# Recent Advances of Engineering Survey Operations for Tunnel Construction in Hong Kong

**Steve Y. W. LAM, People's Republic of China**

**Key words**: Engineering surveying, tunnel, construction

## SUMMARY

This paper reports recent advances of engineering survey operations, that is, operations of geodetic control and deformation monitoring surveys, detail mapping and geometric modelling, and setting-out and as-built surveys, for the design and construction of tunnels in Hong Kong. The advances include integrative approach to: (1) combine measurements collected by different surveying methods and instruments in geodetic control; (2) collect and analyse data by both geodetic and geotechnical systems in monitoring ground displacements and structural deformation; (3) acquire data by both conventional and mobile mapping systems and address them inside CAD and GIS; (4) use remote-controlled video total station and laser guidance system in driving tunnel; (5) collect as-built data and determine the positioning and geometric tolerances for checking against the structural gauge or dynamic envelope of the tunnel.

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## 1. INTRODUCTION

Tunnels are increasingly built for transportation systems of modern cities in order to preserve open aboveground space for enhancing visual environment and people's recreation activities. These tunnels also provide easy passages to underground buildings which can sustain earthquakes and other natural disasters, consume less energy for heating and cooling, and do not need attractive exterior finishes thus having less maintenance and insurance costs. Construction methods include cut-and-cover method for shallow tunnels, drill-and-blast method for driving tunnels through rock, shield method for driving tunnels through sub-aqueous soils and rocks, and joining immersed tubes on seabed to form cross-harbour tunnels. The paper reports recent advances of engineering survey operations (Figure 1), that is, geodetic control and deformation monitoring surveys, detail mapping and geometric modelling systems, and setting-out and as-built surveys, for the design and construction of tunnels in Hong Kong. TQM of the survey operations under ISO 9001(2008) is given in (Lam, 2010) while other survey operations are described in the following sections.

