KGS Fall '92 National Conference/Dredging, Reclamation
and Artificial Islands/16-17 October, 1992/Seoul/Korea

GEOTECHNICAL DECISIONS FOR THE NEW HONG KONG AIRPORT

By Roger Foott[1] and Roy Bell[2]

1.0 Introduction

The new Hong Kong Airport is to be built on the north side of Lantau Island. The construction will involve demolishing the island of Chek Lap Kok and reclaiming surrounding land from the sea. Figure 1 shows the proposed airport site plan. The site was selected during the 1970's and in 1981 a contract was awarded for the airport design. An extensive geotechnical program followed, including site investigation, lab testing, design studies, the construction and interpretation of a test fill, and the selection of an optimal reclamation method. These studies addressed many factors associated with marine reclamation over soft seabed soils of relevance to similar reclamation projects.

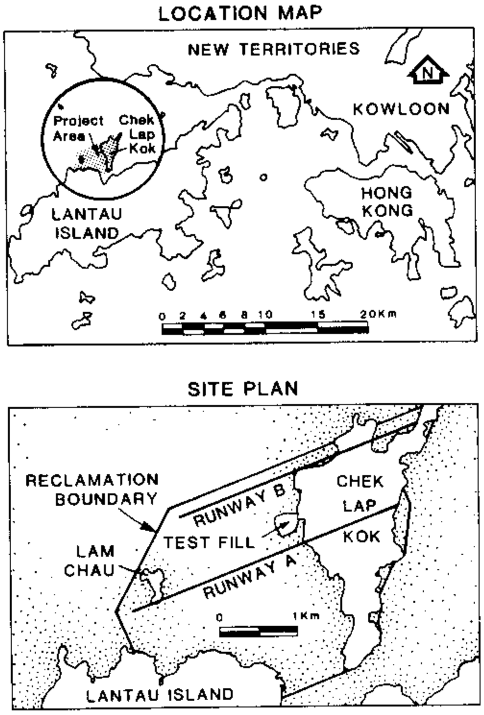

Figure 1 - Airport Location and Site Plan

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Following the world economic slowdown of the early 1980's and concerns about Hong Kong's political future, the Airport project was halted in 1983, prior to the commencement of construction. It was reactivated in about 1990, after of a period of continued economic growth and decisions regarding Hong Kong's sovereignty. A larger Airport than initially conceived was then selected, to meet the capacity demands of a longer design life. The Airport was also to be operational by the 1997 return of sovereignty to the PRC. The resulting short construction schedule and increased airport land requirements, imposed major constraints on the airport reclamation program and led to the adoption of different reclamation techniques.

This paper outlines the 1980's geotechnical design studies. It characterizes the site conditions,and describes the major 1980's design issues and how they were addressed. It then identifies new issues encountered by the 1990's design program and outlines the resulting design decisions, which are incorporated in the intended construction program. The paper's objective is to describe major geotechnical considerations involved in the project and their resolution. It will thus provide information of value to those planning similar reclamation projects.

2.0 1980's Geotechnical Constraints

A major objective of the 1980's Airport design was the development of the site in the most economical manner. This requirement placed great emphasis on the geotechnical evaluation of the site and the selection of the most cost-effective reclamation methodology. Major geotechnical design constraints identified in this process were as follows.

Fill Availability

The demolition of Chek Lap Kok was a clear necessity for airspace reasons. It would also provide fill for the reclamation. Alternate or additional fill sources were limited by the cost of developing remote borrow areas and transporting material to the site. It was therefore highly desirable that the reclamation fill requirements would not exceed the material which could be obtained from Chek Lap Kok. Disposal of excess fill material was also problematic, so a balanced cut-and-fill earthworks project was optimal. Regarding fill types, Chek Lap Kok is a granite island which has experienced extensive weathering and decomposition. It proved capable of producing most of the material types required for a reclamation, but only with carefully programmed excavation and significant materials processing.

Reclamation Behavior

The airport runways would pass from the granite pediment of Chek Lap Kok onto the airport reclamation, as would roadways, utilities, drainage, etc. It was therefore highly desirable that post-construction settlement of the reclamation be limited and known. A stable reclamation area with limited settlement potential was an important design requirement.

Seabed Conditions

The seabed surface was composed of very soft mud up to 15 m in thickness. Its settlement potential under the reclamation loads was up to 5 m, the duration of which would naturally extend over several decades.

Sea Protection Requirements

Hong Kong is subject to typhoons. The Airport will therefore require substantial seawalls to withstand major wave action, plus protection from elevated sea levels due to low barometric pressure, etc. This protection could either be provided by elevated perimeter sea walls or by establishing the airfield (reclamation) elevation at a sufficient height. The latter solution is preferable since it maintains gravity drainage during high sea levels, but it requires a greater thickness (and thus a greater quantity) of fill.

Disposal of Excavated Material

Hong Kong reclamation work characteristically involves some excavation of seabed mud for seawall foundations, etc. Disposal of such material in the 1980's was typically permitted only at designated sea dumping areas having limited capacity. The volume of mud underlying the Airport site greatly exceeded the capacity of the disposal areas then available.

