Hong Kong International Airport— civil engineering design

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Hong Kong's new airport covers an area of 1248 ha, of which three quarters has been reclaimed from the sea. This paper describes the civil engineering design for the HK\$ 50 billion project including the reclamation, runways, 550 000 m² passenger terminal building, ground transportation centre and supporting infrastructure. It covers the early site selection and the factors affecting the layout of the airport. It details the leading role taken by the Authority in the prediction of reclamation settlement and how this was accounted for in the design and construction of the works. It concludes with a brief description of the wide-ranging environmental initiatives which were applied at all stages of this massive project.

The new Hong Kong International Airport has been built on a largely man-made island at Chek Lap Kok and was opened in July 1998. The airport is a replacement for the single runway at the existing international airport at Kai Tak, situated on the Kowloon Peninsula, and which has played such a pivotal role in Hong Kong's development over the past 50 years.

Fig. 1. Replacement airport sites investigated 1946-1989 overlain on Landsat image of November 1994 (courtesy of Civil Engineering Department, Hong Kong government)

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Fig. 2. Chek Lap Kok Island

Alternative sites for a replacement airport were considered as far back as 1946 (Fig. 1).¹ The two sites examined at that time were rejected for aeronautical reasons and high cost. To meet the steadily increasing demand at Kai Tak a new runway (2542 m long), parallel taxiway and passenger terminal were planned in the 1950s and opened in 1958. With the introduction of heavier, wide-bodied aircraft the runway was subsequently extended to 3392 m in 1975. Also in the 1970s it was realized that the single runway at Kai Tak together with constrained operating hours (due to noise over Kowloon) would have a finite capacity. A new airport was needed with dual runways, preferably aligned along an easterly axis into the prevailing winds; and good land access would be essential. Thus the first serious search for alternative sites was made between 1973 and 1975.² The study concluded that Chek Lap Kok (Fig. 2) would be the best choice at an estimated cost of HK\$ 3.6 billion (1974 prices), including the cost of road access on north Lantau. The principal reasons for its selection were that

- all aeronautical criteria would be met for a 24-hour a day operation
- the engineering feasibility for site formation was established
- the programme for the works was less uncertain than other sites
- the environmental impact during construction and for operations was acceptable
- an airport at Chek Lap Kok was compatible with other proposed developments on Lantau Island and also with port activities in the western harbour.

In 1978 studies undertaken by the government

looked at the development of an airport at Chek Lap Kok together with land development potential on north Lantau with a coastal highway and a fixed link crossing to Tsing Yi.

Master planning and financing studies completed in 1982³ established in some detail the feasibility of building the two-runway airport at Chek Lap Kok within a seven-year period at a total cost of HK\$ 15.3 billion (mid-1982 prices). However, due to a downturn in the global economy and uncertainties arising from concurrent Sino-British negotiations on Hong Kong's future, the project was deferred.

However, while planning came to a standstill the growth of air traffic through Kai Tak continued unabated. Between 1980 and 1990 alone, annual passenger numbers rose from 8 million to 20 million and the volume of air cargo passing through the airport trebled.

By 1989, the need for a new airport could no longer be ignored and once again planners focused on Chek Lap Kok, but in a new context. This time the airport was to be studied as part of a combined port and airport development strategy and included a review of alternative sites to Chek Lap Kok.

In October 1989, the Hong Kong government announced the adoption of a strategy based on a new airport at Chek Lap Kok, and a network of supporting road and rail infrastructure to be known as the Airport Core Programme.

Chek Lap Kok was chosen as the airport location ahead of other site options because it met a number of basic criteria. It offered greater economic benefits and could be built and made operational earlier than other considered sites. It also provided greater scope for an integrated and

viable transport infrastructure network, the potential for urban development in the form of Hong Kong's ninth new town and the ability to integrate future port and airport development. The government emphasized that the airport would develop incrementally with expansion capacity for phased development well into the next century.

The Provisional Airport Authority (PAA) was established in April 1990 as a statutory organization to plan, design and construct the new airport. The new airport master plan⁴ was also initiated in July 1990. In September 1991 a memorandum of understanding was signed by the governments of the UK and the People's Republic of China, confirming joint support for the new airport and related core projects. The cost of the PAA's facilities at the airport in money-of-the-day or 'out-turn prices' is HK\$ 49.8 billion. There followed almost four years of discussion between the two governments on the detailed financing arrangements for the projects. During this time, the Hong Kong government sought to maintain progress on the airport in accordance with the requirements of the memorandum by, at various stages, providing interest-free cash advances to the PAA to enable critical works on the project to proceed on a 'step-by-step' basis. In July 1995 Hong Kong's legislative council passed the Airport Authority Bill which enabled the PAA to be reconstituted as the Airport Authority (AA), empowering it to provide, develop, operate and maintain the new airport. On 29 November 1995 the airport committee of the Sino-British joint liaison group signed agreed minutes on the membership of the AA, and this paved the way for establishment of the AA on 1 December 1995.

The above were key events for the AA and had a fundamental influence in the contracting of the design and construction of the airport.

Master plan

The overall objective of the new airport master plan (NAMP) study was defined as 'the preparation of a comprehensive and environmentally acceptable scheme for the planning and implementation of an operationally safe and efficient new airport at Chek Lap Kok, covering progressive development into a two-runway airport operating 24 hours a day'.⁴

The key assumptions made for the NAMP, completed in December 1991, which influenced the planning of the airport facilities included the following.

- Kai Tak Airport would close when the new airport opened.
- All passengers using the new airport would be regarded as international, requiring them to be processed through immigration and customs facilities.
- The master plan would include a multi-modal surface transport system with a high priority given to rail.

Table 1. Air passenger and cargo demand forecasts

Year	Passengers		Cargo: tonnes	
	1991 forecast	1994 forecast	1991 forecast	1994 forecast
1998	29.5 million	33.9 million	1.2 million	1.7 million
2001	33.2 million	40.7 million	1.4 million	2.1 million
2010	44.7 million	65.9 million	2.3 million	3.4 million

- Opportunities for privatization would be maximized.

