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Reclamations and the Interpretation of Marine Geology in Hong Kong: A Comprehensive Approach

Abstract

Although reclamation of land from the sea has always been an aspect of Hong Kong's development, in the last decade the scale of reclamation has increased dramatically fueled by the initiation in 1989 of the Hong Kong Airport Core Programme. This included the construction of the 1248 ha airport platform at Chek Lap Kok and reclamations at West Kowloon, Central and elsewhere in Hong Kong.

These recent reclamations have stimulated a variety of site investigation techniques and methods. The extensive surveys undertaken for locating fill resources has benefitted the interpretation of the marine geology of Hong Kong by providing a widespread grid of reflection seismic lines with associated boreholes and CPTs. This has enabled the stratigraphy to be based on a regional scale appraisal and allowed the geological interpretations of relatively small reclamations to be set in the context of the surrounding geology. This is an important parameter for functions such as drainage pathways or sea wall design and construction whose effects impinge beyond the boundaries of a reclamation.

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INTRODUCTION

Physically Hong Kong is characterised by hilly and mountainous terrain; flat land has always been at a premium, especially near the coast where the major centres of population have grown. The reclamation of land from the sea has therefore been an integral com-

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Ceri James

ponent of Hong Kong's economic growth since the beginning of the century (Martin *et al.*, 1997). However in the last ten years the scale of reclamation has increased dramatically with the initiation in 1989 of the Hong Kong Airport Core Programme (Lam, 1998) which included the construction of the 1248 ha airport platform at Chek Lap Kok and reclamations at West Kowloon, Central and elsewhere in Hong Kong. By 1996 the total area reclaimed in Hong Kong was about 6000 ha and comprised around 5% of its land area. Reclamations are set to continue in the future with planned developments such as major container ports near Lantau Island.

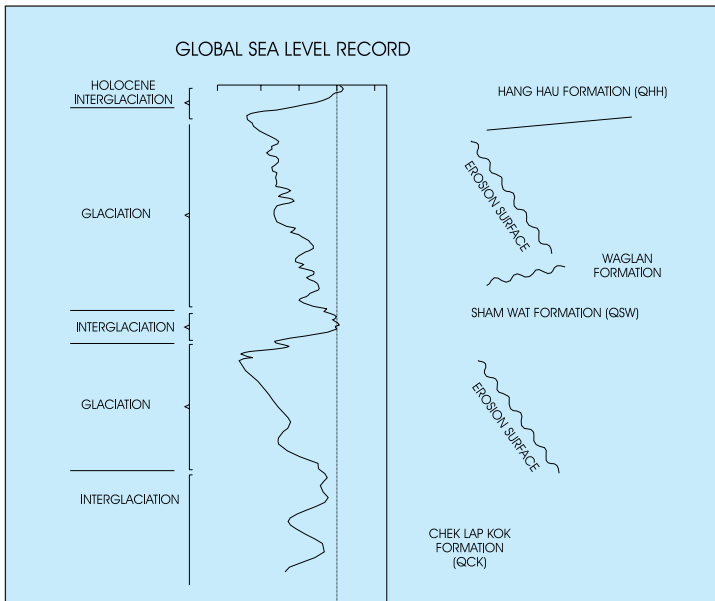


Figure 1. Quaternary sea levels (after James, 1993 and Fyfe et al., 1997).

The enormous scale of these recent reclamations in terms of infrastructure design and construction has stimulated a variety of site investigation techniques and methods which have been imaginatively deployed. The wealth of new site investigation data available, not only from localised reclamation sites, but also from the extensive surveys undertaken for locating fill resources has benefitted the interpretation of the marine geology of Hong Kong by providing a widespread grid of reflection seismic lines with associated boreholes and CPTs. This has enabled the stratigraphy to be based on a regional scale appraisal and allowed the geological interpretations of relatively small reclamations to be set in the context of the surrounding geology. This is a very important parameter for functions such as drainage pathways or sea wall design and construction whose effects impinge beyond the boundaries of a reclamation.

RECLAMATION DESIGN AND CONSTRUCTION

The need to design and assess the behaviour of reclamation platforms both during and after construction has long been acknowledged in Hong Kong.

To model this behaviour geotechnically requires a comprehensive analysis and understanding of the geology at reclamation sites. A framework based on geological interpretation of the site investigation data, which should be as extensive as possible, has to be developed for each reclamation, built up of the various formations and units of sediment and rock which underlie the platform.

Such an interpretative framework can indicate the spatial distribution, both vertical and lateral, of all the geological formations. It is a fundamental building block which should underpin all reclamation design and construction and provide critical information and data including:

- distribution of soft compressible sediment;
- base levels for dredging soft sediment from platform sites;
- distribution of over-consolidated sediment such as palaeosols, which may influence ground movement and control the magnitude and rate of settlement;
- identification of drainage pathways below the reclamation through sand and gravel horizons;
- identification of platform areas which may need ground treatment such as surcharge or dynamic compaction;
- identification of potential problem areas for settlement and stability at seawalls and within the reclamation platform;
- identification of platform areas which should be subject to monitoring by instrumentation such as inclinometers, extensometers and piezometers;
- level of top of decomposed rock and its thickness; this level may also equate with the base of superficial deposits in most reclamations; and
- level of top of Grade III – moderately decomposed rock.