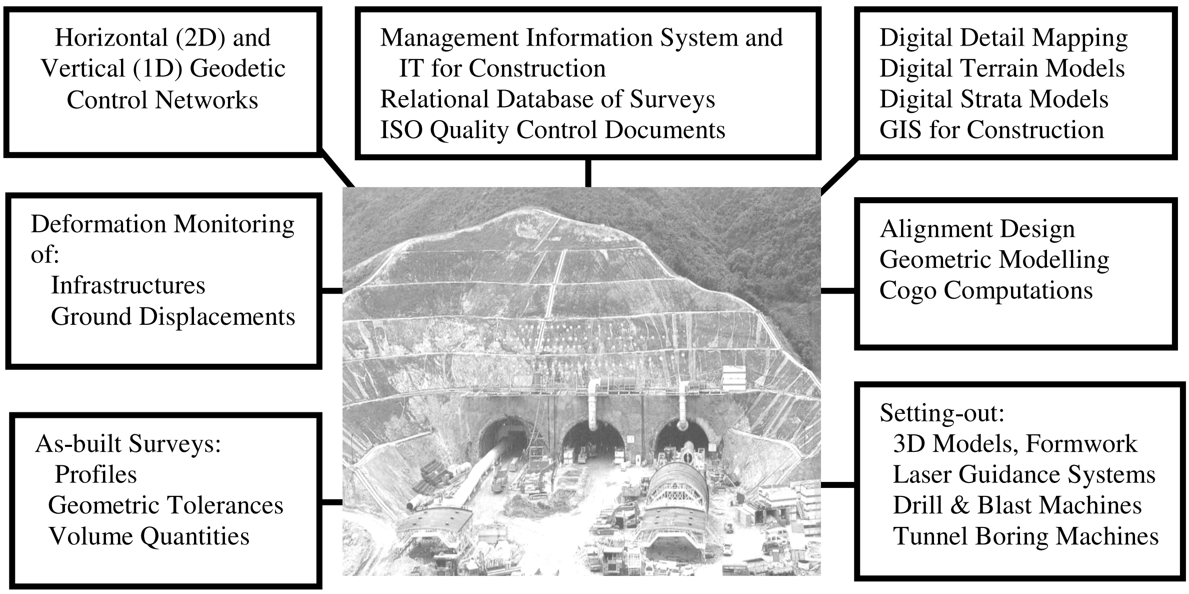



**Figure 1: Engineering survey operations for tunnel construction (Lam and Tang, 2001; Lam, 2005).**

## 2. GEODETIC CONTROL AND DEFORMATION MONITORING

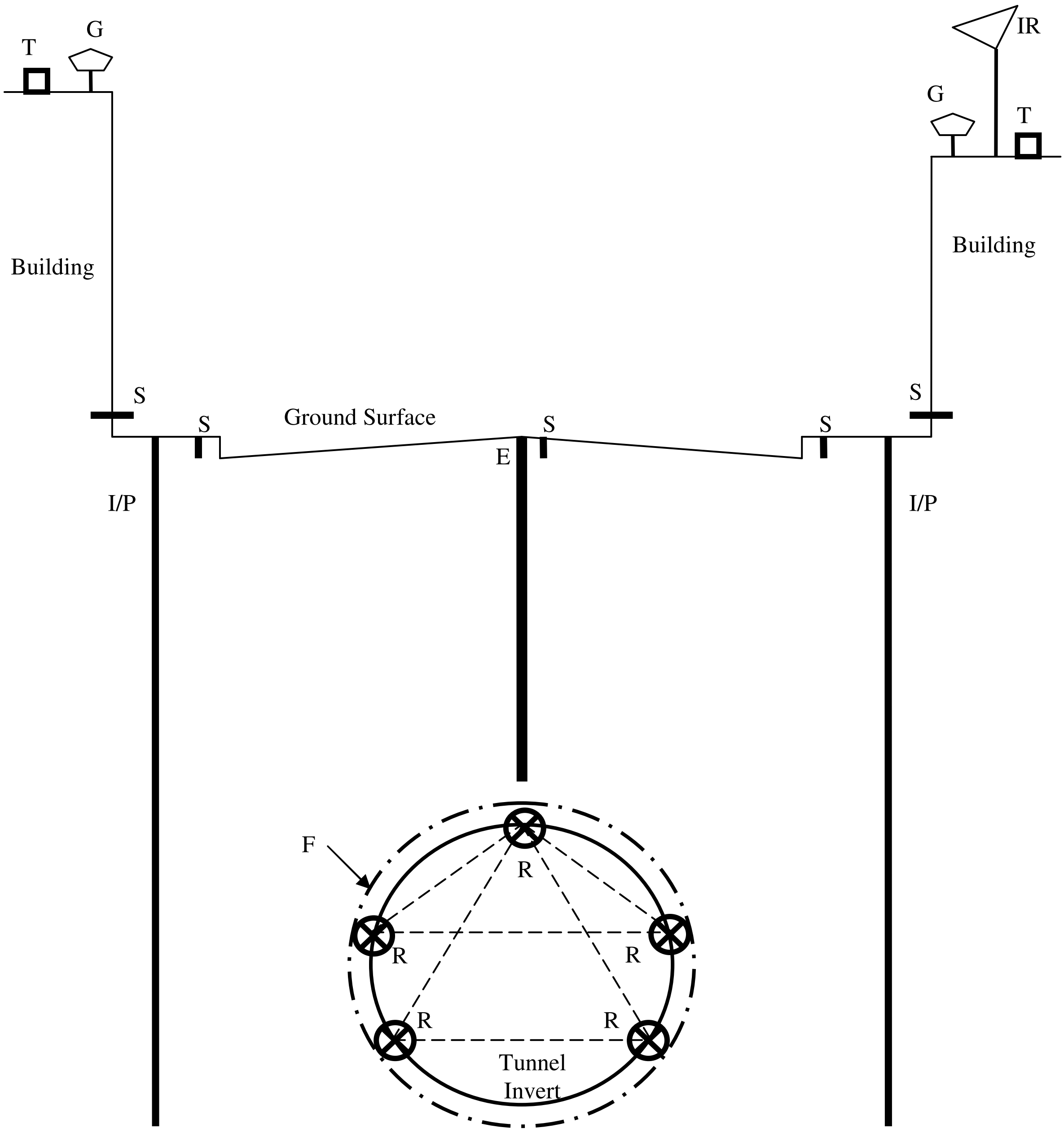
Starting from whole to part, establishment of horizontal and vertical geodetic network and co-ordinate reference system according to (e.g., GSD, 1978, 1983, 1996a, 1996b; FGCS, 1998; HKSAR, 1995), both on ground surface and underground, is required for subsequent survey operations. The establishment comprises the following stages: network design and pre-analysis, monumentation of control points on site, field measurements, data processing and filtering of outliers, network adjustment by the least squares model, and post-analysis knowing the accuracy of coordinates and measurements. In network design and pre-analysis, Paul Cross (1985) recommends computer simulation and linear programming approaches to optimize the quality, precision and economy of control surveys. Based on the layout of the tunnel and its digging from one end or from opposite ends, tunnel surveyors apply methods described by, for example, (Chrzanowski, 1981; Lam, 2005), to estimate positional errors and optimize breakthrough accuracy. Re-alignment of the breakthrough section may be needed in an attempt to avoid or minimize remedial works for the completed liners of the tunnel.