There were three main workstreams undertaken for the NAMP, namely planning, civil engineering and environmental impact assessment, which were carried out in parallel.

Air traffic demand

Air traffic studies carried out as part of the NAMP determined the overall physical size of the airport and the size of the facilities. The air traffic forecasting process employed has been described by Oakervee.⁵ In essence, the predicted per capita gross domestic product was used as the primary variable to determine growth.

Such has been the economic development in the Asia-Pacific region that in 1994 a new air traffic demand forecast covering passengers and cargo was commissioned by the AA, as air traffic growth in the three years since completing the 1991 master plan had been significantly greater than forecast and reported previously.⁵ The 1991 and 1994 forecast figures are given in Table 1.

Since 1987 annual passenger traffic has grown by an average of 9.9%⁶ and in 1996, despite its limitations, Kai Tak had an annual throughput of 30.2 million passengers, making it the third busiest airport in the world in terms of international passengers.

Air cargo tonnage has grown by an average of 11.0% since 1987. Based on preliminary figures from the Airports Council International, Kai Tak was the world's busiest in terms of international cargo in 1996 with a throughput of 1.56 Mt.

The forecast of passenger and cargo aircraft movements was strongly influenced by the relatively high predominance of Boeing 747 and other wide bodied aircraft. Both the 1991 and 1994 forecasts for all aircraft movements are given in Table 2.

The airport plan

Air traffic demand and airspace constraints dictated the layout of the airfield at Chek Lap Kok which covers a total area of 1248 ha. The major planning recommendations in the NAMP were that runway centre-lines should be separated by 1525 m which would allow independent runway operations in accordance with the recommendations of the International Civil Aviation Organization (ICAO); the airport would be

Table 2. Forecasts of all aircraft movements

Year	Movements	
	1991 forecast	1994 forecast
1998	160 000	201 000
2001	177 000	241 100
2010	229 300	369 900

designed for a configuration of two parallel runways bearing 070°/250° N each 3800 m long and 60 m wide; the passenger terminal complex would be located between the runways; and the rail and primary road access would be along the eastern edge of the airport island.

The airport is a phased development and as such has been planned to open with a design capacity of 35 million passengers and 3 Mt of cargo annually. Initially, has a single runway, one passenger processing building, the major part of the Y-shaped concourse with 38 frontal gates (connected to the terminal by airbridges) and 27 remote aircraft stands. Within months of the airport opening, the second runway will become operational, the remainder of the Y-concourse will be constructed and a further 10 frontal gates will be added. Appendix 1 gives a comparison between facilities at the existing airport at Kai Tak and those at the new airport at Chek Lap Kok. Ultimately the airport will have a designed capacity of about 87 million passengers and 9 Mt of cargo annually.

Airport planning is a continuous process and following completion of the NAMP the AA made further design refinements and revisions in the light

of changing data and circumstances. The significant changes (Fig. 3) were that: the southern runway was moved 360 m to the west to reduce reclamation costs and to preserve the eastern coast of Chek Lap Kok Island; the passenger terminal building was moved 190 m westward so that more of the building's foundation work was located on Chek Lap Kok Island to reduce construction costs; and the vehicular tunnels were re-aligned.

The key features of the airport site plan (Fig. 4) are two parallel runways, each 3800 m long, and 35 km of associated taxiways; a passenger terminal building comprising a Y-shaped concourse and processing terminal connected by way of an underground automated people mover and linked to the ground transportation centre (GTC); a high-speed rail and road network serving the GTC; aircraft base maintenance facilities at the western end of the airfield; airport support facilities including air cargo, catering and an aviation fuel tank farm located south of the runways; various government facilities including the air traffic control tower and centre, fire stations, sea rescue stations, airmail centre, a police station and a facility for the government flying service. Commercial developments are also under construction, including a 1100-room hotel, a 1750-space multi-storey car park, a freight forwarding centre, headquarters and crew accommodation for Cathay Pacific and headquarters for Dragonair/CNAC.

Design contracts

The NAMP identified general requirements for all the airport facilities and included outline scheme designs for the passenger terminal building, the airfield, the infrastructure and utilities. The first major detailed design contract for the

Fig. 3. Key changes to the airport site plan

Fig. 4. Airport site plan

airport itself was awarded in March 1992 for the passenger terminal building. For the remainder of the works a large number (30) of contracts were let between 1993 and 1996 to design consultants. A full list of the design contracts is given at Appendix 2. The reasons for this strategy arose from the limited funding available at the time which required all design work to be initiated on a 'step-by-step' basis. Also, the AA's board wished to have participation by a number of designers, each expert in specific areas—airfield pavements, ground lighting, stormwater drainage, utilities, electrical and mechanical works, roads, bridges, ancillary buildings and landscaping.

The allocation of funds on a step-by-step basis led to interface problems such as the stormwater design being awarded before the airfield pavements package and the utilities design before the roads package. This inevitably created complications and led to an iterative design process. The consequences of a large number of design interfaces and design work being undertaken out of sequence were felt throughout the design and construction phases. In addition, the fluid nature of the contracting strategy for the construction works which arose from the uncertainty over future funding meant that the completed designs from several designers had to be split and consolidated to suit each works contract.

Design co-ordination meetings, chaired by the AA and attended by all design managers and representatives from all designers, were held periodically for co-ordination of all designs.

The authors would like to acknowledge the cooperation of designers in dealing with the interfaces and assisting in the co-ordination process. The AA also held quarterly review meetings with all design firms to review progress at a strategic level, which proved beneficial to all concerned.

An example of the AA's initiatives with regard to co-ordination was with respect to the provisions necessary to account for settlement of the airport platform and this is described later in this paper under the heading *Design and construction levels*.