The geological interpretation therefore provides a basis for the assessment of platform performance in terms of total and differential settlement. With regard to dredging and fill requirements it is important in the calculation of material volume, both for any soft sediment dredged from reclamation sites and fill material, to create a platform.

DEVELOPING GEOLOGICAL INTERPRETATIONS

In developing a geological interpretation for a reclamation platform, the aim is to produce a model of the three-dimensional geometry and lithology of the superficial deposits which underlie a site, and the form of the rockhead surface on which they sit. Superficial deposits in this context comprise unlithified, transported material of sedimentary origin deposited within the Quaternary Period, a time span covering the last two million years. Superficial deposits do not include "rock" which may locally have weathered in situ to unlithified deposits.

A number of factors influence the processes of sedimentary deposition and therefore have to be reconciled within a geological interpretation. These are:

- climatic changes during the Quaternary Period;
- global sea level oscillations reflecting these climatic changes;
- morphology of rock outcrops in the reclamation area;

- alluvial, estuarine and marine erosion and deposition; and
- hydrodynamic conditions.

On a regional and global scale the most important factor determining the disposition of the superficial deposits is Quaternary climate change. During the Quaternary, the climate fluctuated between glacial and interglacial cycles. Major oscillations in sea level were associated with these climatic changes. Figure 1 shows the climatic state and global sea level curve for the Late Quaternary.

In Hong Kong these changes in sea level and climate had a profound influence on the geological development of nearshore coastal areas in which reclamations are constructed. During glacial periods, all areas of Hong Kong which are presently beneath the sea became emergent. Exhumed landscapes were formed in superficial deposits, crossed by rivers and streams eroding and depositing sediment. Vegetation covered the landscape, underlain by extensive soil profile development. With subsequent rises in sea level during interglacial periods, landscapes became inundated and modified by the sea. However, soil profiles may remain as palaeosols beneath younger superficial deposits. With rising sea levels upstanding parts of old land surfaces formed of unconsolidated material could be eroded by wave action, cutting the surface on which subsequent estuarine and marine sediments were deposited.

The sequence of events which mark the depositional and erosional history of the superficial deposits of Hong Kong would therefore appear to be complex and

difficult to interpret. However, with a comprehensive site investigation programme and knowledge of the history of sedimentation during the Quaternary in Hong Kong derived from a regional perspective, an interpretation can be constructed to produce a geological framework for reclamation design and construction.

METHODS OF INVESTIGATION AND DATA

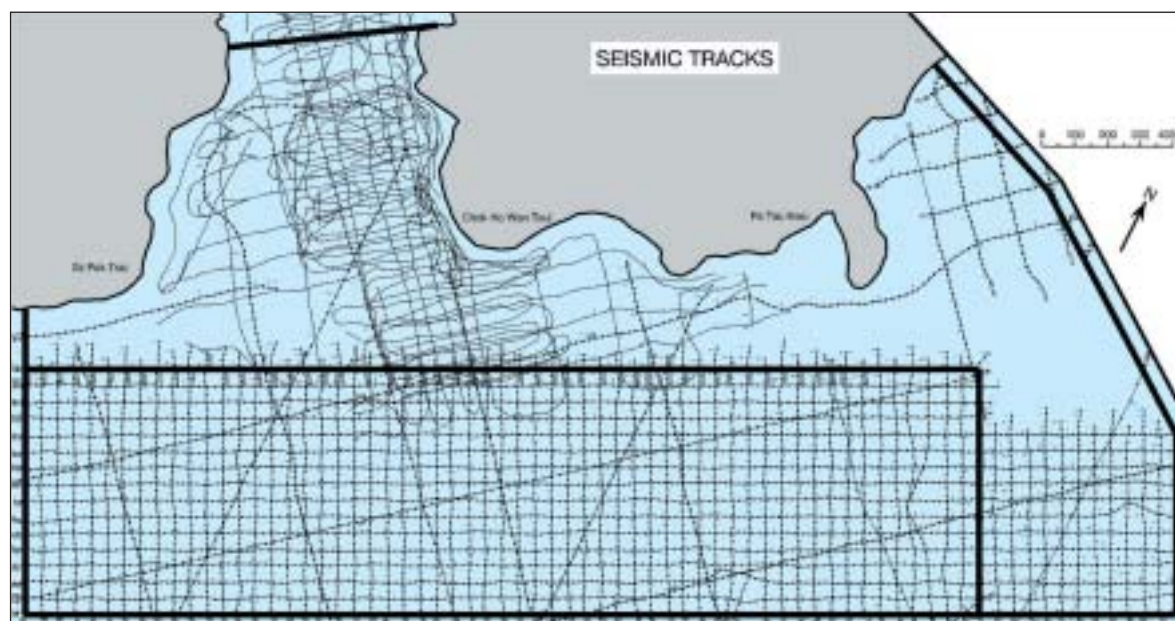
An important element in the quality of a geological interpretation for any reclamation is the quality and extent of site investigation undertaken.

