PRECISE DIGITAL MODELS FOR CONSTRUCTION SURVEYING OF HIGHWAY TUNNELS

LAM YAU WAH STEVE

M. Phil.

THE HONG KONG POLYTECHNIC UNIVERSITY

2001

Abstract of thesis entitled

' Precise Digital Models for Construction Surveying of Highway Tunnels'

submitted by **Lam Yau Wah Steve**

for the degree of **Master of Philosophy**

at The Hong Kong Polytechnic University in **October 2001**.

ABSTRACT

The applications of tunnel surveying systems are, in general, restricted by technical, instrumental, economical and user-oriented conditions. The major technical problems are: (1) different coding and alignment systems have been proliferated among tunnel projects, (2) insufficient geometric models and representations for tunnel objects, (3) inadequate accuracy standards and tolerance criteria governing the surveying of geometric models for construction processes, and (4) incomplete understanding of the surveying techniques and computational geometry for the construction of highway tunnels.

Therefore, this thesis describes the current state of the art surveying techniques and different boundary-based geometric modeling systems suitable for use with microcomputer computers to tackle the aforementioned technical problems in construction surveying of highway tunnels. These precise geometric modeling systems consist of Sweep models, Skinning models, Mesh models, combined Constructive Solid Geometry (CSG) and Boundary Representation (B-Rep) models, and computational geometry for irregular surfaces and tunnel intersections.

While the Sweep models are commonly adopted in existing tunnel software, the other models are not adopted and are conceptualised and designed by the author for future applications in tunnel construction.

The research involves the investigation of parametric models, data structures, algorithms, file formats and other technical information for creating, representing, and manipulating the precise geometric models of the physical parts of highway tunnels to expedite the surveying operations.

Profitability is a product of highly efficient and cost-effective automation in construction surveying. The demand for high accuracy standards in tunnel surveying is highlighted by the increasing adoption of precast or prefabricated components for modern building structures, and the setting-out of computerized machines in driving tunnels. Therefore, these geometric modeling systems are adopted and being developed by the author to fulfill the requirements of the quality control system and accuracy standards in pursuit of such excellence and profitability in tunnel construction projects. Accuracy standards and codes of practice, which govern the accuracy of these geometric models, are investigated and summarized in this thesis. Finally, in order to inspect the overall geometrical deviations of a physical object in tunnel construction, the concept of geometrical tolerances and its applications are proposed by the author.

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ACKNOWLEDGEMENTS

I hereby wish to express my greatest appreciation to The Hong Kong Polytechnic University for providing me the staff development funding and the opportunity to pursue and successfully complete my post-graduate programme in the University.

I am greatly indebted to Professor Yong-qi Chen, Head and Chair Professor of the Department of Land Surveying and Geo-Informatics of the University, for his approval and supervision of my research studies. His valuable guidance, comments and advice will never be forgotten.

I want to express my appreciation to Professor William H. K. Lam of the Department of Civil and Structural Engineering of the University, Dr. Richard Coleman, Associate Professor of the University of Tasmania, and Mr. Yam Khoon Tor, Associate Professor of the Nanyang Technological University, for their valuable comments and intellectual challenge during the examination period and the viva leading to new understanding on the research topics.

Finally, I am very grateful to all members of my family who always support my unalterable interest in tunnel construction.

CHAPTER 1

INTRODUCTION

1.1 An Overview

Highway tunnels, railway tunnels and the utility tunnels are the three main types of tunnel found in the construction industry. In this thesis, the geometric models, conceptualised and designed by the author for construction surveying of highway tunnels, will be reported. Geometric modeling systems for surveying railway tunnels and utility tunnels, which are governed by different geometric design standards and codes of construction practice, will not be included in this thesis.

Construction surveying is an integral part of a tunnel construction project starting from early in the design phase in the office to the completion of construction in the field. It is important because of its intensive involvement in monitoring the alignments and the precise three-dimensional models of tunnel structures both in the office and in the field.

With the advent of low-cost personal computers (PC) in the early 1980's, these computing machines are becoming important tools of our surveying profession. Under the control of application software, the excellent performance of PC in survey operations is reflected not only in mathematical manipulation, but also in storing and retrieving specific pieces of information in the appropriate circumstances.

International competition, decreased availability of skilled labor, and increased emphasis on quality are forcing surveyors and engineers to use computerized systems to automate their design and production processes. Being focused on the importance of computer applications in construction projects, geometric modeling systems for use with digital computers will be investigated so that new automated systems can be created in the near future for surveying and construction of highway tunnels.

The main objectives of this research study are to:

1. Review the surveying techniques, accuracy standards and codes of practice in construction surveying of highway tunnels;
2. Identify existing geometric modeling systems and create the conceptual, functional and operational models of new and precise ones for modern construction processes; and
3. Develop new geometrical tolerance standards for applying these geometric modeling systems in tunnel construction.

In this thesis, the geometric modeling systems are the systems of data structures and algorithms for creating, representing and manipulating geometric models of structural elements such as excavation surfaces, concrete liners, steel ribs, etc., of highway tunnels. These modeling systems are the sweeps, the skinning, the combined Constructive Solid Geometry (CSG) and Boundary Representation (B-Rep) models, the Finite Element Mesh (FEM) models, and the computational geometry for irregular tunnel surfaces and tunnel intersections. The sweeping models are commonly adopted in tunnel surveying systems for the construction of highway tunnels. The remaining ones are proposed by the author to be adopted in tunnel surveying system. These models are organized into fields, records, files, and data structures so that they can be processed and maintained efficiently in microcomputer systems. The study of these models in this research also comprises the following perspectives:

1. Logical and mathematical descriptions of tunnel objects and alignments, in the form of precise digital models, that can be applied in survey computations to position accurately the geometric models of highway tunnels together with their structural members in the field. In terms of mathematical properties, the representation schemes should comply with (a) the domain of the object class, (b) the uniqueness by having a one-to-one correspondence between an object and its representation, and (c) the validity of representing a realistic geometry.
2. Implementation of these digital models, in the form of survey algorithms and data structures, that can comply with their functional requirements and precision of construction surveying.
3. Qualitative analysis of the survey data that can be associated with the geometric models.
4. Future development of more advanced modeling systems to produce/ maintain the state-of-the-art computerized systems for the surveying industry and the construction industry.

1.2 Organization of the Thesis

Survey operations, survey databases, the procedures and the requirements of tunnel surveying for the construction of highway tunnels will be briefly described in Chapter 2. The survey operations follow a complete set of standards, specifications, and office and field procedures for each construction phase of tunnel structures. In this chapter, existing government standards, survey specifications, instrumentation, and software to expedite control surveys, detail mapping, setting-out, as-built surveys and deformation monitoring are discussed. The standards stipulate and govern the accuracy requirements of the geometric models under investigation.