The airport platform

To accommodate all the facilities and allow for phased development of the airport required the creation of 1248 ha of land (Fig. 5). Twenty-five per cent of the airport platform is made up of the former islands of Chek Lap Kok and Lam Chau, which have been excavated to a level of about +6 m PD (principal datum). The remainder of the platform is land which has been reclaimed from the sea as part of a major site preparation contract which began in December 1992, the construction details of which are briefly described in a related paper.⁷ A full description of the design, construction and performance of the site preparation works is given in reference 1.

Design and performance

Chek Lap Kok and Lam Chau Islands are formed predominantly of granite. Completely

decomposed granite (soil) covered the surface of both islands, generally 0.5 to 3 m thick but up to 20 m thick in the vicinity of faults. The offshore geology comprises a complex sequence of interbedded clays and sands. This is overlain by recent (Holocene) marine clays and is underlain by granite bedrock in various states of weathering.⁸

The mean sea level at the site is +1.3 m PD and the average water depth prior to reclamation was typically 5 m, increasing to 15 m in places. The average thickness of the recent soft marine mud was 8 m. The total thickness of the underlying alluvial clays and sands varies from about 10 m to 30 m.

The decision to adopt a dredged reclamation was made at an early stage in the design of the platform because the results from a test embankment constructed in 1982⁹ indicated that if the soft marine mud were to be left in place then an additional 2 m to 3 m of settlement would occur. Also, that wickdrains would be required at very close centres to be effective within the airport's fast-track programme. The selected dredging depth was based on the results of 3200 cone penetration tests carried out on a 50–100 m grid across the site combined with seismic traverses. The dredge levels within the reclamation (i.e. excluding seawall trenches) were defined by removing mud with a net cone penetration test (CPT) tip resistance of less than 500 kPa. The dredge level was specified with a tolerance of –0 m, +1 m.

The seawalls relied upon the strength of the founding materials for stability. For the purposes of assessing short-term stability a minimum undrained shear strength of 35 kPa was adopted. It was found that, in general, this could be met with a net CPT tip resistance of 700 kPa. The dredge level tolerance was specified as +0 m, –1 m to minimize the possibility of mud remaining beneath the seawalls. In all, dredgers removed 68.8 Mm³ of soft marine mud overlying the seabed within the airport footprint to depths up to –29 m PD and transported it to designated dumping grounds within Hong Kong waters.

The total fill requirement was 197 Mm³, of which 108 Mm³ was obtained from the islands of Chek Lap Kok and Lam Chau, 6.6 Mm³ from the levelling of the two Brothers Islands to the east of the airport and 7.3 Mm³ from other ACP contracts. The balance was sand imported from marine borrow areas within Hong Kong waters. The reclamation is surrounded by 13 km of seawall, the majority of which is armoured sloping wall.

Three main material types, A, B, and C, were specified for use as general reclamation fill. A simplified version of the fill allocation plan is shown in Fig. 6. A number of other fill types were adopted for specific uses such as the seawalls. Type A is a well-graded hard durable rock fill with a maximum size of 2 m (Fig. 7) and was reserved for use below the southern runway for its resistance to liquefaction potential. Type B is a well-graded fill from excavation; in practice,

Fig. 5. The airport platform

essentially completely decomposed granite (CDG) with a maximum size of 300 mm and was used in areas where future excavation of the cut-and-cover airfield tunnels were envisaged or in areas where structures were to be founded on piles. Type C is sand from marine sources. A fourth material type, designated type A/B, was agreed during the course of the site preparation contract for use in general fill areas. In practice the material is a rockfill with a small but variable content of CDG. The upper 2 to 3 m of the reclamation comprises a capping layer of either type B or C fill. This permitted subgrade preparation for the airfield pavements and eased excavation for drainage and services trenches as well as final shaping of landscaped areas.

The question of settlement is a key issue for reclamations and was considered from an early stage. To estimate the amount and rate of settlement required, a thorough understanding of the geology and the engineering behaviour of the soils was needed. Site investigations included the reclamation site and the potential sources of fill for reclamation. About 650 marine borings, 170 land borings and 1100 km of seismic traverses were carried out on the airport footprint during the detailed design stage. These investigations were carried out by different organizations over many years and a comprehensive geotechnical digital database was established by the AA. This database links all ground investigation data, stratigraphic layers, laboratory tests and instrumentation results. The database is also linked to engineering drawing applications and has proved a valuable tool in planning, design and analysis.

The majority of the reclamation was constructed by end-tipping of rockfill and bottom dumping or hydraulic placement of marine sand with no subsequent ground treatment. Therefore, where necessary, limited areas of the reclamation have been treated generally by either surcharging or vibrocompaction (Fig. 8). Surcharging, principally using 8 Mt of granite rockfill retained from quar-

Fig. 6. Simplified fill allocation plan

Fig. 7. Grading envelopes for fill types A, B, A/B and C

rying Chek Lap Kok Island and subsequently crushed for aggregates, was designed to accelerate primary consolidation of the alluvial clays and also to improve the creep characteristics of the rockfills. Vibrocompaction of 11 Mm³ of the sandfill was carried out over some 60 ha of land being developed under the current construction phase. The treatment was required to reduce creep settlement of the sandfill and to reduce the potential for vibration induced settlement during follow-on piling and other construction activities. The acceptance criterion for the vibrocompaction works was a minimum CPT value of either 8 MPa or 15 MPa, depending on the intended land use.

An integral part of the reclamation design was the installation and monitoring of surface and sub-surface geotechnical instruments to assess the performance of the reclamation and to allow predictions of future settlement to be refined. The sub-surface instruments comprised clusters of piezometers installed around a central extensometer at approximately 500 m centres. A grid of surface survey markers was constructed across the reclamation at approximately 200 m centres to provide a fuller picture of the surface settlement of the reclamation.

Early predictions of settlement were made using the results of *in situ* and laboratory tests. As more

Fig. 8. Ground treatment areas

monitoring data have become available, the prediction method has changed to an observational approach making full use of the monitoring data. Fuller details of the performance of the reclamation are given in a companion paper.¹⁰ In summary, the remaining or residual settlement from January 1997 to 2040 is typically in the range 200 mm to 500 mm. At the present time (August 1997) the primary consolidation of the alluvial clay is typically 90% complete and creep of the reclamation fills now typically comprises about 50% of the residual settlement.