3.0 Impacts on Reclamation Design

The above geotechnical constraints had major impact on the reclamation design considerations, as follows:

- Optimizing the earthworks involved setting the levels of the Chek Lap Kok excavation and the reclamation fill to provide balanced earthworks. Achieving a balance required estimation of the variable bulking of the excavated material and the settlement of the seabed mud. The size of the project was such that a small change in bulking or settlement could result in large volumes of excess fill or in a material shortfall. The design had to address this potential.

- The characteristic behavior of Chek Lap Kok material would vary greatly with its degree of decomposition. The materials would vary from a sandy silt soil, through variously decomposed rock and soil, to fresh rock of varying fracture and jointing. Economics dictated that the design utilize all these material types and minimize the need to import select materials. Different bulking factors would apply to each material.

- There was insufficient fill material available to replace all the mud if it was excavated, plus inadequate facilities for its disposal. The costs of excavating the mud and replacing it with imported fill would also be high. The fill materials therefore had to be placed on top of the seabed muds for major areas of the reclamation works.

- Reclaiming over the mud would necessitate the use of techniques to accelerate the mud consolidation and settlement. Otherwise the post-construction settlements would disrupt airport facilities and infrastructure, and likely require extensive runway maintenance.

- The amount of mud settlement would be a primary factor in determining the fill quantity requirements and the appropriate airport elevations for balanced earthworks.

- The long-term settlement behavior (including secondary compression) of the mud would be a primary consideration in predicting the adequacy of the reclamation in service.

- The very low strength of the soft muds, plus previous Hong Kong experience, necessitated special consideration of the process and details of placing fill on the seabed, in order to avoid or minimize the creation of mudwaves. Mudwaves could jeopardize the reclamation performance by greatly increasing both the amount and duration of reclamation settlement at the mudwave location.

4.0 1980's Geotechnical Studies

The 1980's geotechnical studies included:

- An offshore site investigation to characterize the sea bed soil profile in the area of intended reclamation.
- A laboratory testing program to establish behavioral parameters for the offshore soil strata.
- Geophysical survey, geologic mapping, and a program of borings, in situ test and lab tests on Chek Lap Kok to investigate the available fill material.
- The design, construction, monitoring and interpretation of a test fill to investigate reclamation techniques and performance for filling over the seabed muds, plus seawall data.
- The development and evaluation of a test quarry on Chek Lap Kok to provide material for test fill and information on Chek Lap Kok material.

These studies have been documented in numerous reports to the Hong Kong Government. They have also been documented in various papers, most notably 3 ASCE publications dealing with the site investigation (Ref. 3 - Koutsoftas, et al 1987), the test fill (Ref. 1 - Foott et al 1987) and the test fill instrumentation (Ref. - 2 Handfelt, et al 1987) The studies are outlined as follows, with the reader referred to the above publications for more detailed descriptions.

Offshore site investigation and laboratory testing

The offshore site investigation consisted of: (1) 77 marine borings; (2) 93 piezocone penetration soundings, (3) 95 pore pressure dissipation tests; (4) extensive field vane testing; (5) in situ variable head permeability tests; (6) marine geophysical testing to provide stratigraphic data; and (7) an extensive laboratory testing program.

The offshore borings were drilled from 20 m x 7 m floating barges using conventional land drilling equipment, with drilling mud and fixed piston sampling in the soft materials. The equipment and procedures worked well for the typical sea conditions of 2 m tidal range and waves of about 0.5 m.

The piezocone was selected to provide relatively continuous penetration and pore pressure response data, plus great sensitivity to possible minor granular drainage layers within the mud. The soundings were performed from a jack up platform with the cone rods protected within a string of casings to prevent buckling. Pressure dissipation tests were performed by halting the cone penetration within the mud and monitoring the reduction in excess pore pressure with time.

Field vane testing used Geonor equipment connected to a special frame supported on the seabed. A 65 mm x 130 mm vane tip was used in the soft mud and a 55 mm x 110 mm tip in stiffer clays encountered at greater depth. Peak strengths were measured using a rotation rate of 6°/min.

Permeability tests were performed using Geonor M206 piezometers pushed to the required position in the soil profile. Testing was performed by adding or removing water from the standpipe to perform variable head tests.

Laboratory testing consisted of: index tests plus consolidation tests; unconsolidated undrained, isotopically and ko-consolidated undrained triaxial compression tests; and ko-consolidated undrained direct simple shear tests. The SHANSEP testing procedure (Ref. 4 - Ladd and Foott, 1974) was used extensively in the testing program to produce normalized parameters which can be applied to any known stress history (i.e. in situ stresses and overconsolidation ratio). This procedure allowed data from throughout any given stratum to be evaluated collectively. The normalized parameters can then be applied anywhere in that stratum.

Figure 2 shows the typical seabed stratigraphy, along the line of the southern runway. The Upper Marine Clay (mud) layer is extremely weak (Figure 3) and compressible. The underlying Upper Alluvial Crust is a very strong, stiff clay layer, overlying a Lower Marine Clay layer with a substantial, though variable, prestress. The underlying granular and decomposed rock strata are strong and relatively incompressible.