In Chapter 3, the coordinate referencing systems for the geometric design and construction of highway tunnels will be presented. Based on a Cartesian coordinate system, the principal alignments of highways and highway tunnels can be established according to the geometric design standards together with their tunnel structures in a three-dimensional space. Different geometric models suitable for modeling tunnel structures will be introduced in this chapter.

Research on geometric modeling involves the study of data structures, algorithms, and file formats for creating, representing and manipulating geometric models of the physical parts and the construction processes of highway tunnels. Geometric modeling systems provide an environment similar to the one in which the physical model is created and naturally manipulated in its design and later constructed in the field. Using a geometric modeling system, the designer deforms, adds, and cuts pieces off the visual model in the process of detailing a shape inside a computer system. The mathematical representation, attribute information and other technical data of geometric models will facilitate setting-out and construction of their physical objects on sites. An important issue is to guarantee that the geometric representation that is extracted from the modeling system is a good approximation of the original volume data set and reliable for programming. Therefore, the following factors are also considered in the selection of the geometric modeling systems:

1. Geometric configuration of tunnel entities,
2. Associated topology,
3. Array sizes allowed among programming compilers,
4. Memory size and allocation of computer systems, and
5. Data management.

Various types of geometric models together with their principal components suitable for tunnel construction are presented in Chapter 3. Four categories of geometric models are introduced, namely the graphical models, the wireframe models, the surface models and the solid models. In this thesis, we focus on the applications of solid modeling systems in tunnel construction for the following reasons:

1. Solid modeling systems are now widely used by engineers and surveyors in tunnel construction projects.

2. Solid modeling systems have been proved successful in the CAD/CAM industry.

3. Solid modelers create unambiguous and complete geometry of an object and differentiate the inside and outside of the space occupied by the object in the three-dimensional space. Thus, the boundary of a solid has been distinctively defined together with the interior of the solid.

4. Hidden-lines/surfaces removal and shaded images can be produced by solid modelers with better and faster boundary evaluation processing than the wireframe and surface models.

5. It is easy to generate desired cross-sections and longitudinal profiles of a solid by applying a plane/solid intersection in sectioning.

6. Solid modelers permit fast construction of finite-element models by which automatic structural analysis of mechanical or structural parts are performed and subjected to a variety of loading conditions.

Common methods of modeling a solid are Constructive Solid Geometry (CSG), Boundary Representation (B-Rep), Sweeping, Skinning and Decomposition Representation (D-Rep). Major geometric procedures needed for solid modeling, regardless of any modeling scheme, are curve/curve, curve/surface, and surface/surface connectivity and intersection calculations. These modeling schemes either decompose a complex solid into simpler and more easily representable volumes, or defining them as volumes enclosed by a set of boundary surfaces.

Most the personal computer systems do not have the memory or processing speed to meet the demands of solid modeling in a satisfactory way. Therefore, in order to ensure adequate memory and to reduce computation time, most of microcomputer systems for surveying operations are still addressing objects in the form of wireframe models.

In Chapter 3, geometric data, topological data and geometric operations for geometric modeling systems will be presented by referring to the ISO 10303 Standards and the Standard for the Exchange of Product Model Data (STEP). These standards are now adopted in Computer-aided Design (CAD), Computer-aided Process Planning(CAPP) and Computer-aided Manufacturing (CAM) in the manufacturing industry to provide a complete, unambiguous, computer-readable definition of the physical and functional characteristics of a product throughout its life cycle. Some of the elements may not be applicable in civil engineering and the building industries. Therefore, only those elements that are suitable for tunnel construction are presented in this chapter.

It is inevitable to design and model highway tunnels from 2D geometry because all the geometric design standards for the design of highways and highway tunnels have been established with the work space on projection planes. Therefore, creation of 3D models from their 2D geometry according to traditional practice will be discussed in Chapter 3. An important issue is to guarantee that the final three-dimensional model that is generated from the data set of its 2D geometry is a precise representation of the original object.

Several techniques are being used for the construction and editing of geometric objects in tunnel projects. Some of them are currently in use and quite popular and others are quite promising for future development. The parametric sweep models and the skinning models are suitable for setting-out and as-built surveying of highway tunnels, and will be presented in Chapter 4 and Chapter 5 respectively. These geometric models are also suitable for use with microcomputer systems.

During the construction phase of a tunnel project, irregular surfaces will be formed after excavation. These irregular surfaces can be represented by Triangular Irregular Network (TIN) surfaces in surveying computations. The modeling technique is given in Chapter 6 with practical examples. Tunnel models formed by mesh generation are presented in Chapter 7. A mesh model is a collection of finite elements that model the tunnel structures so that it can be applied in setting-out, as-built surveying and Finite Element Analysis.

Most of the commercial CAD/CAM softwares in the market are designed based on the applications of combined Constructive Solid Geometry (CSG) and

Boundary Representation (B-Rep) data structures. The combined CSG - B-Rep model plus surface modeling techniques are considered most suitable for CAD/CAPP/CAM of tunnels in future developments. The corresponding algorithms of manipulating geometrical objects and some of the common database structures are described in Chapter 8.

In Chapter 9, the accuracy of geometric models and the determination of their allowable tolerances will be presented. The investigation of geometric accuracy can be considered in three different perspectives. Firstly, positional tolerances allowed for the setting-out and construction of structural elements with respect to a control framework and the ISO 9000 Quality Assurance Programme will be studied based on the theory of positional errors and the past experience in tunnel construction projects. Secondly, the various types of geometric errors associated with the construction surveys of highway tunnels will be researched. Thirdly, the assessments of allowable tolerances for the construction of structural elements of highway tunnels will be investigated. They are the numerical and procedural constraints which describe the allowable error in design or production, and eventually determine the accuracy, quality, and cost of the final product. The following problems are required to be considered and be solved:

1. How to formulate the problems to be faced in finding the tolerance zones of the tunnel entities?

2. What are the methods and mathematical foundation to derive such allowable tolerances in dimensions?

3. What is the basis and current practice for the determination of the parameters needed in tolerance calculations?

Chapter 10 gives conclusions and recommendations for further study.

At the time of reporting, all existing software for tunnel surveying apply only the parametric sweep models in their geometric modeling systems. In this research, the author found that skinning, 3D Delaunay triangulation, mesh models and the combined CSG and B-Rep models will become the principal elements of solid modelers for the next generation of tunnel surveying systems. Some of them had been experimented or applied successfully by the author in the construction of highway tunnels in Hong Kong and other parts of the world. Therefore, their conceptual, functional and operational models are presented in the following chapters.