Survey grid

The first imperative is a survey grid of high resolution reflection seismic records, generally at a maximum spacing of 50 to 100 m. The grid should be rectangular with one axis aligned along a principal feature of the reclamation such as a sea wall or runway. Additional seismic lines should be run along the alignment of any major structures including those which deviate from the grid plan. Figure 2 includes the tracks of seismic surveys undertaken in the Penny's Bay area of Lantau Island and the proposed site of Container Terminals 10 and 11 (James, 1994). It illustrates the difference between a modern survey, undertaken in 1994, with a rectangular grid at 50 m spacing and an older, 1981 survey within Penny's Bay itself, which has an irregular, spaghetti-like plan with no clearly defined individual lines and are therefore more difficult to interpret.

Reflection seismic surveys of Hong Kong reclamations principally employ a boomer acoustic source (Ridley

Figure 2. Seismic surveys at Penny's Bay (James, 1994).



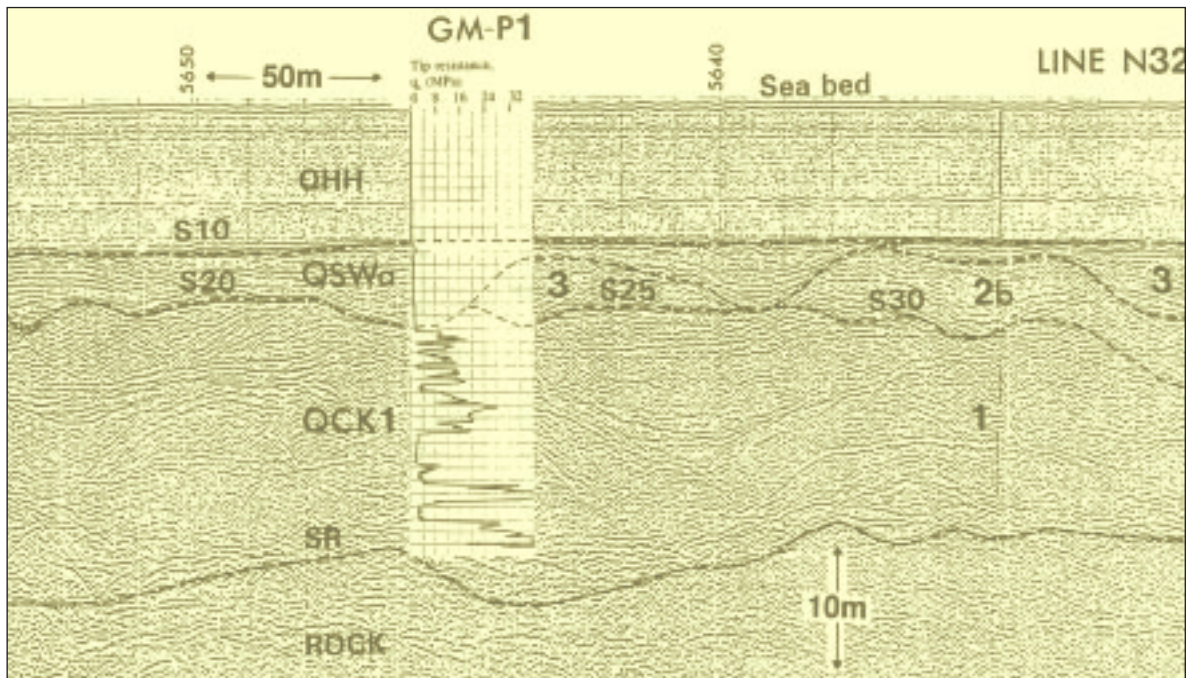


Figure 3. Interpreted seismic record and CPT trace (James *et al.*, 1994).

Thomas *et al.*, 1988). Depth of penetration beneath the sea surface is normally about 100 m, an adequate depth to reach the base of superficial deposits at most coastal reclamation sites. The boomer normally gives excellent resolution within superficial deposits allowing detailed interpretations to be undertaken. Because of the nature of the predominant solid rocks in Hong Kong, mainly granites and volcanics in various states of decomposition, acoustic impedance contrasts are very low and this leads to poor penetration and resolution within these solid rocks, in marked contrast to the normally well resolved superficial deposits.

Boreholes and CPTs

A thorough interpretation will produce seismic records annotated with picked reflectors (Figure 3) delineating the formations and units which have been interpreted. In an ideal site investigation the seismic interpretation should precede any borehole or CPT (cone penetrometer test) survey undertaken to produce lithological and geotechnical data. To calibrate and confirm the seismic interpretation, boreholes and CPTs should be sited to give the optimum amount of data for all formations. They should always be located directly on seismic lines, preferably at the crossover of two lines, allowing the borehole or CPT data to be traced in four directions away from the location.