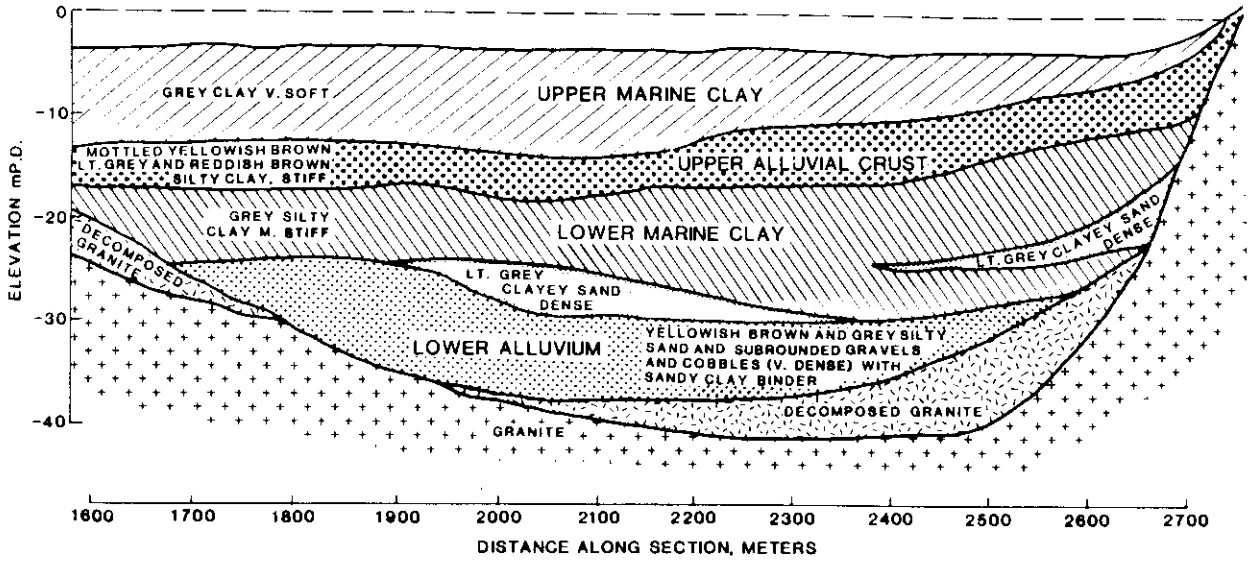
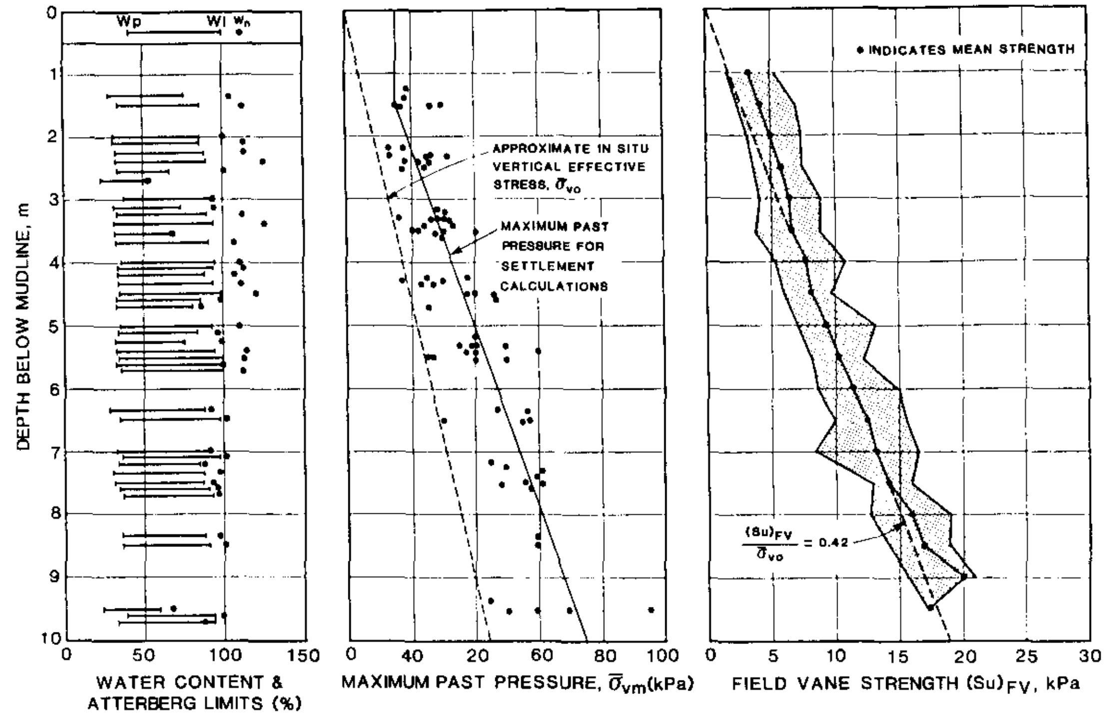