CHAPTER 2

AN OVERVIEW OF SURVEYING OPERATIONS IN TUNNEL CONSTRUCTION

2.1 Introduction

Survey operations consist of the establishment of a control network, detail surveying and mapping, setting-out for the construction of structural elements, as-built surveys on the completion of a structural element, deformation monitoring for the safety of construction workers and the public, and survey business management. Flow-chart for survey operations in a construction project is shown in Figure 2.1. The survey operations follow a complete set of standards, specifications, and office and field procedures in each phase of the project. Under ISO 9000 standards, survey data are categorized into six main groups as shown in Figure 2.2 (Lam and Tang, 2000). It is important to identify the requirements and priorities for the surveys and develop a strategy for collecting, managing and delivering the data to the users on time. A review of surveying techniques for the construction of highway tunnels can be found in (Lam and Tang, 2001a).

Accuracy standards, specifications and work procedures for each of the survey operations are summarized in the following sections. These accuracy standards and work procedures will govern the precision and functional requirements of the digital models as well as the geometric modeling systems under investigation for construction surveying of highway tunnels.

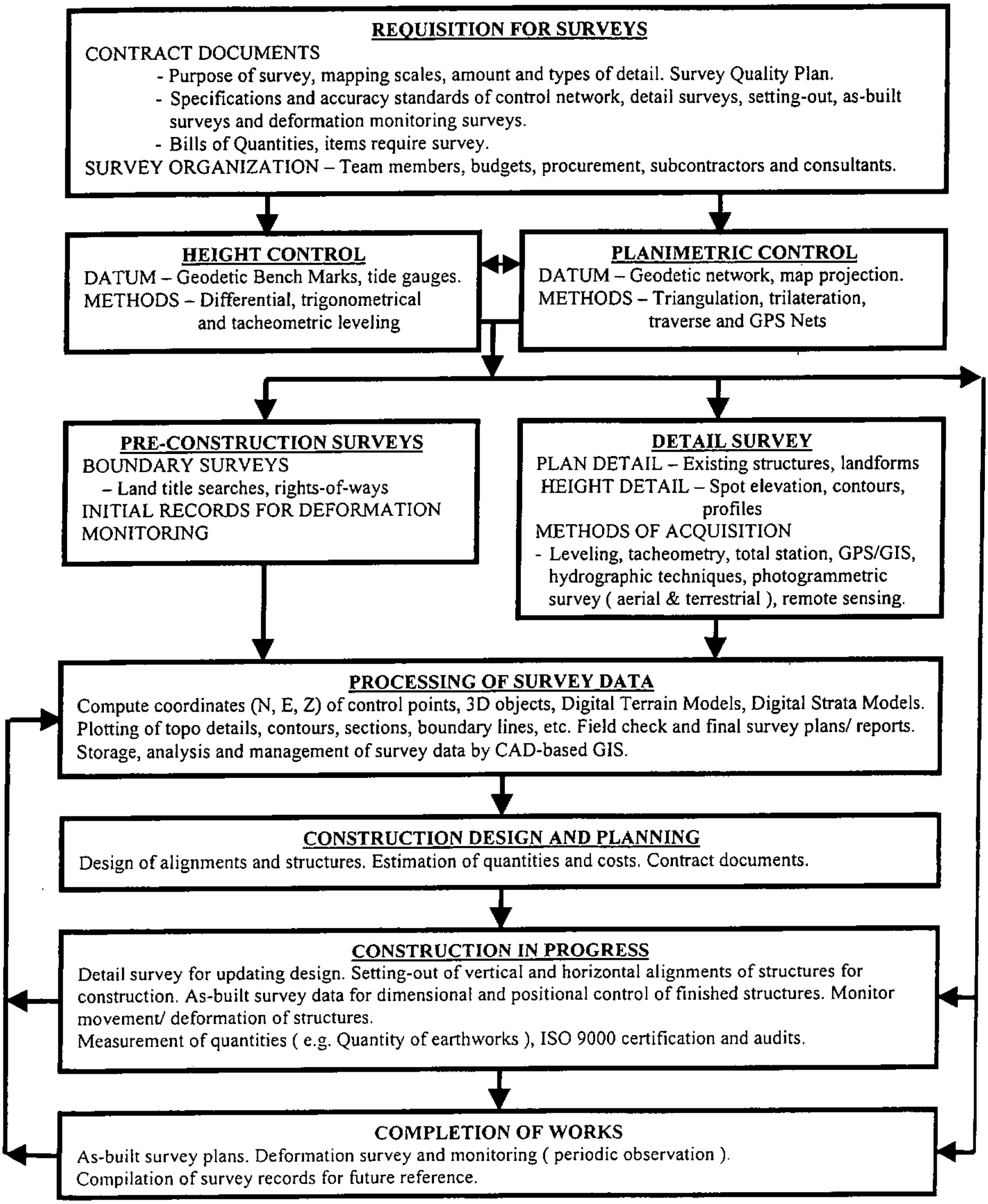


Figure 2.1 Flow chart of survey operations in a construction project.