The airport platform was substantially completed in 37 months and involved the movement of about 360 Mm³ of material. The rapid pace of construction was assisted by a practical application of engineering requirements and a carefully programmed fill allocation plan taking best advantage of the various fill types available. This minimized the requirements for fill processing and ensured that the fill placed in a particular area met the specific engineering needs of the future planned construction. This approach also minimized the requirement for ground improvement thereby reducing both cost and time.

Design and construction levels

The effect of the platform settlement coupled with the different times at which works were due to be constructed influenced the amount of over-build necessary to achieve design levels in the long term.

Although each designer made his own settle-

ment assessment it soon became clear that the AA were in the best position to address this issue from their overall knowledge of the platform behaviour. It was also known that contractors were reluctant to take on risk associated with the settlement of the platform. The AA therefore took on responsibility for settlement during construction of the follow-on works and established the concept of installation levels.

The designers were required to design their works such that the facilities would remain operational throughout the airport's life and to standardize their designs for a fixed date of January 1997. The AA then provided contractors with rates of settlement for various zones of the reclamation. This information was derived from time-settlement curves prepared for many points on the platform. The construction period for the works represented a small window within the overall time-settlement curve (Fig. 9) and was therefore approximated to a straight line. The AA issued settlement rates expressed as mm per month and the contractor then determined his installation levels from this information and from his own programme for the works by taking the linear rate of settlement multiplied by the number of months prior to January 1997 and adding this amount to the design levels.

Airfield pavements

Air traffic forecasts and airspace considerations had determined that the Civil Aviation

Table 3. Principal airfield planning dimensions (in m)

Criterion	ICAO code E annex 14	ICAO code F guidelines	FAA group V	FAA group VI	Design dimensions adopted
Runway centreline (CL) to taxiway CL	182.5	192	120	180	192
Runway width	45	60	45	60	60
Runway shoulder width	7.5	7.5	10.5	12	7.5
Taxiway CL to taxiway CL	80	99	81	99	99
Taxiway CL to obstacle	47.5	57	48.5	59	57
Taxilane CL to obstacle	42.5	54	42	51	54
Taxiway/taxilane width	23	29	23	30	29
Taxiway shoulder width	10.5	7.5	10.5	12	15.5

Department (CAD, which is responsible for aircraft movements in the air and on the ground until the aircraft comes to rest at its assigned stand at which point the AA takes over responsibility) and the AA would need the capability to operate two runways simultaneously, 24 hours a day. The system of runways and taxiways occupy about 30% of the total airport site (Fig. 10). The 'rapid exit' taxiways shown permit aircraft to clear the runway more quickly than a 90° turn thus improving runway capacity.

At airport opening it is estimated that over 75% of departures¹¹ will be wide bodied aircraft, and thus all frontal stands and the majority of remote stands have been designed to accommodate ICAO designated code E aircraft (e.g. Boeing 747-400). The length of selected stands have also been safeguarded to ensure that the new large aircraft (NLA) can be accommodated.

Throughout the design phase, and even now, there has been much uncertainty about the size and introduction of NLAs and ICAO have only issued guidelines rather than a code F standard. These guidelines, together with the Federal Aviation Administration (FAA) group VI design criteria, were used as a basis for designing the geometry of the airfield. The principal planning criteria are shown in Table 3.

This paper briefly summarizes the design of the pavements only, as available space precludes discussion of the associated aspects such as aircraft approach and ground lighting, high mast lighting, preconditioned air, fixed ground power, HV ducting, communications, potable and fire water mains, aviation fuel distribution, irrigation mains, stormwater drainage, oil-interception, aircraft wash, parking aids and miscellaneous buildings.

The design aircraft for the structural design of the pavements was a Boeing 747-400 with an all-up weight of 400 t. The Boeing 777 and MD11 aircraft give similar pavement loadings. Growth versions of these aircraft such as the Boeing 747-600, MD12 and Airbus A3XX are expected to increase the all-up weight to between 550 and 770 t, but revised landing gear configuration and increased number of wheels

Fig. 9. Interpretation of predicted settlement to derive settlement rates

will result in similar pavement stresses.

Underground structures such as culverts and tunnels have been designed to carry aircraft up to 770 t.

Surface winds at the new airport are predominantly from the east and favour a flow of operations in this direction (runways 07L and 07R) approximately 70% of the time, with the remaining 30% operating from runways 25R and 25L. However, with a 5 knot tailwind aircraft could continue to operate in the 250° direction for up to about 45% of the time. Thus, for the purposes of runway pave-

Fig. 10. Type and layout of airfield pavements

ment design it was assumed that the runway utilization could be 70% departures from 07L/07R and 45% from 25R/25L. A detailed traffic analysis was undertaken based on information from CAD regarding aircraft fleet mix and planned taxiing operations on the ground to establish coverages by the design aircraft over the pavements.

The principal factors which affected the choice of pavement were settlement, ride quality, fuel resistance, duration of loading and cost. Based on these design considerations, asphalt surfaced flexible pavements were selected for the runway/taxiway system on the reclamation, rigid pavement quality concrete for aprons and taxi-lanes on the original island and interlocking concrete blocks for apron areas subject to significant differential settlements.

The pavements have been designed using both the 1989 UK PSA *A Guide To Airfield Pavement Design And Evaluation*¹⁰ and the US LEDFAA method following its release in 1995 by the US FAA.¹² The first is a semi-empirical method in line with those recognized by ICAO and is based on many decades of experience gained from evaluating the performance of existing pavements. The second is based on a linear elastic design approach which calculates stresses and strains in each pavement layer. It uses these stresses and strains to determine pavement thickness by an iterative process using established fatigue equations. Both of these design approaches yielded similar pavement structures.

After applying the various traffic scenarios, expected loading and settlement criteria many different pavement sections were developed across the airport. These were then rationalized into just 16 types to ease the construction process as many of the scenarios gave rise to similar thickness requirements. In all, the airfield pavement works cover 3 700 000 m².