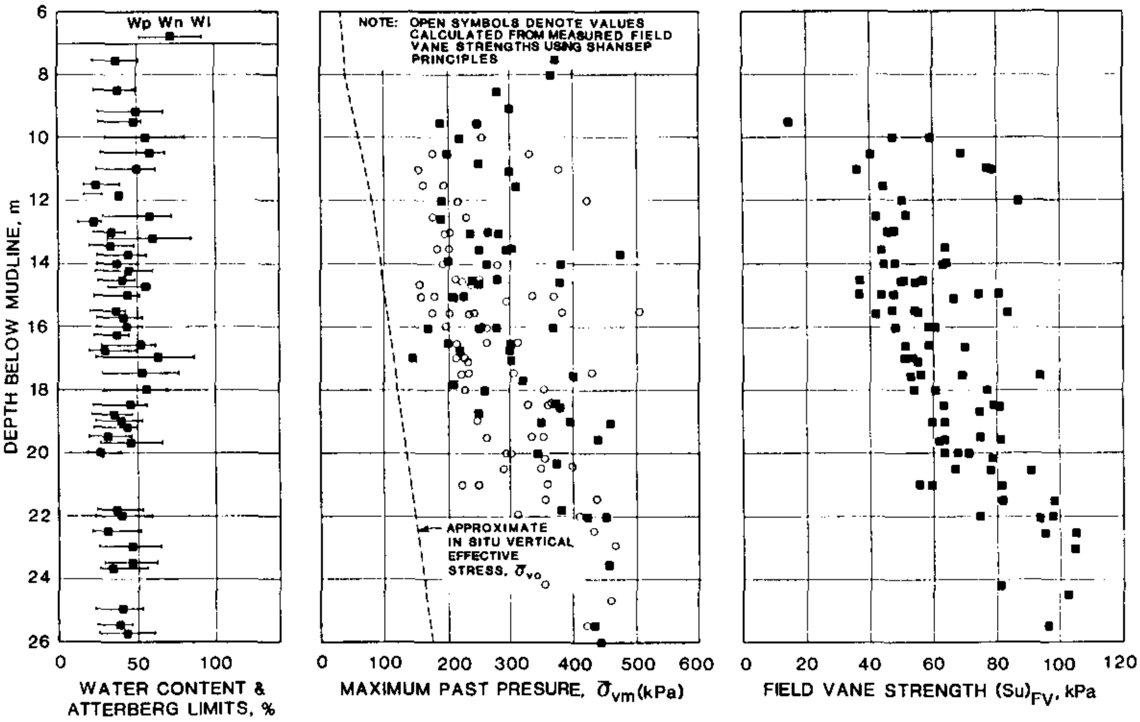
Figure 2 - Typical Seabed Stratigraphy

Chek Lap Kok Investigation

Geophysical traces supplemented by 34 borings and in situ permeability tests, plus careful geologic mapping, were used to characterize the fill material which would be obtained by levelling the island. The bedrock material is granite which has been heavily weathered in many areas. The resulting decomposition penetrates up to 100 m or more at some locations. The completely decomposed granite is a clayey sandy silt, and partial decomposition yields all grades of material between this soil and hard rock. Initial assessment were made regarding the proportions of the various materials that might be expected, what locations might be developed as hard rock quarries, what rock particle sizes could be obtained, etc. It was important that the reclamation design permit the use of all the material that would be obtained from the island. It was also important that the design would not require material that the island could not provide. The proportions of soil, rock and intermediate fill would also have an important influence on the overall bulking factor which would apply to the island borrow and thus the total volume of fill material available.



(a) UPPER MARINE CLAY (MUD)



(b) LOWER MARINE CLAY

Figure 3 - Seabed Mud Characteristics

Test Fill

Preliminary reclamation design clearly showed that filling over the top of the seabed mud would be necessary. The alternative of excavating the mud and replacing it with fill was impractical for reasons of limited fill availability, limited mud disposal capacity, and cost. The in-place mud volume was over 60 million cu m. This volume would typically increase during excavation due to mixing with water.

Preliminary design also showed that filling over the mud and allowing settlements of up to 5 m to take place over several decades was incompatible with an effective airport operation. Measures to accelerate the mud consolidation and limit post-construction settlement were essential.

Vertical drains were the obvious answer and two types of installation appeared practically feasible for the required overwater installation: plastic wick drains and large diameter displacement sand drains. Plastic drains were relatively new and there was not much experience with overwater application, but it appeared feasible. Displacement sand drains had been widely used and the Japanese construction industry had extensive overwater installation capability. Neither of these technologies was proven for the present case of extremely weak clay and the expected vertical compression of up to 50%. It was necessary to prove conclusively that the drains could work in this material and continue to work when subject to large vertical deformation. Inadequate performance could jeopardize the viability of the entire project.

A test fill to evaluate the drain effectiveness was therefore constructed at a location on the west side of Chek Lap Kok, where the bedrock shelved steeply away from the island and the full seabed stratigraphy was present. In addition to investigating drain behavior, the test fill also investigated the viability of filling in layers on the seabed to prevent mud wave formation, and the performance of a seawall founded beneath the mud.

Figure 4 shows the test fill in plan. The central area was 100 m square and was divided into quadrants to investigate drain performance. Two quadrants used a plastic drain (Alidrain) at triangular spacings of 1.5 and 3 m. Another quadrant used 50 cm diameter displacement sand drains at 3 m triangular spacing, and the fourth quadrant had no drains and served as a control.