On ground surface, horizontal control network is optimized by a combination of triangulation, trilateration, traverse and GPS observations while vertical control network (vertical bench marks) are established independently from the horizontal survey by precise levelling of the control points. Before driving the tunnels from portals in opposite directions, first-order vertical control points at tunnel portals are checked independently by GPS even though with third-order accuracy. Horizontal control network is then extended to the underground tunnels by zig-zag or braced traverses through access portals, inclined shafts and stairwells. The transfer of horizontal control points through vertical ventilation shafts can be achieved by co-planning method, Weisbach method, or braced quadrilateral method depending on available instrumentation. In modern practice, the braced quadrilateral method is often applied with least squares computational software in plumbing the horizontal control points from ground surface to the bottom of the shaft. After the coordinates of horizontal coordinates of horizontal control points at the intersection of the tunnel and the shaft have been fixed, gyro-theodolite is used to establish and maintain direction in driving the tunnel. The transfer of vertical control from ground surface down to underground tunnels depends on the configuration of the access. For ramps and inclined shafts, precise differential levelling is used; for vertical shafts, vertical EDM and precise tape are used.

During the lifecycle of the project, these control points are being used in Structural Health Monitoring (SHM) of ground displacements and structural deformation for the safety of the workers and the public. In which, geodetic instruments (e.g., precise level, geodetic total station, multi-antenna GPS and interferomatric synthetic aperture radar (InSAR)) and geotechnical instruments (e.g., fibre-optic sensors) are being applied. Typical instruments for monitoring tunnel cross-section are shown in Figure 2. Based upon the magnitude of vibration of the structure and its deformed model, inversion algorithms (e.g., Balageas et al., 2006) have been developed for reverse engineering analysis to determine the stiffness of building materials and thus ensure the stability and safety of the structure under stress. The monitoring relies more on geodetic data than geotechnical ones because it is difficult to re-calibrate geotechnical instruments after they are being installed on or embedded inside the structures. Until recently, it has been found that the use of differential InSAR (D-InSAR) and ground reflectors is highly cost-effective for monitoring displacements of ground surface on both the local and regional scale (Ye et al., 2004; Strozzi et al., 2005). Such data are being collected by remote sensing platforms, for example, GeoSAR of NASA and RADARSAT-2 of Canada Space Agency. This will further enhance project appraisal as well as construction safety.

## 3. TOPOGRAPHIC MAPPING AND GEOMETRIC MODELLING

Mapping of all features, both on ground surface and underground, and integrating them properly into Web-based geographic information system (GIS) according to, e.g., ISO 19100 series of standards, and into computer-aided design (CAD) systems to facilitate project planning, engineering design and construction. The different layers of GIS data may include information on lot boundaries, buildings, roads, utilities, topography, street directory maps, borehole records, geological maps and memoirs, rainfall records, ground water conditions, etc. Depending on the accuracy required of the survey, these data can be acquired by ground-based total station and 3D mobile mapping system. The mobile mapping system integrates data from GPS receiver, inertial measurement unit (IMU), laser scanners (over 8000 3D-points per second) and digital camera (over 15 frames per second) which can be mounted on trucks, hydro vessels or aircrafts. Point clouds and digital imagery are then uploaded into CAD, GIS and downstream engineering software for alignment design and geometric modelling of the tunnel (e.g., Lam and Tang, 2003). The resulting model is then segmented into regions or structural components for project appraisal, architectural design, design and analysis of new structures, computing quantities of earthwork and materials of the designed for cost estimation, contract administration and project scheduling.