The number of boreholes and CPTs undertaken for a site investigation will depend on the area covered by the reclamation, the complexity of the geology and the structures to be built on the reclamation, as well as the

finance available. For example, the marine geological interpretation for the new airport at Chek Lap Kok (James *et al.* 1994), which covered an area of about 938 ha, utilised 236 boreholes and 404 deep CPTs.

The vast majority of these were sited for engineering and construction criteria rather than geological and only a minority are located exactly on seismic lines.

Calibration of the geophysical data

The final part of any investigation is the calibration of the geophysical data from seismic and CPT sources. The physical and lithological results from borehole logging and any specialist input from palaeontologists, petrologists, geotechnical engineers and other specialists is used to produce a comprehensive geological interpretation with delineated formations and units described in detail and illustrated with isopach and base level maps, and cross sections along the major structures such as sea walls and runways.

MARINE GEOLOGY AND STRATIGRAPHY

The offshore superficial deposits of Hong Kong mapped by the Hong Kong Geological Survey have previously been subdivided into two formations, the Hang Hau Formation and the Chek Lap Kok Formation, based on lithological and palaeontological evidence from boreholes and on interpretations of seismic character (Strange and Shaw, 1986; Langford *et al.*, 1989). The subdivision has a chronological element,

with the Hang Hau Formation being younger than the Chek Lap Kok Formation.

A two-fold subdivision of the offshore superficial deposits has long been recognised in geological and geotechnical investigations in Hong Kong, with the terms "alluvium" and "marine deposits" given to sediments which could nominally be ascribed to the Chek Lap Kok and Hang Hau formations respectively.

From the interpretation of seismic records across the whole offshore area of Hong Kong a more complex series of units than a simple twofold subdivision has emerged. Two new formations, the Waglan Formation and the Sham Wat Formation have been recognised (Fyfe *et al.* 1997) which sit between the Chek Lap Kok Formation and the Hang Hau Formation (Table I).

Waglan Formation

The Waglan Formation is confined to the south-eastern waters of Hong Kong and therefore is likely to be of no consequence in coastal reclamations.

Hang Hau Formation

The Hang Hau Formation (QHH) consists of relatively homogenous very soft to soft, greenish grey silty clay. Undrained shear strengths range from <3 kPa to 20 kPa and SPT N values are generally zero. Moisture content is high, around 100%. It is the most widely developed of the superficial deposits in Hong Kong and generally forms a blanket of sediment over all the underlying superficial deposits and rock and has a well-developed unconformity at its base. In many coastal areas the base of the formation is deeply channelled with sediment up to 29 m thick (Figure 7). The delineation of these soft sediment channels is important to the design of a reclamation. The form of this basal surface would be crucial as a base level for dredging in dredged reclamations and also in estimating settlement rates and areas of ground treatment for drained reclamations. A tight grid of seismic lines enables the thickness and geometry of the soft mud to be delineated for a reliable reclamation design.

The Sham Wat Formation (James, 1993) is of limited extent in western and southern waters, but was identified beneath the platform of the new airport at Chek Lap Kok (James *et al.*, 1994) (Figure 6). It comprises a generally firm grey silty clay and is firmer, <40 to 60 kPa, and has a lower moisture content, <80%, than the overlying Hang Hau Formation.

Chek Lap Kok Formation

The Chek Lap Kok Formation is the most lithologically, seismically and geotechnically variable of the formations within the superficial deposits of Hong Kong. In many areas the formation can exhibit abrupt variation in sediment type both laterally and vertically and this is corroborated by an absence of distinctive seismic

Table I. Offshore Quaternary stratigraphy of Hong Kong.

Formation	Age
Hang Hau	Holocene
Waglan	Late Pleistocene
Sham Wat	Late Pleistocene
Chek Lap Kok	Pleistocene

reflectors and sequences which can be traced extensively on a regional scale. Where seismic lines are greater than 500 m apart it is difficult to produce continuity and interpret distinctive sequences and units within the Chek Lap Kok Formation. However, at some reclamation sites, such as the new airport, where the seismic grid is at a spacing of 100 m or less, characteristic seismic reflectors and sequences can be deduced from the interpretation of seismic records which allows the Chek Lap Kok Formation to be subdivided into units (Figure 4).

RECLAMATION GEOLOGY

The regional stratigraphy outlined above has been used as the basis for the detailed interpretation of the geology of two reclamation sites in Hong Kong. Firstly, at the site of the Hong Kong International Airport at Chek Lap Kok (James *et al.*, 1994) and secondly, in the area of Penny's Bay and the proposed sites of Container Terminal 10 and 11 (James, 1994).