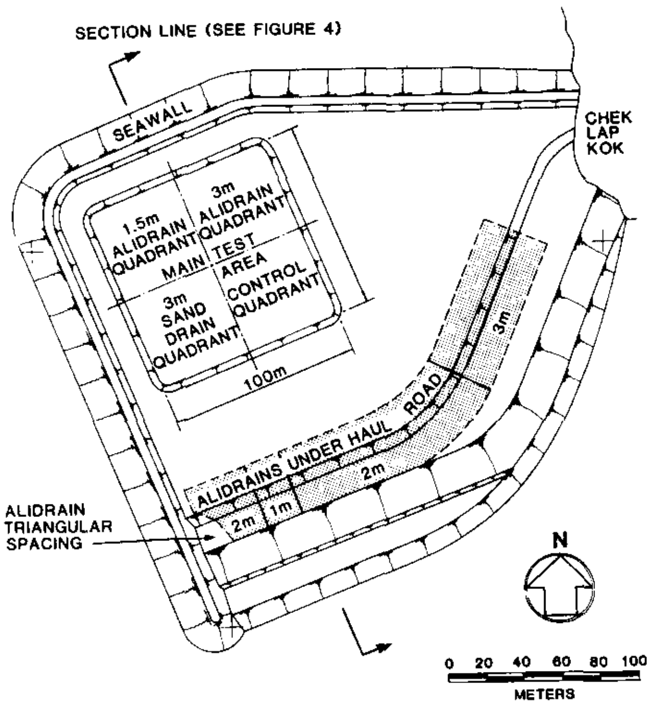


Figure 4 - Plan of Test Fill

Figure 5 shows the sequence of test fill construction. First a trench was excavated in the mud and backfilled to form a base for the seawall constructed on two sides of the fill. Then the "haul road" area was formed as a sequence of fill layers placed over a zone of plastic drains. This is zone of drains provided early indication of their effectiveness and also strengthened an area of the mud to provide adequate stability for the test fill against failure in the direction of the haul road, which was not confined by a seawall. The main test area was then filled and the vertical drains installed under carefully controlled conditions. Settlement and pore pressure dissipation was monitored below each quadrant for the initial fill loading, after which a further lift of fill was placed and monitoring continued.

The test fill was very successful. The haul road filling brought the mud to the point of incipient failure on the southern side, from which the in situ strength was calculated and the mud behavior near failure observed. The northern side of the haul road showed that filling in layers could avoid mud wave formation. The seawall excavation showed that the trench walls would stand near vertical for short periods of time, and provided experience with seawall behavior.

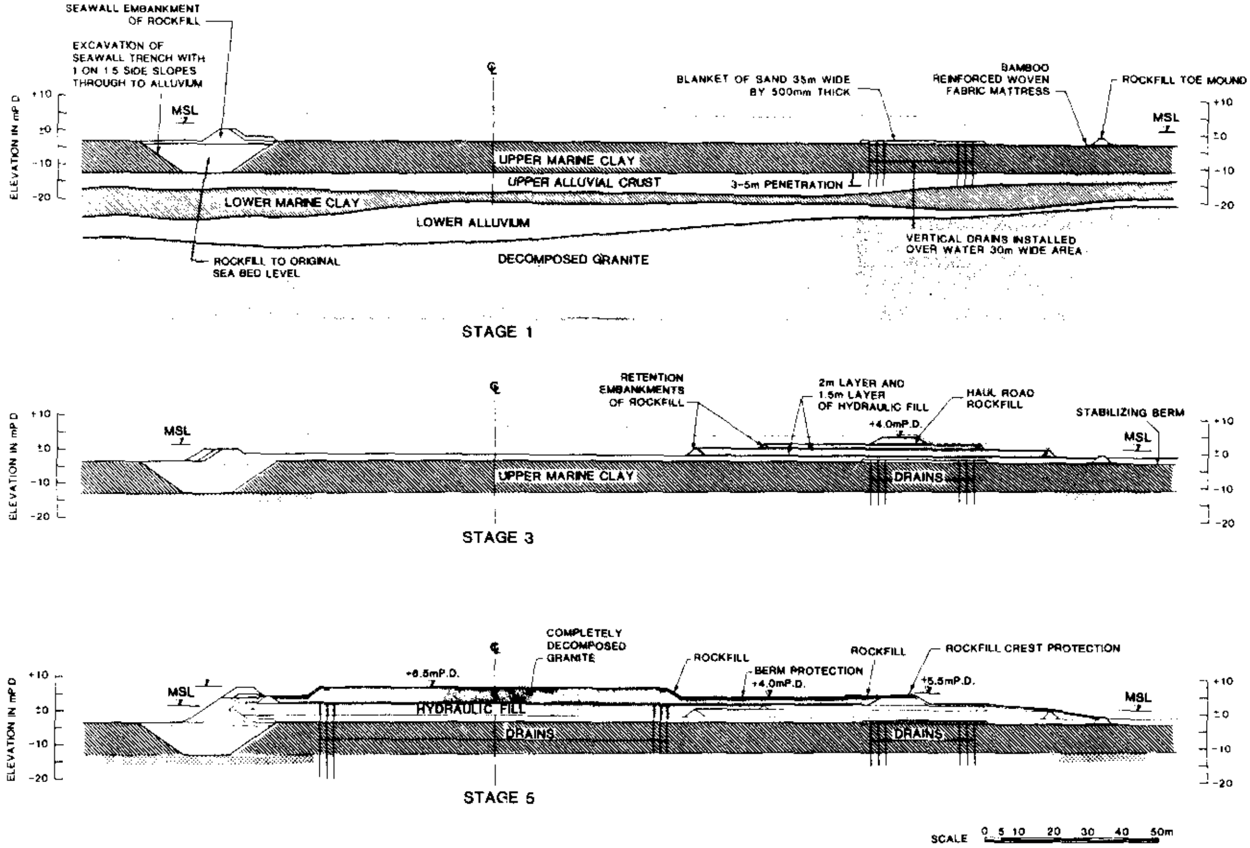


Figure 5 - Test Fill Construction Stages

The main test area provided information regarding drain behavior. Figure 6 shows the settlement profile across two quadrants at various Contract Days (CD) after commencement of the work. Uniform observed settlement across the central portion of each quadrant indicates that one-dimensional conditions representative of a large area of fill had been achieved.