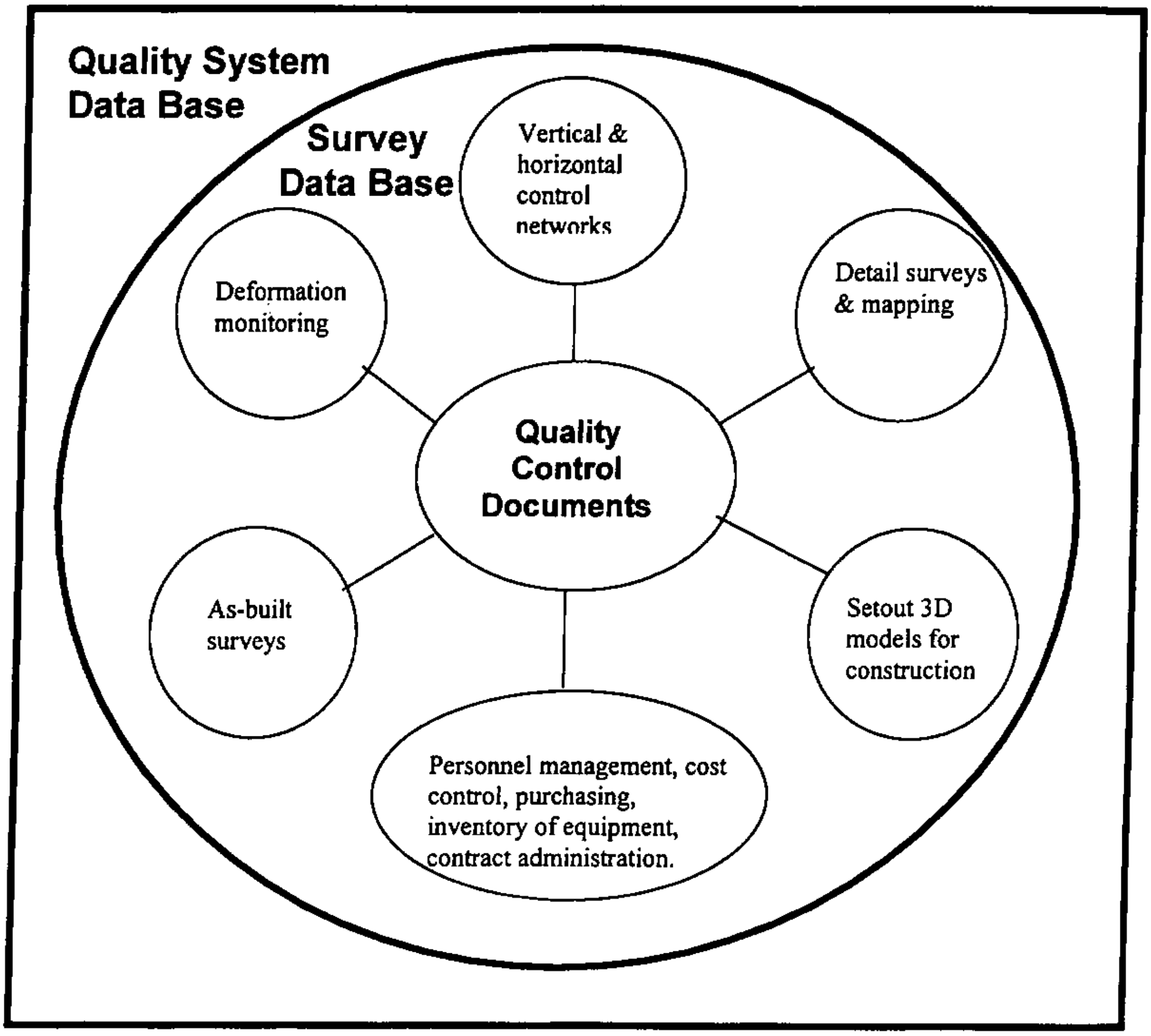


Figure 2.2 Modules of survey database within a SOP(Survey Quality Plan)
(Lam and Tang, 2000).

2.2 Control Survey and Deformation Monitoring

Control surveys are being carried out to provide coordinated networks for detail mapping, engineering planning, geometric and dimensional control, setting-out and deformation monitoring of complex structures in tunnel projects. Example of a horizontal control network for the construction of a tunnel is given in Figure 2.3.

The establishment of horizontal control network comprises of four main stages namely network design and pre-analysis, field measurements, network adjustment and post-analysis. Primary and surface control points are established using precise total station and GPS. Horizontal control points will be extended from ground surface to the underground tunnels by zig-zag or braced control traverses through the access portals, inclined shafts and stairwells. The zig-zag traverses should avoid lines grazing tunnel walls and minimize lateral refraction errors. The transfer of horizontal control points through vertical shafts (Figure 2.4) can be achieved by co-planing method, Weisbach method or braced quadrilateral method. In modern practice, the braced quadrilateral method is normally applied in shaft plumbing. After coordinates of control points have been transferred to the bottom of the shaft, gyro-theodolite will be used by surveyors to establish and maintain azimuth in driving the tunnels.

Although GPS is not suitable for surveying inside tunnel interiors where GPS antennas can not be exposed to the satellites via direct line of sight, its measurements between non-intervisible start points at tunnel portals will improve the accuracy of driving the tunnels from opposite ends. GPS data can also be combined with terrestrial and geophysical measurements in network analysis to achieve more accurate results (Krakiwksy and Thomson, 1974; Leick, 1994; Vanicek and Krakiwksy, 1986; and Wolf and Ghilani, 1997).

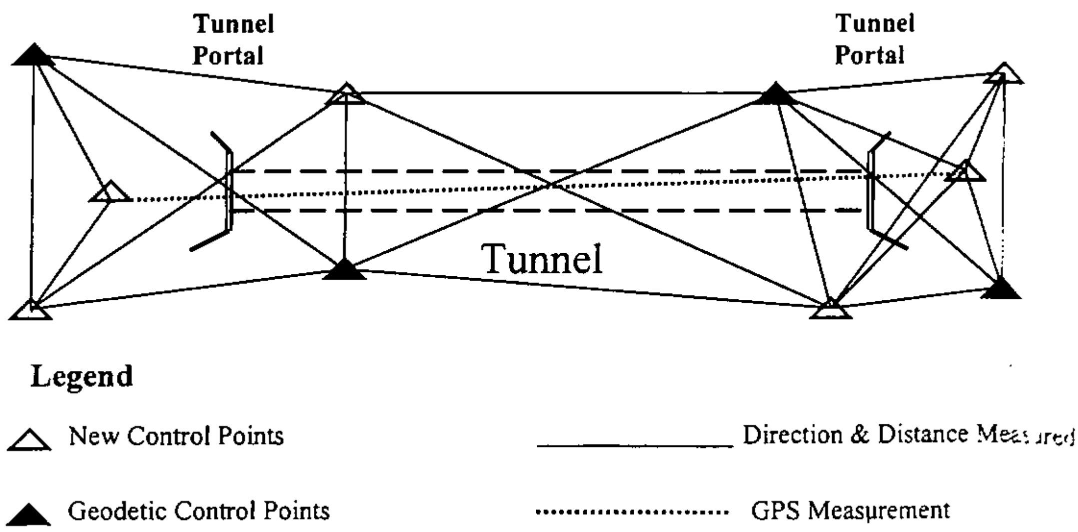


Figure 2.3 Plan view of a control network for tunnel construction

Based upon the layout of a tunnel and its driving from opposite directions, proper methods of finding its positional errors and optimizing its breakthrough accuracy are given in (Chrzanowski, 1981; Robinson et al., 1995). Accuracy of breakthrough and allowable tolerances of setting-out operations are two main factors to be considered in creating the geometric models for the tunnels.