**Legend:**
E: Rod extensometer to monitor ground displacements at different depths
F: Fiber-optic sensors embedded in liners for measuring stress, strain and vibration
G: GPS receiver/antenna
R: Reflectors for use with geodetic total station to monitor displacements and convergence
S: Settlement bolts for precise levelling
T: Biaxial tiltmeters
I/P: Inclinometer and piezometer
IR: InSAR reflector

**Figure 2: Monitoring of tunnel cross-section by geodetic and geotechnical instruments.**

## 4. SETTING-OUT AND AS-BUILT SURVEYS

When the precise tunnel geometric models are available in computer, the points to be staked are then extracted from the cross-section interpolated at the required chainage, and coordinated so that construction layout from nearby control points is feasible with the use of modern total stations. For setting-out of immersed tubes (e.g., cross-harbour tunnels), long prefabricated sections are set out and joined under-water. For rock tunnels constructed by drill-and-blast method, surveyors are responsible for setting out the laser guidance system at predetermined position and entering laser offset tables, vertical and horizontal alignments of tunnel centre, designed cross-sections and drill plan into the computer of the drill-and-blast machine.

If tunnel boring machine (TBM) is used in which the whole cross-section of the tunnel head is advanced simultaneously, 3-D coordinates and (X, Y) offsets of the laser-line(s) at chainage intervals will be provided by the surveyor to the TBM operator who steers the machine by observing laser beam targets mounted on the machine. Some TBM have sensors to detect and display the position of the laser while driving the TBM on the correct alignment. TBMs are also guided by video total station which measures angles and distance to the reflectors on the TBM. From the coordinates of the reflectors, positioning parameters (start and end chainages of the drive, X-offset (left/right), Y-offset (up/down), lead, tilt and roll) are determined in real-time and transmitted continuously to the TBM operator in steering the machine. In this case, alignment laser and control targets are not needed in the setting-out and the surveyor stays inside the computer chamber. It greatly increases the accuracy of survey measurements and reduces the risk of setting-out at the tunnel head.

As-built surveys are required to check tolerances of finished structures by the following methods:

(1) Measuring offsets directly to a structure gauge (i.e., cross-section template) being mounted on a trolley and driven along the tunnel. This method time-consuming and labour intensive for large cross-sectional envelope.

(2) The application of laser profiler which emits laser beams at angular intervals on a rotating plane either vertically or orthogonal to the tunnel centre-line. For those rotating on the orthogonal cross-section, the axis of rotation must be set parallel to the gradient and radial to the horizontal alignment at the required chainage. For those rotating on a vertical plane, the instrument must be set to scan on the required vertical plane. The resulting data are then corrected onto orthogonal plane by applying tunnel gradient at the cross-section. The task requires total station for setting up the profiler and is time-consuming without proper tunnel software.

(3) The use of reflectorless total station by which points outcropped from tunnel surface are automatically recorded, processed and analysed by laptop computer system in the field (e.g., TMS of Leica Geosystems and Amberg Technologies). These coordinated points are then joined to form 3D Triangulated Integrated Network (TIN) surface for plotting undercuts and overcuts on cross-sections at regular interval and for plotting undercut contours or areas of undercut over 50 mm (Figure 3). The reports are used by construction workers to remove the undercuts in the field.

(4) The use of survey trolley for checking both the railway track and its tunnel (e.g., Swiss trolley of Terra International). The trolley is equipped with longitudinal and lateral inclinometers, track gauge meter, odometer, total station reflector, GPS receiver, laser scanner, digital camera and data collector and is driven on the track to collect the coordinates of rails and the cross-sectional elements (e.g., tunnel lining). Data recorded by sensors, auto-tracking total stations, GPS receivers and laser scanner will be combined together for checking against the designed alignments, cross-section templates and the railway standards.

(5) The use of light weight LISAR scanner (e.g., ILRIS-3D of Optech Inc.) and reflectorless total station with built-in scanner and digital camera (e.g., Topcon's Imaging System) are becoming popular. These imaging stations are not manufactured specifically for tunnel construction and require customization programming to plot undercuts and overcuts from their TIN models.