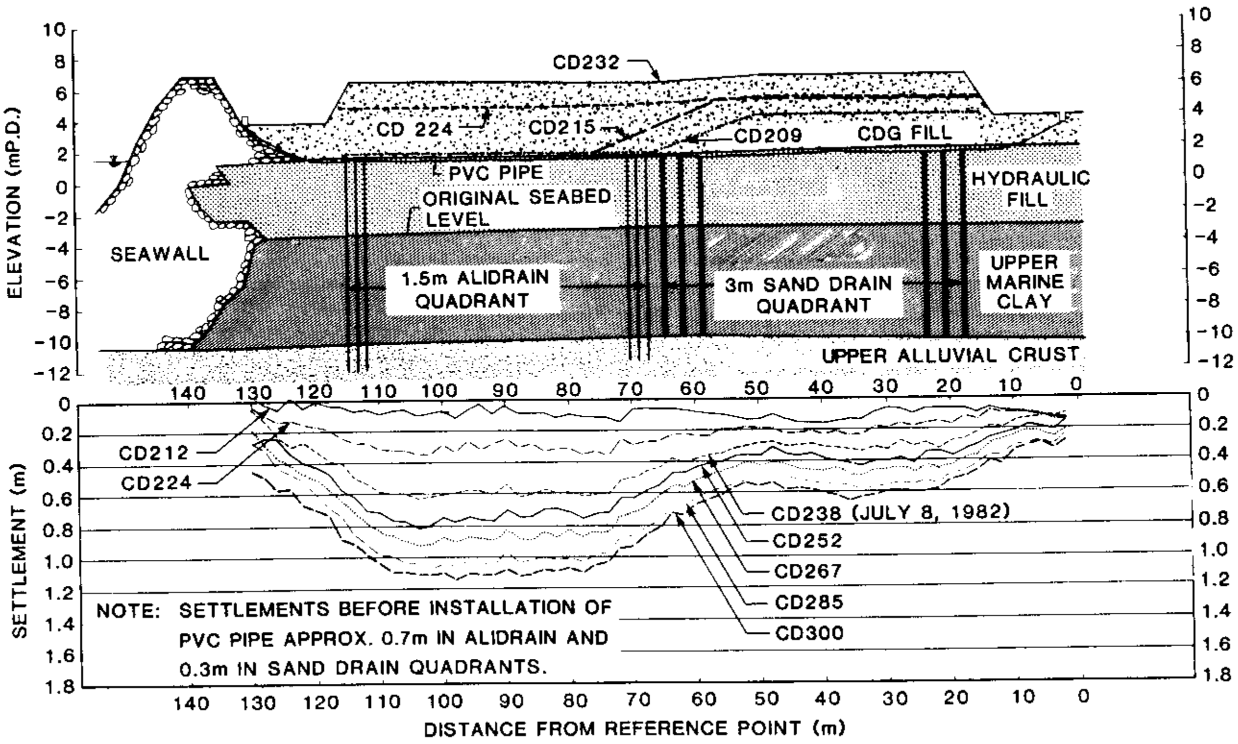


Figure 6 - Settlement Profile Across Main Test Fill

Figure 7 shows settlement of the mud in the various quadrants. The SE quadrant (control area, no drains) settled the slowest, with settlement of the sand drain quadrant (SW) being not much faster. The sand drains were thus found not to be effective in this application, due to the very soft mud becoming fluid and flowing into the drains to block them off.

The plastic wick drains were much more effective, particularly when placed at 1.5 m spacing (NW quadrant). The wicks functioned even after large vertical strains had taken place in the mud; they achieved most of the expected settlement within 12 months of filling. Note, however, that continued long-term monitoring and evaluation of the test fill performance (Ref. 5 - RMP Encon 1988) indicated that the 1.5 m spaced wick drains, which were installed through both the mud and the Lower Marine Clay strata, appeared to be ineffective in the lower clay after the second fill application. This indication may reflect the effect of the higher lateral stresses in the deeper stratum, with the possibility that the drains were approaching their limit of effectiveness. It would not be prudent to extrapolate the good test fill behavior too far in terms of mud thickness, fill loads, etc.