Vertical control points are established independently of horizontal control surveys in order to achieve millimeter accuracy by precise leveling. Control stations should be established in undisturbed areas covering the whole site and in the vicinity under the scheme of deformation monitoring. Before driving the tunnels in opposite directions towards the breakthrough point, independent checks on orthometric height differences between vertical control points at tunnel ends should be carried out by GPS (Figure 2.3). GPS determines heights with respect to the chosen reference ellipsoid while orthometric heights are referenced to the local geoid. The following equation provides the relationship of the two heights:

$$h = H + N \tag{2.1}$$

where h = ellipsoidal height determined by GPS;

H = orthometric height or reduced level determined by spirit leveling technique;

N = geoid-ellipsoid separation (also known as geoidal height).

There are two principal methods to determine geoid-ellipsoid separation for the transformation of GPS ellipsoidal heights to orthometric heights, namely the gravimetric method and the geometric method. The geometric method is recommended by the author in construction projects because gravimetric data are usually not available from local government for accurate transformation. Besides, errors in applying the gravimetric method are difficult to predict and can vary considerably according to location.

In the construction of highway tunnels in Hong Kong, the author applied Delaunay triangulation of planar surfaces to represent the geometric models of geoid-ellipsoid separation. The equation of the plane of a triangle is given by:

$$N = A + B (E_P) + C (N_P) \qquad (2.2)$$

where N is the geoid-ellipsoid separation at point P;

E_P and N_P are easting and northing respectively of point P with respect to the plane coordinate system of the construction site;

A, B and C are coefficients of the plane equation.

In order to determine the three coefficients, a minimum of three coordinated level benchmarks that surround the site and have GPS-derived heights must be available. Thereafter, geoid-ellipsoid separation at any GPS position can be interpolated on its triangular plane by Equation (2.2), and its orthometric heights can be found by Equations (2.1). From the experience of the author, this planar or linear approximation method achieves centimeter-accurate orthometric heights by GPS over small construction areas.

A more rigorous approach is to apply a multiple regression equation as given by (Defense Mapping Agency, 1991; Aw et al., 1995). Other approach is recommended by (Featherstone et al., 1998) in which the gravimetric geoid model is combined with and constrained by using geometrically derived geoid heights that surround the survey area. This geodetic method can be used to transform GPS heights more accurately than either method alone.

The transfer of vertical control points and alignments from ground surface into underground tunnels depends on the configuration of the access. If the accesses are ramps or inclined shafts, the techniques of differential leveling are used. If the accesses are vertical shafts, the transfer of vertical control points through the shafts will be accomplished by measuring the height difference using vertical EDM (Figure 2.5) and steel tapes.

Pseudolite systems are now being experimented by survey scientists in mining tunnels. In the research, a GPS antenna can be installed on these systems to transit GPS signals so that GPS receivers can be applied in precise positioning indoors (Cross, P., 2001).

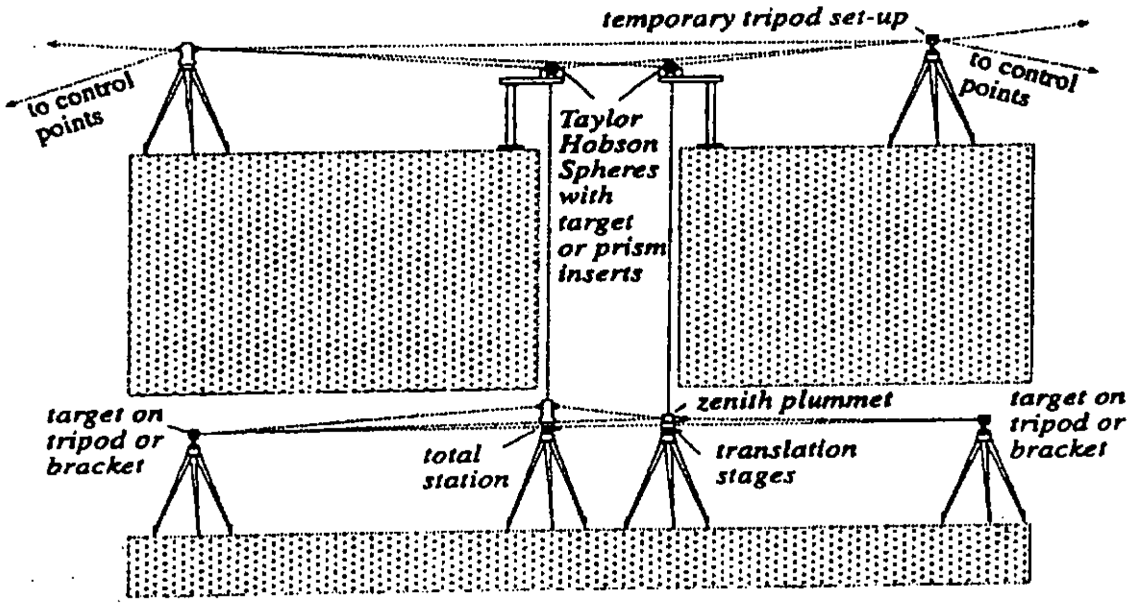


Figure 2.4 Shaft transfer of horizontal control points
(Robinson et al., 1995, Figure 4).

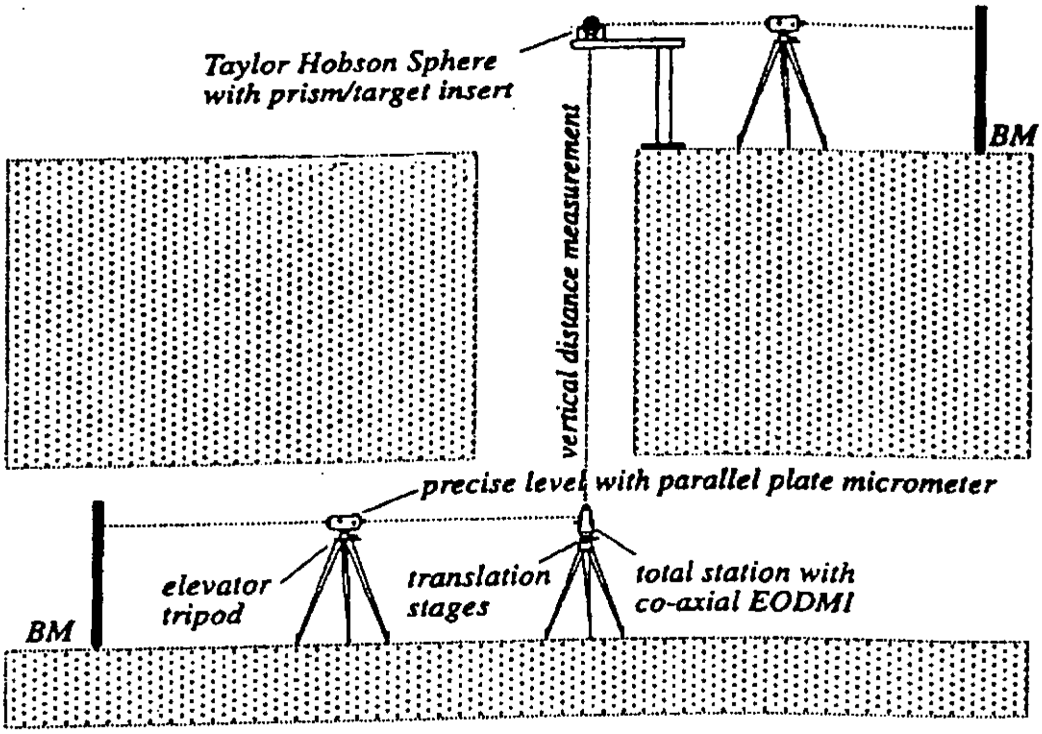


Figure 2.5 Shaft transfer of vertical control points
(Robinson et al., 1995, Figure 5).