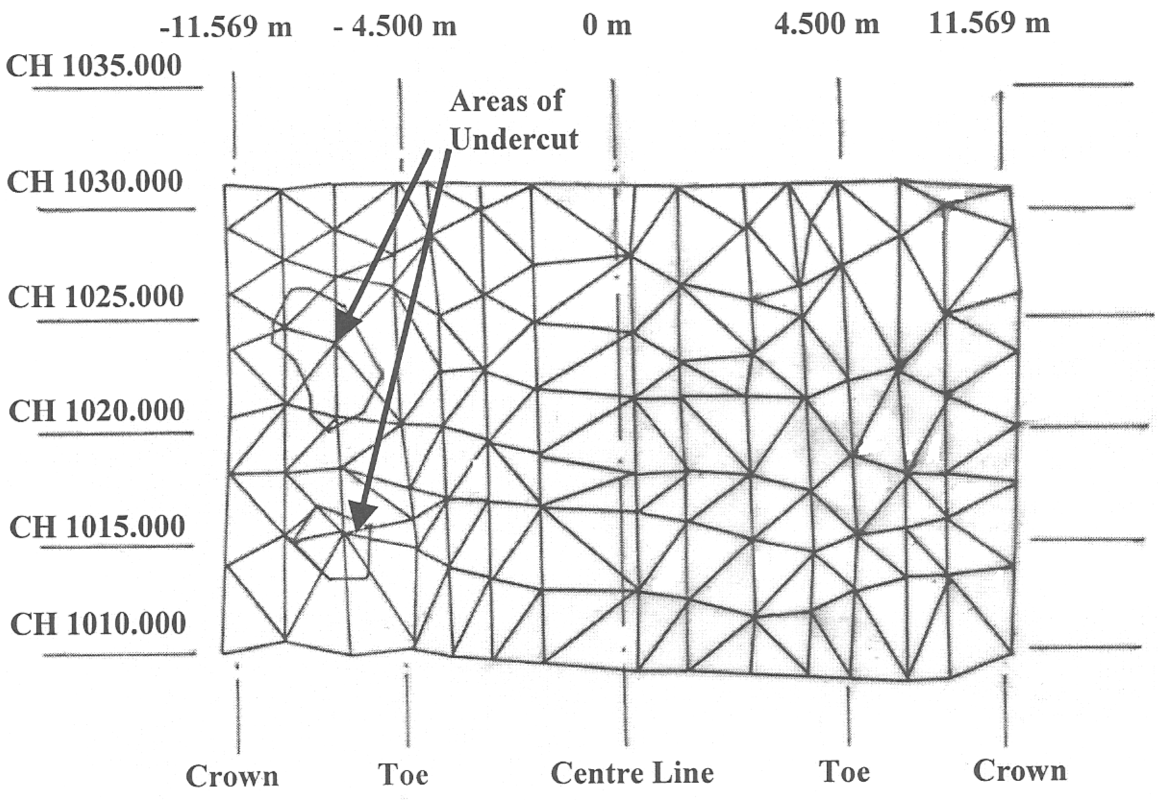



**Figure 3: TIN of undercut areas on plan.**

## 5. CONCLUSIONS

Recent advances of engineering survey operations (Figure 1) including the operations of geodetic control and deformation monitoring surveys, detail mapping and geometric modelling systems, and setting-out and as-built surveys for the design and construction of tunnels, are briefly presented in this paper. In geodetic control, the author recommends that horizontal control network should be optimized by a combination of triangulation, trilateration, traverse and GPS observations, and that computer simulation in both least squares and non-least-squares approach (e.g., linear programming model) should be applied in its design and pre-analysis. In monitoring ground displacements and structural deformation, integrative approach of combining both geodetic and geotechnical measurements is recommended (Figure 2). In topographic mapping for project appraisal and engineering designs, conventional ground-based total station and mobile mapping system are being used to acquire the required and useful data which should be plotted and addressed according to CAD and ISO standards inside Web-based GIS. In the setting-out and as-built surveys of tunnel structures, remote controlled video total station and mobile sensors on survey trolley have proved themselves highly efficient and cost-effective. Continual research is undertaken to investigate and advance the survey operations for various types of tunnels and their associated structures. If readers have any valuable comments on all aspects of tunnel surveying and construction, it is hoped that they would be brought to the attention of the author.

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## BIOGRAPHICAL NOTES

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