Asphalt pavements

The initial structural design of the asphalt surfaced pavements considered the use of a bound (cement or bitumen) base in accordance with the PSA design guide. However, unbound bases with relatively thin asphalt surfaces have provided the desired performance at many airports. These pavements require very high quality aggregates with strict grading requirements with a consistent level of compaction to prevent premature rutting.

Following the identification of suitable high quality aggregates, a pavement using crushed rock base and sub-base courses was selected on economic grounds, being significantly less costly than a pavement with a bound base. Crushed rock aggregates of the specified quality for the sub-base course were available on site, retained from quarrying Chek Lap Kok. For the base course and the Marshall asphalt layers, crushed rock with a minimum specified 10% fines value of 180 kN was imported from nearby provinces in China.

Transverse sawn grooves (6 mm x 6 mm at 32 mm centres) were specified in the runway wearing course to provide the required frictional characteristics.

The total area of both runway/taxiway systems is 2 600 000 m² and they have a design life of 20 years. Within this period overlays will be placed because of the oxidation and weathering of the asphalt which occur in tropical climates and also, in limited areas, for shape correction. Fig. 11(a) shows a cross-section of a typical asphalt pavement.

Concrete pavements

For the aprons, concrete paving is preferred because of its ability to resist high loads from stationary aircraft and its resistance to fuel and oil spillage from aircraft or ground support vehicles. Thus conventional rigid concrete pavements have generally been adopted for the aprons. During the early phase of design both continuously reinforced and unreinforced jointed concrete pavements were considered, and the latter were selected on the basis of lower capital costs.

The rigid concrete pavements which cover an area of 700 000 m² have a design life of 45 years.¹⁰ The majority of these pavements are on the original island; elsewhere *in situ* plate tests using a 762 mm dia. plate gave values of sub-grade reaction for the compacted fill of between 100 and 150 kPa/mm. A conservative value of 40 kPa/mm was selected for design purposes. The unreinforced pavement is typically 450 mm thick on a 175 mm dry lean concrete base (Fig. 11(b)). The specified 28-day characteristic flexural strength was 4.5 MPa. Typical bay sizes are 6 m x 6 m. Mesh reinforcement and trimmer bars were specified for irregular bays and around penetrations. Transverse joints were saw cut at approximately 10 to 15 h after concrete placement and steel dowels were provided at longitudinal joints. Load transfer across the transverse joints is by aggregate interlock at the sawn joint. All joints were sealed with a fuel-resistant sealant. Surface texture of the finished concrete was specified as a minimum of 0.7 mm using the sand patch test method.

Concrete blocks

In apron areas where a rigid concrete pavement could not tolerate the estimated differential movements, interlocking shaped concrete blocks 80 mm thick have been adopted (Fig. 11(c)). The blocks are nominally 225 mm by 112.5 mm and have a characteristic compressive cube strength of 60 MPa. The joint spacing was specified as 2–4 mm to ensure interlock via the jointing sand. To achieve this the contractor monitored mould wear and replaced the mould when the block plan dimensions increased by 1.25 mm which occurred at about 80 000 cycles.¹³ Some 16 million blocks were required to cover 400 000 m² of apron.

Beneath the southern runway the eastern tunnel has been designed to carry vehicles from the

Fig. 11. Typical pavement types (a) asphalt, (b) rigid concrete, (c) concrete blocks

airport support facilities in the south to the passenger terminal aprons, and the western tunnel is for future access to the midfield. Both tunnels are each about 700 m long and have a utilities cell and dual carriageways to allow traffic from land-

side to airside without affecting operations of the southern runway. The eastern tunnel has been commissioned but the western is for utilities only at present and will be fitted out when the mid-field area is developed (Fig. 10).

Infrastructure

In addition to the terminal building for passenger handling and the aircraft operations, the airport demands significant supporting infrastructure. This includes

- (a) air cargo handling and freight forwarding facilities
- (b) in-flight catering services
- (c) aviation fuel storage and distribution
- (d) aircraft maintenance, line maintenance and ramp handling
- (e) government facilities
- (f) building and E&M airport maintenance depots
- (g) utilities and drainage
- (h) roads, tunnels and bridges.

Items (a) to (d) are being developed by commercial franchisees, item (e) by government and items (f) to (h) by the AA.

Franchises

At airport opening two air cargo franchisees will have a capacity to handle at least 1.6 Mt of cargo which will quickly rise to 3 Mt. A freight forwarding facility where cargo is consolidated for direct dispatch is also being built. Three aircraft catering facilities are being built and between them will produce about 95 000 meals per day during the first year of operation.

The design, construction and operation of the aviation fuelling system has been licensed to industry specialists. Two 450 mm diameter under-sea pipelines will bring jet A1 fuel on to the airport, where 15 days of storage is provided. The throughput is about 10 000 000 litres per day initially. A fuel hydrant distribution system, which transfers fuel from the tank farm to the aircraft stands for aircraft refuelling, was designed and constructed by the AA on behalf of the licensee. It is sized for busy-hour demands for the year 2010 and is expandable for further growth. An aircraft maintenance facility is under construction at the west end of the airport. The main component is a 220 m x 66 m structural steel hangar capable of accommodating three Boeing 747s and two A320s side by side.

Utilities

The following utilities and services have been provided airport-wide

- potable and firefighting water
- HV and LV electricity supply and distribution
- stormwater drainage and related oil interception system
- sewerage system
- irrigation system
- gas distribution
- seawater for flushing and cooling
- security system

- voice and data communications
- aircraft approach and ground lighting.

Generally, all utilities have been placed within segregated reserves adjacent to primary road corridors (Fig. 12). This was a planning objective to ensure that future maintenance and upgrading of the utility systems would have minimal disruption to airport operations.

Development of the road and utility infrastructure is similar to a new town development, as in addition to the 34 million passengers who will pass through the airport in the opening year it is anticipated that some 45 000 people will be employed at the airport.