Commercial software, which are available in the market for automated computation and optimization of vertical and horizontal control networks, are for instance, GeoLab, STAR*NET-GPS, STAR*LEV, APS (Tang, 1995), OSND and MDMS (Tang et al., 1996). Some of them are able to compute networks and analyze deformations of thousands of control stations and handle both conventional measurements and GPS vectors, separately or combined.

Accuracy standards governing the quality of the final results of survey control network can be found in the following documents:

1. Bureau of Surveying & Mapping (1992). *CH2001-92 Specifications for Global Positioning System Surveys* (in Chinese). People's Republic of China.
2. Federal Geodetic Control Committee (1974). *Classification, Standards of Accuracy, and General Specifications of Geodetic Control Surveys*. National Geodetic Survey, NOAA, U.S.A.
3. Federal Geodetic Control Committee (1988). *Geometric Geodetic Accuracy Standards and Specifications for using GPS Relative Positioning Techniques.* National Geodetic Survey, NOAA, U.S.A.
4. Geodetic Survey Division (1996). *Accuracy Standards for Positioning.* Geomatics Canada.
5. Survey & Mapping Office (1970). *Metrication Instructions No. 1 and No. 2 – Survey Specifications for Control Surveys.* Lands Department, Hong Kong SAR.

Before the 80's, accuracy standards for horizontal control surveys were expressed in linear units as parts per million (ppm) value. In modern construction practice, the statistic used to represent the accuracy of the horizontal coordinates of a point is the 95% confidence ellipse. If the confidence ellipse represents network accuracy, the accuracy of the point with respect to the defined reference system is represented. If the confidence ellipse represents a relative accuracy, the accuracy of the point with respect to another adjacent point is represented. In the new standards, a control survey point will no longer be referred to as a first order or second order point, but rather, for example, as a 1 centimetre point or 2 centimetre point as implemented in Canadian practice (Geodetic Survey Division, 1996). The new standards have been developed so that they are compatible with modern positioning capabilities and consistent with the changing delivery mechanism of any geospatial reference system.

Performance standards governing the procedures of a surveying control network can be found in the following documents:

1. Beijing Survey & Mapping Design Institute (1997). *Technical Specifications for Urban Surveying using Global Positioning System* (in Chinese). People's Republic of China.

2. Geodetic Survey Division (1996). *Guidelines and Specifications for GPS Surveys.* Geomatics Canada.

3. Geodetic Survey Division (1983). *A Guide to Precise Leveling.* Geomatics Canada.

4. Survey & Mapping Office (1969). *Technical Instruction No. 25A – Precise Leveling.* Lands Department, Hong Kong SAR.

5. Surveys and Mapping Branch (1978). *Specifications and Recommendations for Control Surveys and Survey Markers.* Natural Resources Canada.

Horizontal and vertical control points are also used as referencing positions to monitor settlements as well as deformations of building structures and tunnels during the period of construction. Survey methods have proved to be a useful tool for stability monitoring, especially when used in conjunction with geotechnical methods. There are two major deformation analysis methods. One method uses measurement differences while the other method uses coordinate differences. The measurement difference method requires that the same angle and/ or distance be measured in two epochs. The coordinate difference method is more flexible and requires that position of the same control point be measured in two epochs regardless of which measurements were made to determine its coordinate difference. Another advantage of the coordinate difference method is that the survey result can be independently adjusted and checked to ensure data quality. By comparing coordinate difference from the two epochs, the computed movement vectors extending outside their error ellipses indicate significant movement and the control point is probably unstable.

Underground monitoring shall consist of (a) convergence measurements and (b) measurement of rock bolt loads. Measurement of rock bolt loads is required to detect geological movements around the tunnel. For convergence measurements, depending on existing rock type, three or five survey targets are installed on tunnel cross-sections at 10 ~ 50 m intervals as shown in Figure 2.6.

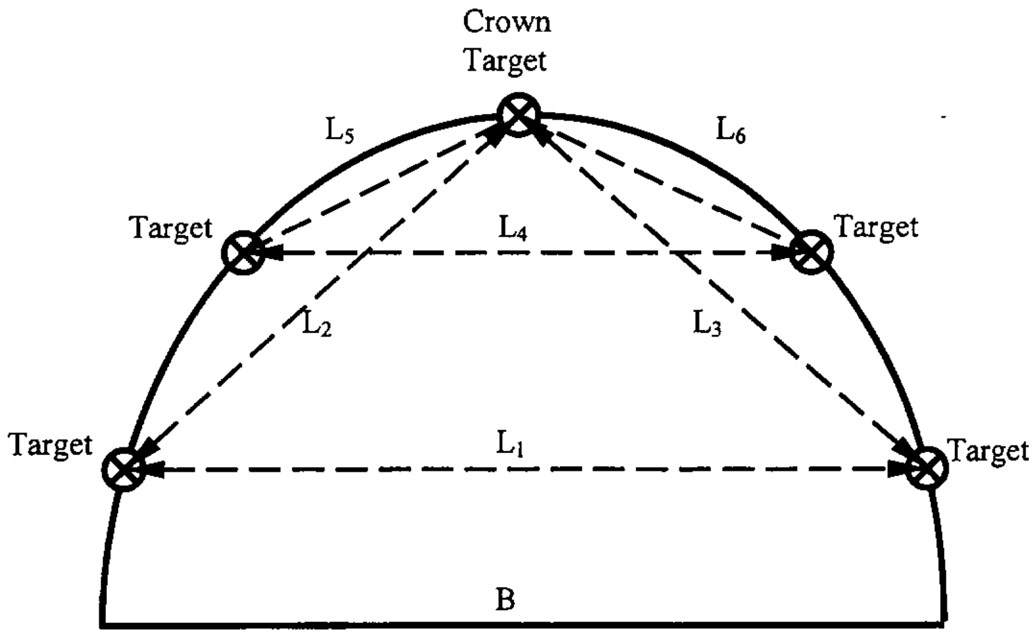


Figure 2.6 Location of survey targets for convergence measurements.