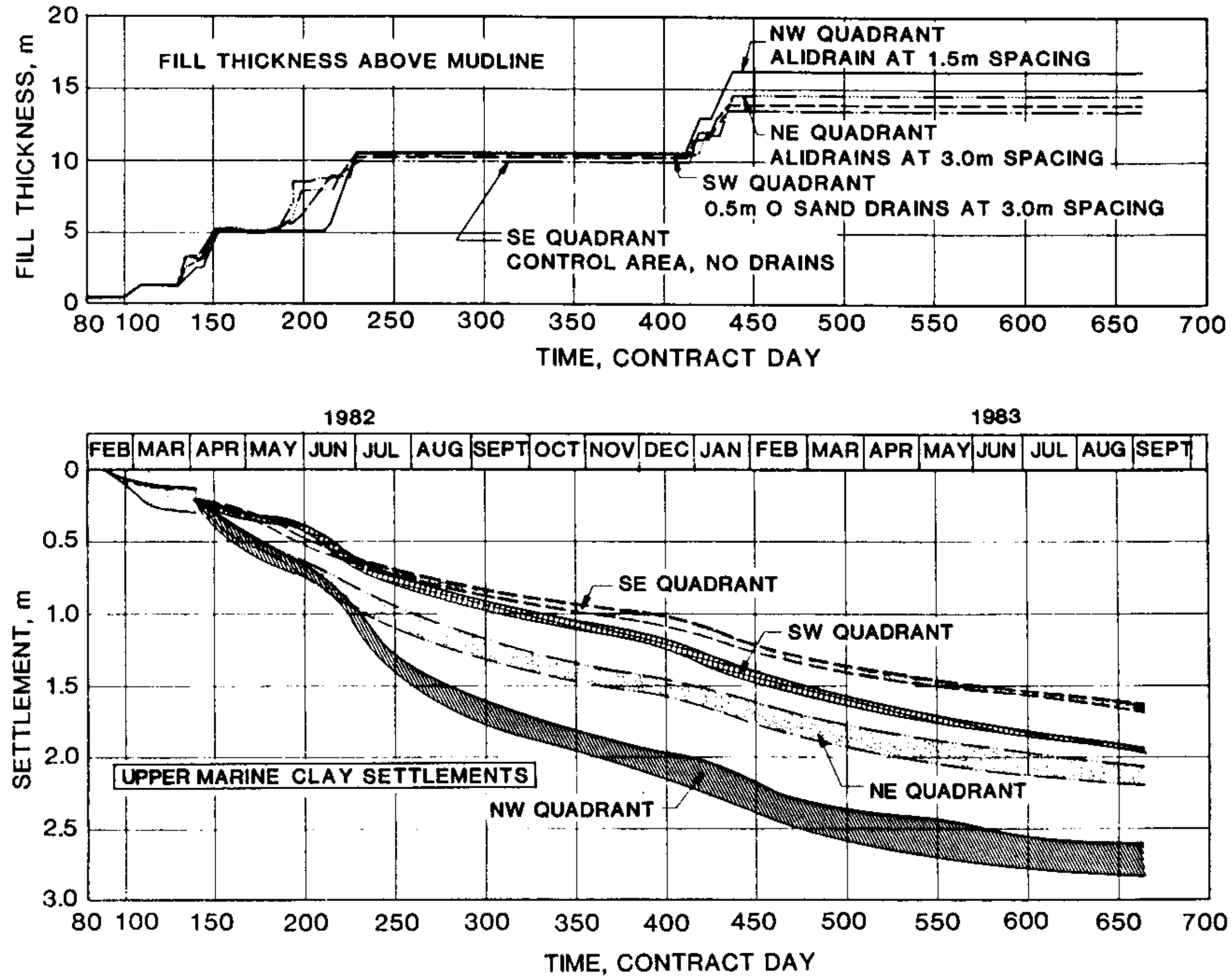


Figure 7 - Settlement of Seabed Mud in Main Test Area

Test Quarry

A test quarry was developed on Chek Lap Kok to provide fill material for the test fill construction and also preliminary information on the borrow material characteristics and availability. A location having hard rock near the surface was selected close to the test fill location. It produced the full range of expected fill materials, including variously decomposed rock. The materials were evaluated for indication of probable proportions of different types of materials, the availability and gradations of hard rock particles, and typical bulking factors. Such indications were, however, only preliminary and more detailed evaluation of these factors was recommended during final detailed design.

5.0 1980's Reclamation Design Recommendations

Based on the results of the above geotechnical studies, the optimum reclamation design to meet the constraints and requirements of the 1980's was as follows.

The perimeter seawalls would be constructed as rubble mounds placed in trenches dredged through the seabed muds and faced with suitably sized rock. They would be designed and built as freestanding structures constructed sufficiently in advance of the reclamation filling to protect it from sea damage e.g. from a typhoon during construction. The limited quantities of mud excavated for the trenches would be dumped in designated marine disposal areas.

The reclamation would be performed by filling over the seabed muds using materials derived from Chek Lap Kok. First a "capping layer" of completely decomposed granite (cdg) would be spread across the seabed to provide a distinct seabed surface and consolidate the top of the seabed mud layer. Approximately 1 m of processed free-draining material would be placed above the cdg and wick drains installed through it from floating installation equipment, using triangular drain spacing of 1.5 to 2 m. Quarry-run material from Chek Lap Kok would then be placed over the drains in approximately 2 m lifts and with a sufficient setback between lift faces to prevent overstressing the mud layer. Underwater filling would be from marine equipment, changing to land equipment as the fill came above the water level. At a depth of about 3 m below the final reclamation surface (approximate El +7m), the quarry run material would be "blinded" in any areas of open-pored texture. The remaining fill would have limitation on maximum particle sizes to facilitate subsequent excavation. It would be placed as compacted fill.

