloon Reclamation (WKR) is a major new reclamation project that was commenced in the early 1990's on the western shore of the Kowloon peninsula. The primary planning function of the new reclamation, was to provide a much-needed transport corridor, combining the West Kowloon Expressway and the Lantau and Airport Railway mass transit rail link. These transport links, were both included in the Hong Kong Government's Airport Core Programme (ACP), which is the overall project management scheme which was set up to control programming for all the key infrastructure projects associated with the construction of Hong Kong's replacement airport.

The reclamation works for the WKR was split into several different construction contracts which were each to be completed at different stages. This approach was necessary from a construction management view, due to the sheer size of the whole reclamation, and also because of its location next to one of the worlds most densely populated urban areas. In order to meet the tight construction programme that involved a complicated scheme of sectional completion, and to accommodate a variety of different major structures, the WKR construction works included ground treatment programmes that resembled a patchwork quilt. The soft marine mud on the seabed, was either dredged out or left in place to be subsequently treated with vertical drains, depending on the time available for consolidation. The application of pre-loads using surcharge fill was scheduled in many parts of the reclamation, whilst certain areas of the reclamation fill were treated with vibro compaction, to avoid the later settlement of the sand fill. With all these activities being carried out at different times and places in different parts of the site, problems would appear to be inevitable. Through good project management, these were largely avoided.

In one section of the reclamation works, where partial dredging of the marine mud had been specified in the design, the sand fill had been contaminated with lenses of the soft marine mud during placement. This phenomenon is not unusual where sand fill is placed on the marine mud, and is largely due to a displacement of the mud by the sand. The problem is often referred to as mud waves, due to the appearance of wave-like mounds of displaced mud near the leading edge of a reclamation. Part of the West Kowloon Expressway was located in this section of reclamation, and the presence of mud lenses was discovered during the vibro compaction works associated with the expressway construction contract. The vibration of the vibroflot caused liquefaction of the sand/mud mixture, and the compaction treatment was rendered ineffective in those areas. A programme of CPT soundings was instigated and these confirmed some contamination of the reclamation fill. The reclamation area containing the mud contamination was to accommodate the expressway on-grade, together with multi-cell drainage culverts, and major fill embankments for several of the expressway slip-roads, and the remedial treatment of these lenses appeared necessary to avoid future settlement problems. A combination of vertical drains and surcharge treatment was assessed, with an alternative of stone columns installed using the vibro replacement method. The former treatment would require a massive mobilisation of drain installation plant, and the time taken for drain installation, and the placing, holding and removal of the surcharge mounds, would cause serious project delays. With the stone column option, some of the requisite plant was already on site, and additional vibroflots could be mobilised if required. Field trials had been carried out on the site, and the performance of these indicated that this would be an relatively expedient method for treating the problem areas, but would likewise cause delays. As might be expected, the subsequent discussion of the project delays resulting from either of these remedial measures was not well received by the ACP project managers, and further investigation into the nature and expected behaviour of the mud lenses was investigated using vibrocore sampling. This further investigation showed that the mud lenses were rather more sandy, and far less extensive than had been previously thought, avoiding much of the expensive ground treatment that had earlier been considered. To the relief of all those involved!

This case history illustrates how ground treatment may be used in reclamation construction, in a variety of ways, including remedial works. It also demonstrates the importance of care in the filling operation, and also highlights a slightly grey area on a CPT interpretation chart, namely identifying the true nature of soft/loose sand/silt/clay mixtures.

CONCLUSIONS

The modern techniques of ground treatment allow reclamations to be rapidly built and to a high finished standard. The construction environment that exists in Hong Kong illustrates this very well. However, it is seen that when the reclamation construction is completed under a tight programme, a high quality of geotechnical investigation data is essential, otherwise there is a very real risk of significant and expensive delays. To arrive at a workable and efficient reclamation design including ground treatment works, the geotechnical engineer needs to be aware of a broad scope of planning and construction issues.

REFERENCES

1 Hong Kong Geological Survey. 1986. *1:20,000 Solid and Superficial Geology Sheet 11, Hong Kong & Kowloon* . Series HGM20.

2 Greenwood, D A and Kirsch, K 1983. Specialist Ground Treatment by Vibratory and Dynamic Methods, *Piling and Ground Treatment - Proceedings of the international conference on advances in piling and ground treatment for foundations. ICE London March, 1983.* Thomas Telford Ltd., London.

3 Brown, R E 1977. Vibroflotation Compaction of Cohesionless Soils, *Journal of the Geotechnical Engineering Division*, ASCE Vol. 103, No. GT12, 1437-1451.

4 Mitchell, J K and Katti, R K 1981. *Soil Improvement State-of-the-Art Report*, Proc. 10th Int. Conf., ICSMFE, Stokholm 1981

5 Broms B B 1993. Lime Stabilisation, *Chapter 4 - Ground Improvement Ed. M P Mosely*, Blackie Academic & Professional, Glasgow 1993