Table 2.1 Frequency of convergence measurements (Particular Specifications of Route 3 Tai Lam Tunnel. Hong Kong Highways Department, 1995)

First 7 days after installation	24 hour intervals
From day 8 to day 22 inclusive	3-day intervals
From day 23 until directed by the Project Manager	Weekly intervals

Deformation of tunnel cross-sections can be measured directly by repetitive extensometer readings between survey markers or indirectly by total station. The operation of the first method may not be permitted as it would block the traffic flow and stop the construction works inside the tunnel. The latter method is thus more commonly used because it will not obstruct construction works. In addition, the survey data can be processed by computer program in the field to determine the 3D coordinates of the survey markers together with the following outputs for checking convergence and relative displacement of the tunnel:

1. Ratio (%) of linear displacement (ΔL) to the slope length (L) between survey markers.
2. Ratio (%) of vertical displacement of the crown marker to the width (B) of tunneling.

Frequency of monitoring convergence is recommended, for instance, in Table 2.1. Other types of deformation under monitoring are settlement and heave (vertical displacement), lateral deformation (horizontal displacement), and length deformation (longitudinal and dimensional displacements). A generalized approach to process, analyze and manage deformation measurements can be found in (Chen, 1983, 1988; Tang et al., 1996). Based upon the geometric model and its deformed model, inversion algorithms have been developed to determine the properties of the building materials and thus the safety of the tunnel structure under stress.

2.3 Detail Surveying and Mapping

Detail surveying and 3D mapping are required of any construction projects. InRoads® and MOSS® are two popular highway software which offer 3D surface modeling technology for land surveyors and civil engineers working with topographical data from data collection, reduction and adjustment, through contouring, profiling and volume computation to drawing production and setting-out. From the topographical data on ground surface and underground, the 3D geometric model of existing structures can be created by which the Engineer is able to design alignments of site formation, roads, drainage systems and other infrastructures. The final geometric model of the design will also provide data for cost estimation, contracting and construction schedules.

In tunnel projects, DSMs(Digital Strata Models) will be generated from stratigraphic and structural geologic data in a solid volume modeling system which allows geotechnical engineers and tunnel engineers to integrate the data, interpret geologic features, and visualize attributes in their true 3D spatial relationships for the purposes of structural design and environmental protection. These geologic data are also important in view of cost-saving and ensuring site safety in tunnel construction.

Currently, most of the civil engineering and construction software in the PC software market is not capable of addressing geologic data from site investigations. These geologic data may be derived from different sources, such as boreholes, monitoring wells, exploration trenches or mapping records. Very few geologic and geotechnical engineering software are available but not fully applicable in the tunnel construction industry.

It is practical to address underground strata on stratified layers inside a computer system according to the classification of soils and rocks (Figure 2.7 and Figure 2.8). Soils may be classified according to (BS 5930, Table 15; Geotechnical Control Office, 1997, Table 20). Rocks will be grouped into types I, II, III, IV and V according to their Rock Mass Quality (Q values) (Barton et al., 1974) in normal construction practice by NATM(New Austrian Tunneling Method). The integration of DSMs with TMS(Terrain Modeling Survey)® is being programmed by the author to expedite site investigation and structural design in tunnel projects. The relationship among geologic stratigraphy, behavior and engineering properties of soils and rocks; and the design of tunneling support are also under investigation by the author in ongoing research but this work is not presented in this thesis. When the DSM is available, finite element modeling can be implemented for the design and structural analysis of tunnel components. Examples of finite element models generated from soil/ rock stratification data for structural analysis of a tunnel design are given in Figure 2.9 (Yi, 1997).

Accuracy of topographical features in a detail survey are governed mainly by its mapping scale, survey instrumentation, survey methods and positional error of identifying physical objects. Positional errors of identifying physical objects in the field are given in Table 2.2.

Table 2.2 Precision of various types of topographical features (Blachut et al., 1979, P. 202).

Type of point	*Identification error in position*
Sharp corners of solid buildings	± 1 to ± 2 cm
Boundaries marked with concrete monuments	± 1 cm
Sidewalk curbs	± 1 to ± 2 cm
Permanent fences	± 2 cm
Lamp or other posts	± 5 cm
Wooden fences	± 5 cm
Boundaries marked with wooden posts	± 5 cm
Trees	± 5 cm to ± 7 cm
Edges of embankments or cuts	± 10 cm to ± 15 cm
Balks	± 15 cm to ± 20 cm
Cultivation limits	± 20 cm to ± 50 cm

Other accuracy standards governing the quality of survey and mapping plans for construction projects can be found in the following specifications:

1. Survey & Mapping Office (1999). *1:1000 Basic Mapping Specification.* Lands Department, Hong Kong SAR.

2. Survey & Mapping Office (1995a). *Basic Mapping System Specification.* Lands Department, Hong Kong SAR.

3. Engineering Survey Offices (1994). *1:200 and 1:500 Survey and Drafting Specifications.* Joint publication of six government departments in Hong Kong.