The reclamation design anticipated the work being performed in sequence across the airport site to meet the airport development schedule. Each area of reclamation would be filled to an elevation computed to provide a suitable settlement allowance. An additional surcharge fill of 2 m would be placed above the reclamation fill and left in place for 12 months, during which time the mud would consolidate. Removal of the surcharge for use in another reclamation area would then terminate the consolidation process and reduce secondary compression settlement. With this approach the reclamation program was estimated to require 4 years to complete. It would provide a stable airport platform with minimal settlement expected in the mud. Settlement in the

Lower Marine Clays would continue for a longer period but be relatively small and acceptable.

The airfield elevations and grades were designed to meet appropriate aeronautical and civil engineering (drainage) standards, while also providing a balanced earthworks project. The intention was to establish a material balance for an assumed reasonable lower limit of bulking factors, and have an overflow spoil area adjacent to the reclamation to accommodate the expected surplus of fill material resulting from actual bulking factors, which were expected to be higher than those assumed.

6.0 1990's Geotechnical Constraints

As noted, the 1980's design work was suspended in 1983 and reactivated in about 1990. In the interim the status of Hong Kong had changed significantly and a new set of planning constraints and requirements had developed. Significant changes in geotechnical constraints had also occurred. Most significantly, plastic wick drains had been used in large scale reclamations, and substantial quantities of marine sand had been discovered at various locations around Hong Kong. However this sand was frequently overlain by mud thicknesses up to 20 m. Significant changes in the geotechnical constraints as the 1990's design work progressed were thus as follows:

- A considerably larger reclamation area (938 ha compared with about 600 ha for the previous design) was required. This change moved the reclamation into deeper water and over greater mud thickness (up to 20 m).
- A balanced earthworks project was no longer a requirement, with marine sand available to make up any fill shortfall.
- The airport was to be operational by mid-1997.

7.0 Changes in Reclamation Design and Contracting

The new geotechnical constraints plus a continuing erosion of the available construction period, necessitated radical changes in reclamation design. Most significant of the new constraints was probably the schedule. Reclamation construction is now anticipated to commence in the latter part of 1992, with much of the work to be completed by the end of 1993 if the 1997 opening is to be achieved. The available construction period has thus been radically reduced.

This schedule virtually prohibits the use of techniques to reclaim over the mud, at least in major portions of the site. There is simply not sufficient time to allow for consolidation, even using wick drains. Accordingly, the Airport designers decided to perform the reclamation by first removing all the mud and making up the fill shortfall using marine sand. The ramifications of this change are substantial. The mud quantity at the Airport site is 80 million cu m or more. Large mud overburden quantities will also need to be removed at the marine sand borrow sites. Disposal of the excavated mud is reported to require barge transportation for a distance of 75 km. About 80 million cu m of sand fill will be needed in addition to the product of Chek Lap Kok, to make up the volume of mud excavation. The design has thus shifted from a relatively complex procedure of reclamation over the mud, to a simpler reclamation technique but involving greatly increased quantities of work.

Also significant is the contract form used for the construction. Normal Hong Kong practice is to perform extensive engineering studies and produce a detailed design and quantities. The contractor bids this design and is paid on measured quantities, with the Engineer maintaining the responsibility and control of the design and its compliance. For the airport reclamation, a different approach has been adopted. The bidding contractors were provided with geotechnical data (borings, soundings, geophysical profiles, etc.) but only limited engineering interpretation. They were also given the limits of the work and the performance requirements. They then made their own estimates of quantities and decisions regarding marine borrow areas, mud disposal sites, expected fill material types, quantities and characteristics, etc. The bid was thus essentially a lump sum to achieve the required reclamation product, with the contractor arguably responsible for the effectiveness of major elements of what would conventionally be considered the "design".

These design and contracting procedures are intended to achieve a massive construction program in very little time and with reduced chance of cost overruns, by using relatively simplistic design and contracting approaches. Presumably the urgency of the project justifies any increased costs and risks involved in taking this approach. If successful it will be a spectacular achievement, in keeping with Hong Kong's reputation and history.

Acknowledgements

The 1980's geotechnical studies were performed by Dames & Moore, operating as part of an RMP Encon design team. Roger Foott was geotechnical Project Director. Roy Bell developed the test fill design and was in charge of instrumentation. Many geotechnical personnel contributed to the success of the studies, particularly Demetrious Koutsoftas and Leo Handfelt. Any opinions expressed or conclusions reached in this paper are entirely those of the writers.

References

1. Foott, R., Koutsoftas, D.C., and Handfelt, L.D. "Test Fill at Chek Lap Kok, Hong Kong," Journal of Geotechnical Engineering, ASCE, Vol. 113, No. 2, Feb. 1987, pp. 106-126.

2. Handfelt, L.D., Koutsoftas, D.C., and Foott, R. "Instrumentation for Test Fill in Hong Kong," Journal of Geotechnical Engineering, ASCE, Vol. 113, No. 2, Feb. 1987, pp. 127-146.

3. Koutsoftas, D.C., Foott, R., and Handfelt, L.D. "Geotechnical Investigations Offshore Hong Kong," Journal of Geotechnical Engineering, ASCE, Vol. 113, No. 2, Feb. 1987, pp. 87-105.

4. Ladd, C.C., Foott, R. "New Design Procedure for Stability of Soft Clays," Journal of Geotechnical Engineering Division, ASCE, Vol. 100, No. GT7, July 1974, pp. 763-786.

5. RMP Encon, "Final Report, Check Lap Kok Airport Master Plan Review," Civil Aviation Department, Hong Kong, Oct. 1988.