The provision of complete utility networks covering the entire airport represented a major design and construction effort. The complexity of the networks, the challenging construction sequence to suit third parties, the required early phasing of commissioning all contributed to the difficulties of effective site co-ordination. The use of 3-D computer models and clash analysis programmes assisted in this process.

Roads

The required capacity of the primary road access for travellers to the passenger terminal building has been greatly reduced by the implementation of the airport railway which forms the backbone for air passenger access. The principles adopted in the road network planning included segregation of private vehicles from commercial/industrial traffic; free-flow traffic management; minimal recirculation; provision of alternative emergency routes; and direct access to major land users.

Even with the estimated 43% of arriving and departing passengers taking the airport railway, it is estimated that by the year 2010 traffic flows on the main approach road to the passenger terminal building will exceed 3500 pcu (passenger car units) per hour in each direction. To the south, cargo and maintenance traffic will increase the flows to over 5000 pcu/h each way.

A dual three-lane expressway provides the trunk route for all traffic accessing the airport from the urban areas. On the airport the most southerly grade-separated interchange, which consists of five multi-span bridge structures, provides access to the cargo, catering and aircraft maintenance areas, effectively segregating the majority of heavy goods vehicles from passenger vehicles. The 1.5 km long primary access from this interchange to the passenger terminal building allows four lanes in each direction to facilitate effective weaving movements for traffic gaining access to the various levels and locations within the ground transportation centre.

It is vital to airport operations that the primary access corridor functions efficiently. As well as directional signage, dynamic flight information sig-

Fig. 12. Road and
utilities network

nage is also provided. The AA has implemented a comprehensive traffic control and surveillance system incorporating variable message signage to minimize disruption to passenger movements in the event of an incident on the approach roads.

Ground transportation centre

The focal point of the landside road network is the ground transportation centre located between the passenger terminal building and the proposed second terminal (Fig. 13), which facilitates passenger interchange between aircraft and the various ground transportation modes. These include the airport express railway, public buses and air-buses, tour coaches, hotel buses and limousines, baggage vans, taxis and private cars.

Segregated provisions have been made for each transport mode with emphasis placed on speed and efficiency of transfer, convenience, comfort and safety for all passengers, well-wishers and airport employees. At the core of the centre is the rail station¹⁴ with direct air-conditioned links to the terminal. Departing air passengers travel along ramps with moving walkways to the check-in area within the terminal. Arriving air passengers have a similar ease of access from the terminal to their choice of ground transport, the rail departure platform being on the same level as air passenger arrivals (Fig. 14). The station is expandable to serve the future second terminal while maintaining the same level of service. Beyond 2010, up to 50% of air passengers and well-wishers are expected to enter and leave the airport through this station.

The ground level of the centre is occupied by the road arrivals traffic. Separate pick-up areas are provided for public buses, tour coaches, hotel

vehicles and taxis; the latter incorporates a 24-taxi simultaneous pick up system. Private car pick-up facilities for arriving passengers are provided in the multi-storey and at grade car parks.

The highest level of the centre is occupied by the road departures traffic. A departures forecourt and median strip provide a total kerb length of 650 m along the face of the processing terminal at airport opening. This allows taxis, public buses, hotel vehicles and private cars to drop off their passengers at this level.

Passenger terminal building

Whether travellers enter the check-in area of the passenger terminal building from the forecourt or from the station platform, they find themselves within a breathtaking interior space. The dominant feature is the roof, comprising 18 ha of steel barrel vaults (Fig. 15). The 36 m spans create a feeling of light and space and the geometry is aligned to lead passengers naturally through check-in, immigration and security towards their departure gate. The roof is high over the processing terminal, cantilevering 27 m over the forecourt, reducing in height over the east hall and along the central concourse before rising again over the west hall. Each 36 m x 36 m vaulted roof panel is formed of a lattice of straight 6 m long I-beams, 406 mm deep for the majority of the building and 457 mm deep members for the diagonal concourses. The architectural requirement for constant depth and flange width required varying forces within the members to be accommodated by changes in flange thickness. The roof geometry is revealed by exposing the bottom flange of all diagonal elements and within the triangles so formed are soffit lining panels (perforat-

ed metal panels with acoustic insulation) positioned flush with the flanges.

Critical wind pressures were determined from wind tunnel tests which indicated that the Hong Kong code for wind loading was not conservative¹⁵ for low-level structures in such exposed conditions. Seismic design was based on the New York code in the absence (at the time of design) of guidance for Hong Kong. The design required the impact of the sequence of roof module erection on the flexible concrete columns to be assessed to ensure that the final structure was within tolerance. Some vaults, primarily those over the processing terminal, are

tied to reduce the impact of thrusts on the cantilever concrete columns.

Three important connection details emerged from the design. First, that of a typical node where six elements are joined: the solution adopted was a node plate as depicted in Fig. 16. The second was the column head connections (Fig. 17) where within the confines of a 1200 mm dia. reinforced concrete column top, two 100–150 t, 36 m span roof modules had to be located together with a 150 mm dia. downpipe and conduits for electrical services. The third was the connection detail to link the undulating roof with the

Fig. 13. (top). Plan of terminal building and ground transportation centre

Fig. 14. (above). Section through processing hall and ground transportation centre

Fig. 15. 3-D study
internal view of roof

cladding: the solution was a cast stainless-steel armature connection or 'wishbone' (Fig. 18).

The roof covering comprises a waterproof membrane, a vapour barrier and thermal and sound insulation layers on a steel deck. Internally, the soffit lining panels reflect light from luminaires mounted on the roof gantry and from daylight which enters the building through the skylights.

The contract for the design of the passenger terminal building was awarded to the Mott Consortium in March 1992. The consortium comprised Mott Connell, the Hong Kong practice of Mott MacDonald (UK) and Connell Wagner (Australia), which was responsible for engineering design and consortium management, and Foster and Partners which undertook the architectural design, in association with BAA, which carried out operational planning and systems design. As sub-consultant, Ove Arup and Partners designed the roof and architectural steelwork. W. T. Partnership was the quantity surveyor and O'Brien Kreitzberg provided design project scheduling.