Hong Kong International Airport

The James *et al.* (1994) interpretation at Chek Lap Kok was commissioned by the Airport Authority in July 1993. The purpose of the study was primarily the same criteria as those outlined above in the reclamation design and construction section with an emphasis on providing the Airport Authority with a geological framework as a backbone to the design, construction and monitoring of the platform. Although the interpretation was not used in the original design exercise for dredging at the reclamation, it was intended to be used by the Airport Authority to clarify dredge levels and highlight particular areas which might require modifications to the proposed dredging operations (Plant *et al.*, 1998).

The soft mud of the Hang Hau Formation (marine mud) is highly compressible and traditional practice up to the late 1980s in Hong Kong had been to reclaim over the soft marine mud (Martin *et al.*, 1997) with ground treatment, usually by vertical drains, to accelerate consolidation of the mud. This "drained" alternative was considered in the design options at Chek Lap Kok but the disadvantages included the relatively large amount

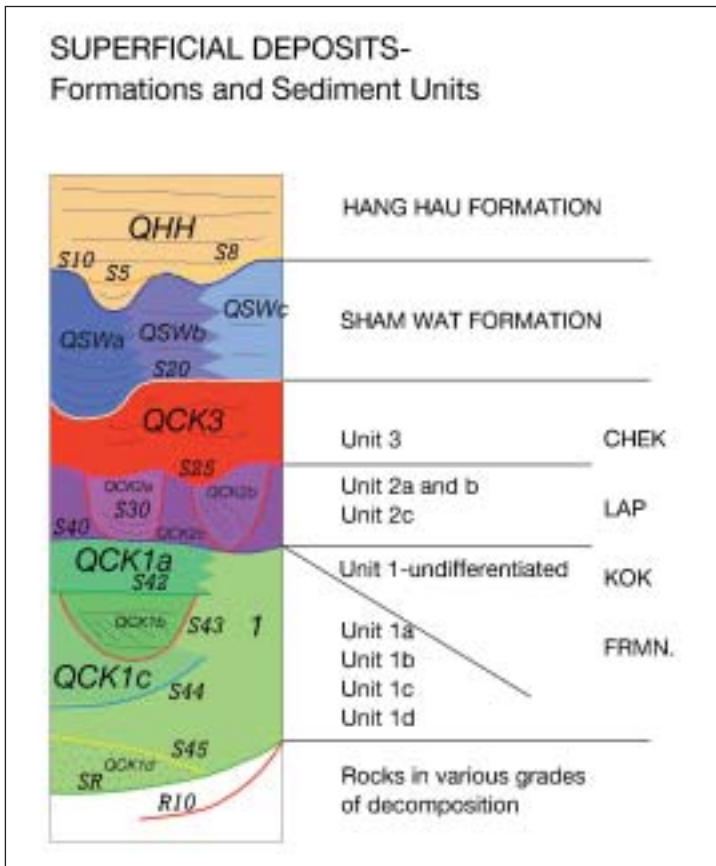


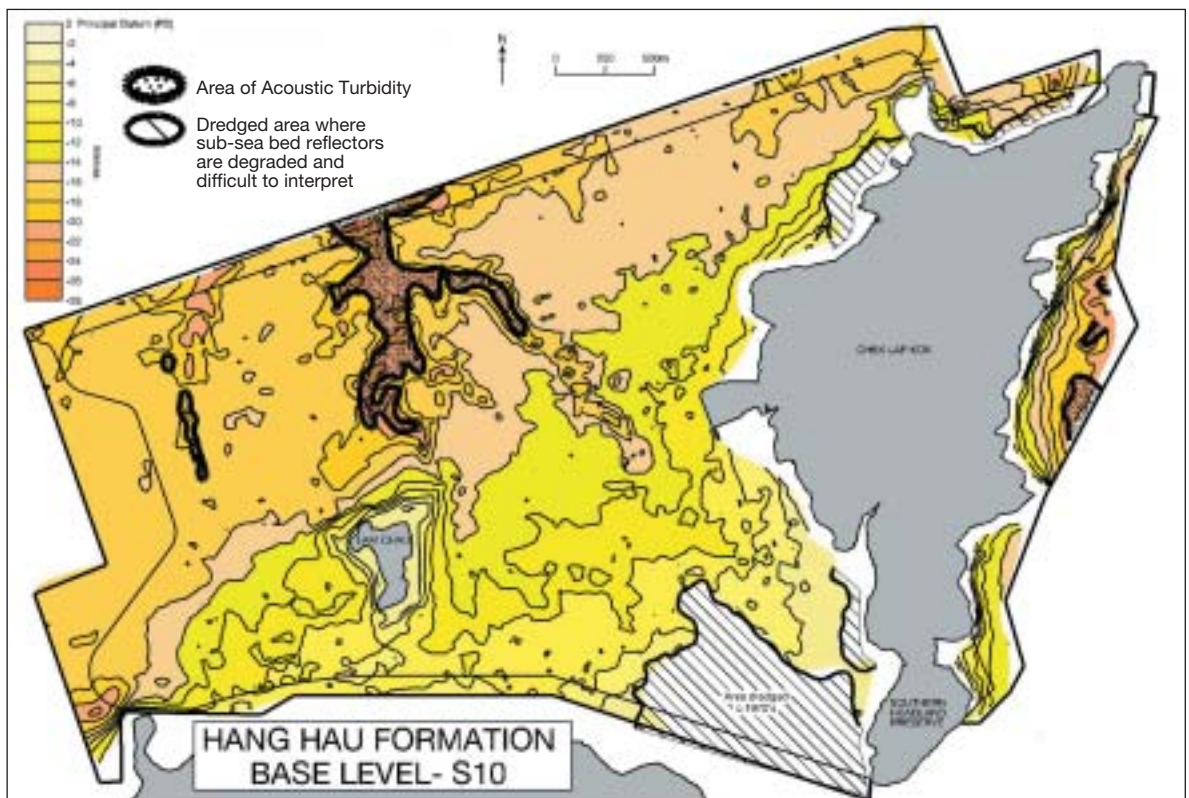
Figure 4. Stratigraphy at Hong Kong International Airport (James et al., 1994).

Figure 5. Hang Hau Formation base level at Hong Kong International Airport (James et al., 1994).

of settlement and the fact that it would have occurred too slowly, plus the assumption of a degree of uncertainty about the length and rate of consolidation and the practicality of surcharging. Although the “dredged” option meant a larger volume of reclamation fill was required compared to the “drained” option to replace the dredged soft mud, it was chosen because of the short time available for construction before the airport was to open (Plant *et al.*, 1998).

The Hang Hau Formation forms a blanket of sediment beneath the sea bed over most of the airport site. It covers all the underlying older superficial deposits and its base is a well developed erosion surface or unconformity. Although much of the basal surface is almost planar there is a small network of channels which vary in amplitude from less than 3 m to about 10 m. A few of these channels (Figure 5) are also marked by acoustic turbidity on seismic records formed by the presence of gas within the mud. Elsewhere on seismic records the base of the formation is marked by a distinctive, well-developed, high amplitude, continuous reflector (Figure 3).

The base of the Hang Hau Formation is generally well seen and distinguishable as a good basal reflector on seismic records and over much of the reclamation this should equate with the dredge level. An area where seismics cannot be used to determine the base of the Hang Hau Formation is where the reflectors are obscured on seismic records by acoustic turbidity; these



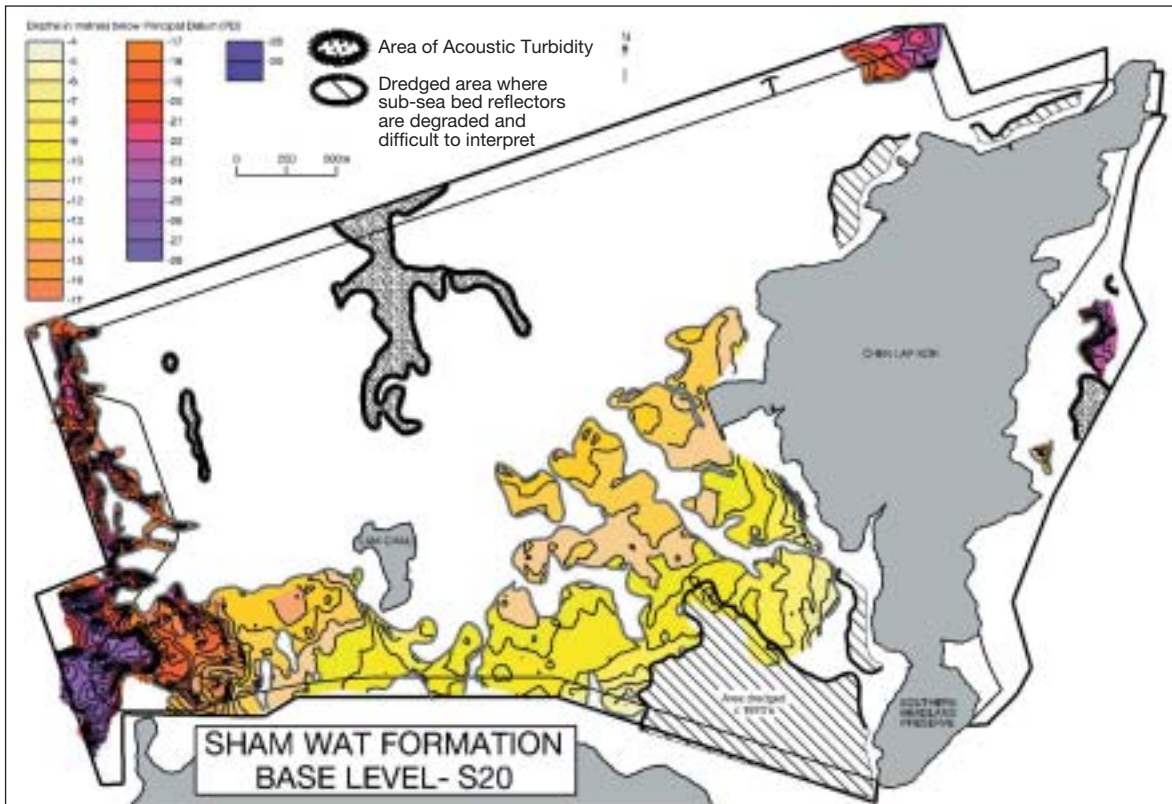
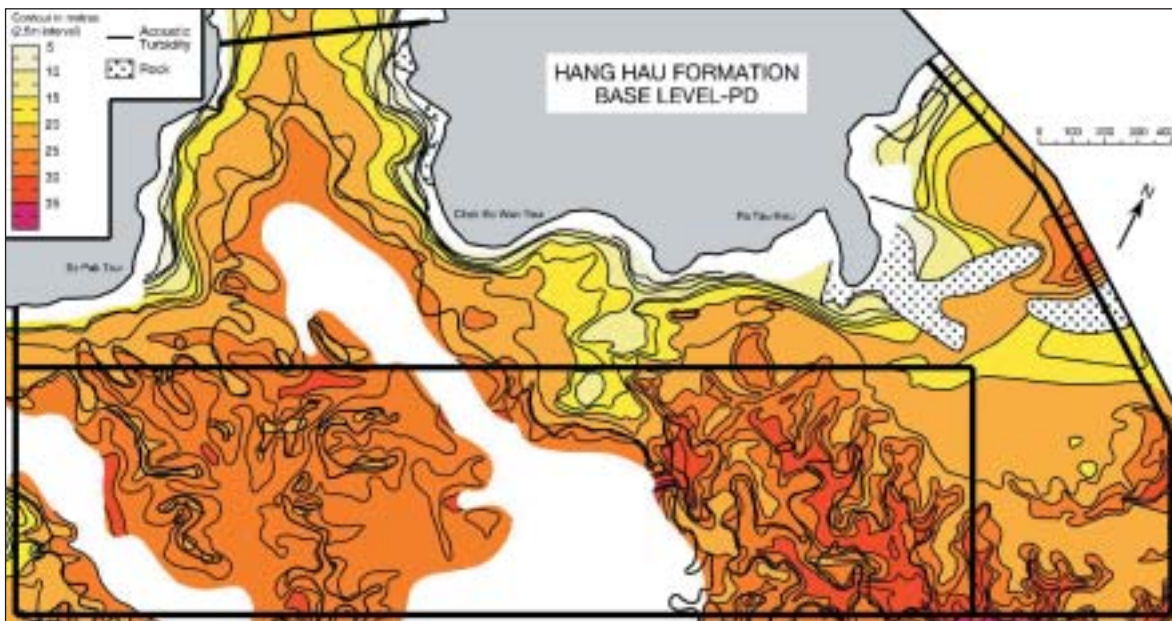


Figure 6. Sham Wat Formation base level at Hong Kong International Airport (James et al., 1994).

areas are not extensive at Chek Lap Kok. To resolve the dredge levels, a suite of 3202 dredge level CPTs were undertaken across the site and the "Base of Unsuitable Material" (BUM), i.e. the material to be dredged, was determined by the designers for each CPT location (Plant et al., 1998). Typically the marine mud of the Hang Hau Formation has a net CPT tip resistance (q_{net})