The first phase of the building is designed to handle 35 million passengers per annum. The projected one-way standard busy rate (SBR: defined as the projected activity during the 30th busiest hour in the year; this is a more reliable measure of an airport's busy periods than a peak rate which will experience large fluctuations from year to year) for this annual throughput is 5500 passengers/h. The gross floor area of the building in the first phase is 515 000 m² and is over 1.3 km long, making it one of the largest single terminal buildings in the world. The concourses provide direct access through fixed link bridges and apron drive loading bridges to 38 aircraft stands, at airport opening, rising to 48 on completion of the north-west concourse (Fig. 13). An automated people mover and moving walkways will

Fig. 16. Node plate
detail

ensure that people are able to move through the building quickly and comfortably.

Building services have been integrated within the structure to minimize obstructions to the passenger processing facilities and within the roof. Thus, from a double-height basement containing the chiller plant which draws in seawater for cooling, conditioned air is fed vertically to the various levels of the building by way of binnacles. Also, within the basement is the heart of the baggage handling system capable of handling 19 200 bags per hour at saturation. It incorporates a machine-automated explosive detection system which simplifies check-in as it enables all X-raying for hold baggage to be carried out within the baggage handling system.

Due to the large footprint of the building which straddles both the original island of Chek Lap Kok and reclaimed land, many different types of foundation have been employed including pad-and-strip footings, rafts, bored and H-piles. Below ground level, the basement and tunnels are designed as water-retaining structures and to

Fig. 17. Column head detail

Fig. 18. (below).
Connection detail
between roof and
cladding

counteract uplift pressures passive tension anchors drilled into rock have generally been used. This solution was determined to be more economical in the long term than providing a drained basement. A long section through the processing terminal is shown in Fig. 14 and a cross-section through the central concourse is shown in Fig. 19. The automated people mover is located in the central pair of tunnels and initially operates along the central concourse between stations at the east and west halls. However, the tunnel has been constructed over 2 km long extending eastwards to the future processing terminal and westwards beyond the cross-field taxiways in readiness to serve the mid-field concourse development.

The main structural frame of the building is *in situ* reinforced concrete. During the scheme design six alternative forms of construction were examined ranging from *in situ* concrete with various combinations of precast concrete to an all-steel solution. The *in situ* concrete was selected on cost and programme grounds. While the troughed and coffered floor slabs were detailed to offer the possibility of precasting, the contractor chose an all *in situ* construction. Generally, the structural frame comprises 700 mm deep beams spanning 12 m with ribs at 1.5 m centres and a 125 mm thick slab between ribs. Two different stability systems have been used. In the processing terminal horizontal loads are resisted by the framing action of beams, ribs and columns. In the

concourses lateral stability is provided by shear walls which have been carefully positioned to avoid constraining flexibility to reconfigure the accommodation. Within the main concrete frame, retail, office and toilet cabins are steel framed as are the fixed-link bridges linking the concourses with the aircraft loading bridges.

The departures level cladding comprises a panelized glass system with aluminum frames supported by bow back steel mullions (Fig. 20). The glazed wall is up to 28 m high allowing daylight to penetrate the open plan terminal. Laminated toughened glass with a polyvinyl butyral interlayer and internal coating has been used to achieve the necessary solar control. The cladding below departures level is made up of a combination of glazed, solid steel and louvered panels which are modularized to allow for future changes to requirements, which is a common event in ramp-level accommodation.

The building has been designed to facilitate future expansion and at present the design and construction of a 35 000 m² extension to the north-west concourse is underway. Provision has also been made on the north and south sides of the processing terminal to extend the building by 72 m (two roof bays) on each side.

Environmental initiatives

Right from the planning stage the AA has been committed to making the new airport one of the most environmentally acceptable infrastructure projects in Hong Kong, and indeed the region. A major reason for the choice of Chek Lap Kok for the new airport was on environmental grounds as

more than 350 000 people are directly affected by the major flight paths of Hong Kong's Kai Tak Airport; whereas, it is estimated that fewer than 100 people will experience high noise levels at the new airport where the aircraft approach and departure tracks are over the sea. Fig. 21 compares the more stringent 25 NEF (noise exposure forecast) contour for the new airport at the year 2000 with the 30 NEF contour at Kai Tak Airport.

An environmental impact assessment was undertaken as part of the NAMP to investigate the consequences of construction and operation of the airport and to recommend mitigation measures where necessary. Because of uncertainties

Fig. 19. (top). Cross-section through central concourse (elevations in mm)

Fig. 20. (above). Architectural perspective view of meeters and greeters cladding

Fig. 21. Comparison of noise exposure forecast contours

Fig. 22. (below). Bubble curtain to alternate sound waves

in projected construction and operation methods a conservative approach was taken and during the detailed design environmental reviews were updated and designs and mitigation measures modified. Throughout the design and construction stages the AA reported regularly and sought agreement from Hong Kong's various environmental agencies. The AA established its own environmental group within its engineering department to monitor environmental issues and plan for operations. To achieve its environmental aims the AA incorporated a number of practical measures into the design, such as a 'grey water' treatment plant which recycles waste water from the passenger terminal building, catering facilities and aircraft wash stands for irrigation purposes, interceptors built into the drainage system in aircraft fuelling areas to stop potential pollutants from flowing into the sea and fuel spill containment traps at stormwater outfalls. Dedicated systems have also been designed for the treatment of effluents arising from the fire training facility as well as the AA's vehicle wash facility.

Water quality of the sea around the airport has been given a high priority and is regularly monitored. Particular attention has been paid to potential effects on the Chinese white dolphins (*Sousa chinensis*) found in these waters. An aviation fuel transfer facility has been constructed close to the airport and with the advice of cetacean experts the AA has implemented, in co-operation with the aviation fuel operator and its contractor, all practicable environmental mitigation measures which have been recommended. During construction, these measures included the installation of an underwater 'bubble curtain' to attenuate sound pressure

waves during piling operations (Fig. 22).