of less than 500 kPa and this was taken as a representative value for the soft mud. In addition, to avoid interpreting thin sands within the muds as the BUM, which would have $q_{net} > 500$ kPa, the criterion that net tip resistance should exceed 500 kPa for a depth of at least 500 mm below the BUM was added. The BUM interpretation from the CPTs was also corroborated by

Figure 7. Hang Hau Formation base level at Penny's Bay (James, 1994).



reference to the seismic records and any disparities were resolved within the design process.

During offshore regional mapping by the Hong Kong Geological Survey around Lantau Island a distinctive sequence was recognised on seismic records beneath the Hang Hau Formation. Borehole and CPT evidence confirmed the sequence had distinctive physical as well as geophysical characteristics and it was formally recognised as the Sham Wat Formation (James, 1993)

To the unfamiliar it is easy in borehole cores to misinterpret the Sham Wat Formation as the Hang Hau Formation. They are both predominantly grey silty clay, although the Sham Wat Formation is generally firmer, <40 to 60 kPa, and has a lower moisture content, <80%, than the overlying Hang Hau Formation. However, the Sham Wat Formation does have a distinctive character on seismic records with a strong reflector at its base and contains continuous, sub-parallel, undulating reflectors which drape over channel interfluvies and down into channel deeps.

West of the airport site at Chek Lap Kok, the Sham Wat Formation infills a major channel system which encroaches beneath the platform from the south-west (Figure 6). Its base in the deepest channel is at -29 mPD with a thickness of sediment up to 18 m, and its tributaries branch north-west along the western margin of the platform.

In this area of the platform the Sham Wat Formation also has a characteristic CPT signal compared to the overlying Hang Hau Formation. At the interface between the two formations there is generally an increase of 200 to 300 kPa in the value of net tip resistance (q_{net}) at the top of the Sham Wat Formation. Typical values for q_{net} are 500 to 800 kPa increasing gradually with depth to 1000 kPa at the base of the formation. The higher values of tip resistance, pore pressure and skin friction for the Sham Wat Formation compared to the overlying Hang Hau Formation indicates a greater degree of consolidation has occurred within the sediments of the Sham Wat Formation. Across most of this area there is a good correlation between the CPT response for the Sham Wat Formation and its interpreted sequence on the seismic records.

The recognition and delineation of the form and extent of the Sham Wat Formation was an important factor in aiding the design and construction of the western area of the platform beyond Lam Chau.

The sea wall at the western end of the southern runway overlies a Sham Wat Formation infilled channel and the initial design dredge levels for the sea wall in this area were the deepest for the site at -29 mPD and entailed dredging the Hang Hau Formation and the Sham Wat Formation. Calculations were undertaken to

evaluate a higher dredge level within the Sham Wat Formation and although settlement would be higher, a change to a base level of -22 mPD was considered acceptable and adopted as the deepest dredging limit (Plant *et al.*, 1998).

In total almost 69 Mm³ was dredged from the platform area, predominantly soft mud of the Hang Hau Formation and some soft to firm mud of the Sham Wat Formation and minor sediment from the Chek Lap Kok Formation. The average thickness of the dredged mud was 7.5 m with the thickest sequence dredged, at 21 m, within the major gas filled channel of the Hang Hau Formation which ran across the northern runway and northern sea walls (Figure 5) (Plant *et al.*, 1998).

The extensive seismic, borehole and CPT data set enabled an extensive appraisal to be undertaken of the Chek Lap Kok Formation and produced a comprehensive stratigraphy for the formation, and in greater detail than had previously been produced in Hong Kong reclamations. The Chek Lap Kok Formation has been subdivided into three units (James *et al.*, 1994), numbered QCK Unit 3, QCK Unit 2, QCK Unit 1 (Figure 4). Two of the units (QCK Unit 1 and QCK Unit 2) have been further divided. The subdivision has been based on lithological and seismic criteria, such as continuity of reflectors marking erosional events, and units with distinctive seismic signatures. The formation includes firm to stiff palaeosols, channel sands, and soft to firm estuarine clays. It is this formation that provides the platform on which the reclamation fill has been placed.

The mapping of the various units within the formation was a significant contribution to the design and construction of the reclamation as it proceeded and continues to be relevant to the monitoring of platform performance.

Penny's Bay and the site of Container Terminals 10 and 11

Penny's Bay lies at the south-eastern end of Lantau Island at the opposite end of the island to the site of the airport at Chek Lap Kok. The geological interpretation (James, 1994) was undertaken during the design stage of the reclamation prior to any planned construction.

The interpretation is based on a 50 m grid of modern boomer seismic reflection lines over the site of the container terminals and older records of poorer quality in Penny's Bay. The site investigation also included 109 boreholes, 41 vibrocores and 22 CPTs. The stratigraphy at the site is primarily a two-fold succession of soft mud of the Hang Hau Formation overlying a complex mixture of firm to stiff silty clay with some sand and silt which forms the Chek Lap Kok Formation. The Sham Wat Formation was not recognised at the site.

In terms of reclamation design the form of the soft mud of the Hang Hau Formation is important in terms of settlement considerations. It is constrained in extensive channel systems (Figure 7) with two major channels in the west infilled with up to 29 m of soft mud and a narrower dendritic set in the east infilled to a maximum thickness of 27 m.

The two major channels and the area in Penny's Bay contain a large accumulation of gas within the sediment which forms areas of acoustic turbidity on the seismic records. These obliterate seismic reflectors which trace features such as the base of the Hang Hau Formation. In these areas of acoustic turbidity the interpretation has to rely on point source information such as boreholes and CPTs and any surfaces such as the base of the soft mud has to be extrapolated between them. The upper ten metres of the Hang Hau Formation is generally not obliterated by acoustic turbidity and the form of the reflectors can be used to map out channels within the zone with acoustic turbidity and therefore provide a basis for planning a CPT survey programme to delineate the base of the soft mud.

Conclusions

The comprehensive approach to the interpretation of the marine geology of any reclamation site is based on excellent site investigation provided by a tight grid of seismic reflection profiles calibrated with borehole and CPT surveys. These should be analysed with a knowledge of the regional geology to provide a context for the reclamation and a detailed stratigraphy. The geological framework and information obtained from such an approach is crucial in enabling the planning, design and construction to proceed on schedule and to budget, without any unforeseen ground conditions delaying progress.

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