Key to the airport operating framework is the AA's requirement for its business partners to prepare and implement environmental management plans for their operations. These plans require each operator to identify key issues related to air or noise emissions and effluent discharges, detail licensing points and present an environmental management strategy. The airport community has co-operated well in the preparation of these plans. Experience gained from the overall process is that detailed environmental impact assessments must be incorporated at the earliest possible stages of project planning and be continued throughout the design phase, targeting stakeholders as soon as possible. The drafting, monitoring, audit and mitigation processes are major responsibilities for all airport organizations.

Concluding remarks

Hong Kong is used to accepting the challenges presented by major engineering projects. This brief paper has attempted to summarize the key planning and design tasks involved with the new airport which has dwarfed previous Hong Kong efforts and perhaps ranks as one of the most significant of engineering projects anywhere in recent times.

To achieve the objectives within a time scale of less than eight years is a tribute to the massive human endeavour which has had to be undertaken.

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Appendix 1. Hong Kong's airport facilities—comparative statistics

	Existing airport at Kai Tak	New airport at Chek Lap Kok Phase 1(a)
Total airport site	333.8 ha	1 248 ha
Annual passengers		
actual passengers in 1996 (excl. transit)	29.5 million	
design capacity		35 million
Air cargo tonnage		
actual cargo in 1996	1.56 million	
design capacity		3 million
Airfield		
Runways	1	1 (2)*
Runway length	3393 m	3800 m
Taxiway system	7.1 km	26 km (35 km)*
Apron area	1.03 km ²	1.25 km ² (1.33 km ²)*
Total passenger terminal area	66 000 m ²	515 000 m ² (550 000 m ²)*
retail area	13 600 m ²	30 000 m ² (31 300 m ²)*
retail outlets	40	120
Aircraft gates	69	78 (88)*
frontal (connected to terminal by airbridge) (48)*	8	38**
remote	56	27
air cargo	5	13
Check-in counters	210	288
Immigration control desks	170	224
arrivals	92	128
departures	78	96
Customs inspection positions (arrivals)	52	76
Security screening positions (departures)	12	16
Baggage reclaim units	6	12
Passenger facilities		
moving walkways	0	48
automated people mover	0	1
car parking spaces	1732	3100
taxi loading spaces	15	24
bus stops	6	17
lounge seating	3812	12 530
flight information display boards	283	2000

Note:

* Following commissioning of second runway, extension of the north-west concourse and associated facilities.

** Temporary closure of one frontal gate is planned due to the construction work for the extension of the north-west concourse.

PLANT AND
OAKERVEE

Contract Number		Consultant/contractor	Date of award
100	Masterplan design	Greiner-Maunsell	July 1990
101	Terminal building detailed design	The Mott Consortium	Mar. 1992
105	Site preparation contract design	Greiner-Maunsell	Aug. 1992
106	Lok On Pai refurbishment design	Llewellyn-Davies	Sept. 1992
110	Airport expressway, rail link and roads design	Halcrow Asia Partnership Ltd	Sept. 1993
111A	Ground transportation centre and approach roads design	Ove Arup and Partners (HK) Ltd	Oct. 1993
111B	Airport railway design (GTC)	Ove Arup and Partners (HK) Ltd	Oct. 1993
120	Temporary utilities design	Hyder Consulting Ltd (formerly Acer Consultants (Far East) Ltd)	May 1993
121	Permanent utilities design	Parsons Brinkerhoff (Asia) Ltd	May 1993
122	Stormwater, sewerage and irrigation design	Scott Wilson Kirkpatrick (HK) Ltd	May 1993
125	Fuel distribution system design	Parsons Brinkerhoff (Asia) Ltd	Oct. 1993
126	Aviation fuel receiving facility design	MMBP-Atkins	Oct. 1994
127	Feasibility study and environmental impact assessment for aviation fuel pipeline	Montgomery Watson HK Ltd	June 1995
140	Software quality management	Engineering Centre for Software	Dec. 1995
141	Communications systems design	Parsons Brinkerhoff (Asia) Ltd	Oct. 1993
142	Security systems design	Parsons Brinkerhoff (Asia) Ltd	Oct. 1993
145	Waste management study	Montgomery Watson HK Ltd	Sept. 1993
150	Airfield tunnels design	Hyder Consulting Ltd (formerly Acer Consultants (Far East) Ltd)	May 1993
151	Airfield pavements design	MMBP-Atkins	July 1993
152	Airfield ground lighting design	Gibb-Harris and Sutherland	July 1993
153	Apron lighting design	Rust Asia Pacific Ltd	July 1993
155	Perimeter fence and ancillaries design	Mouchel Asia Ltd	Nov. 1993
156	Northern runway and north-west apron design	MMBP-Atkins	July 1996
157	Northern runway and north-west apron airfield lighting design	Gibb-Harris and Sutherland	July 1996
162	Airport ancillary buildings design	Ho and Partners	Jun 1995
170	Landscaping design	Scott Wilson Kirkpatrick (HK) Ltd	Apr. 1994
190	New airport transport study	Wilbur Smith Associates	July 1992
192	Noise mitigation measures study	Llewellyn-Davies	Oct. 1992
193	Urban design guidelines and study	Urbis Travers Morgan Ltd	Dec. 1993
199G	Marine geology of Chek-lap Kok	British Geological Survey	Aug. 1993
202	Supply of geotechnical instruments	Sinco Slope Indicator Co. (Furgo)	Jan. 1993
		RS Technical Instruments	Jan. 1993
		Geokon Inc.	Jan. 1993
		Geotechnical Instruments (HK) Ltd	Jan. 1993
255	Site investigation and laboratory testing (land)	Intrusion-Prepakt Foundation Ltd	Sept. 1993
256	Marine site investigation and laboratory testing	Lam Geotechnical Ltd	Oct. 1993

Appendix 2.
Consultants and contractors concerned with design of Hong Kong's new airport