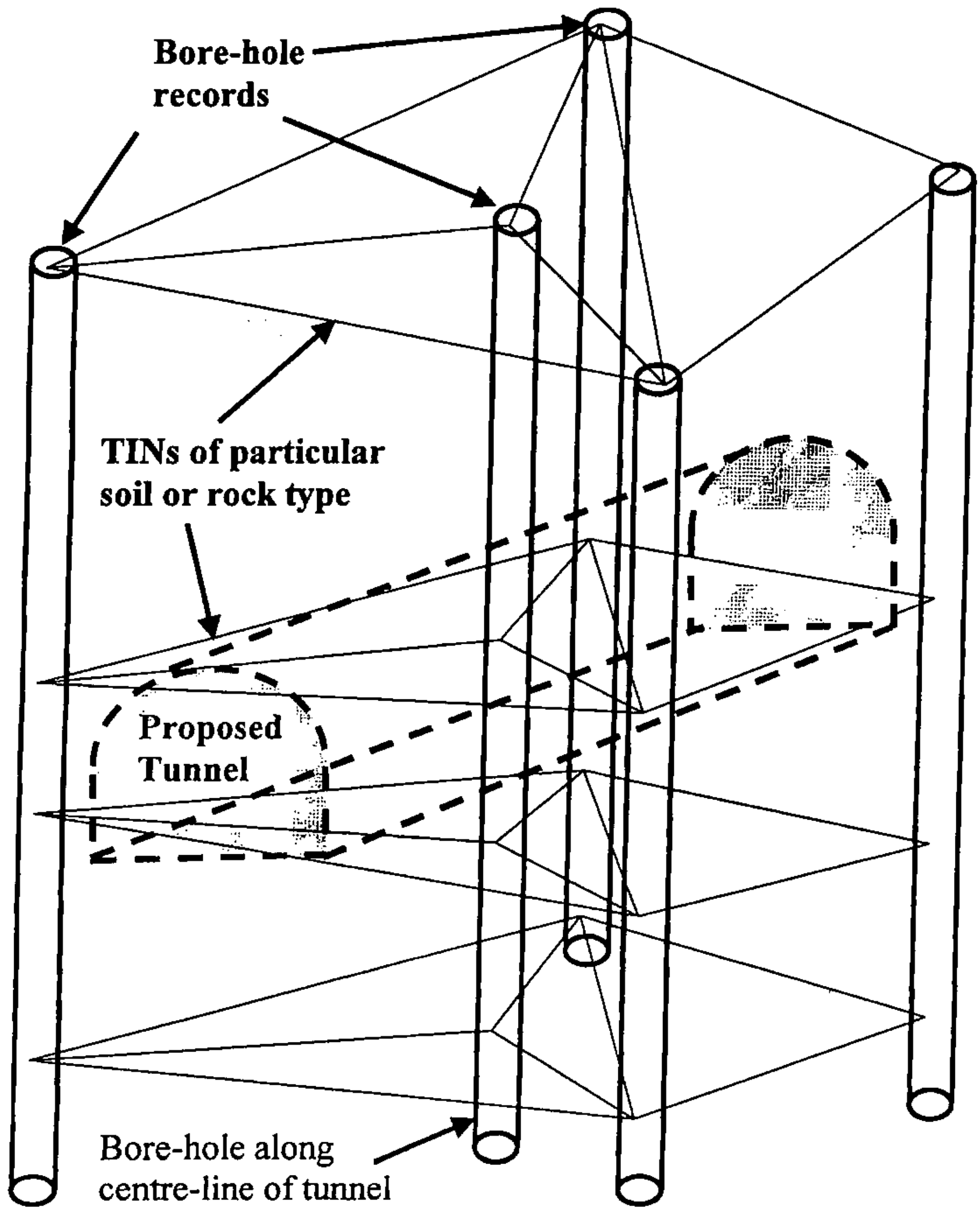


Figure 2.7 Digital strata model formed by stratified layers from borehole records.

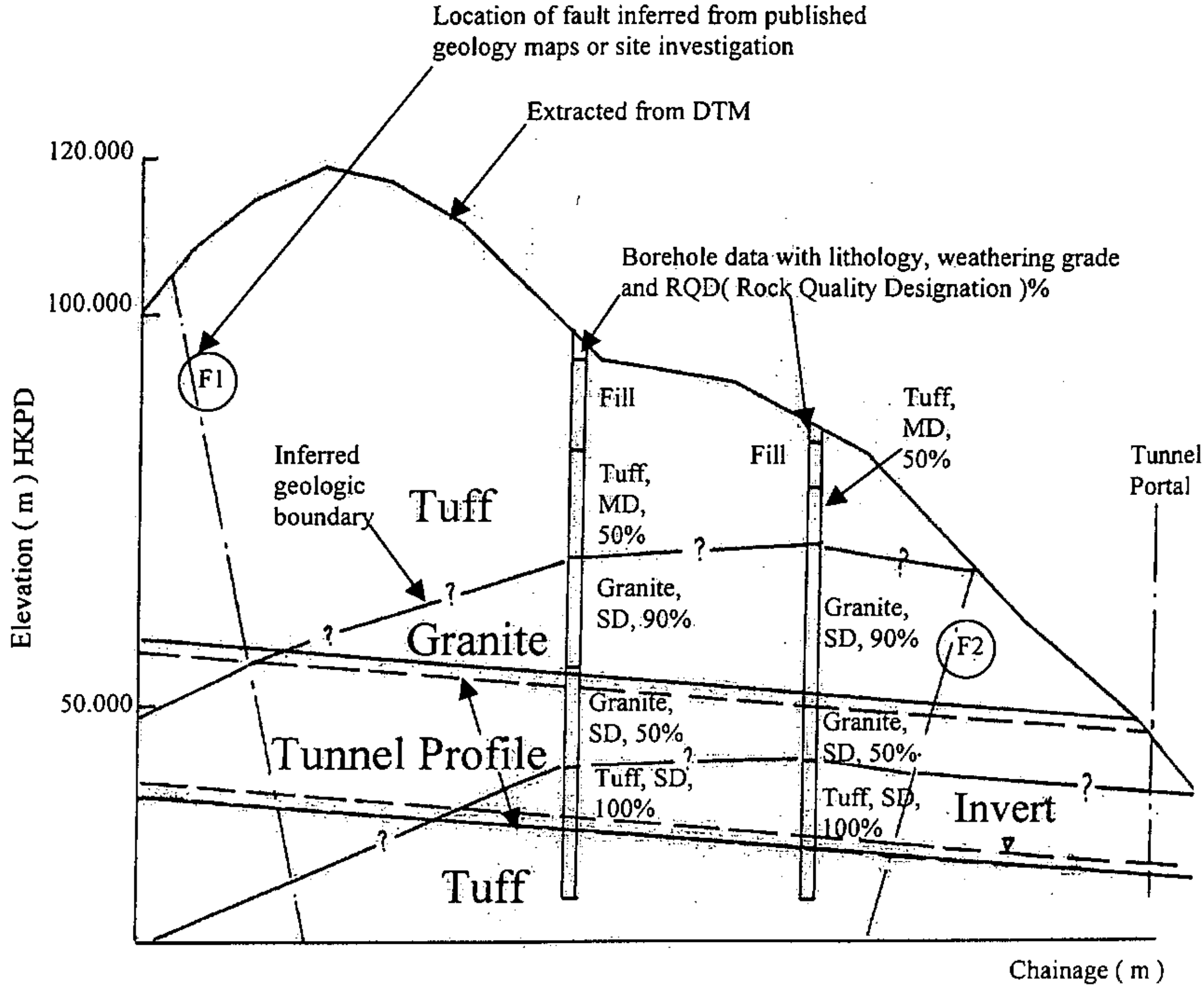


Figure 2.8 Longitudinal profile extracted from Digital Strata Model (Lam and Tang, 2001a).

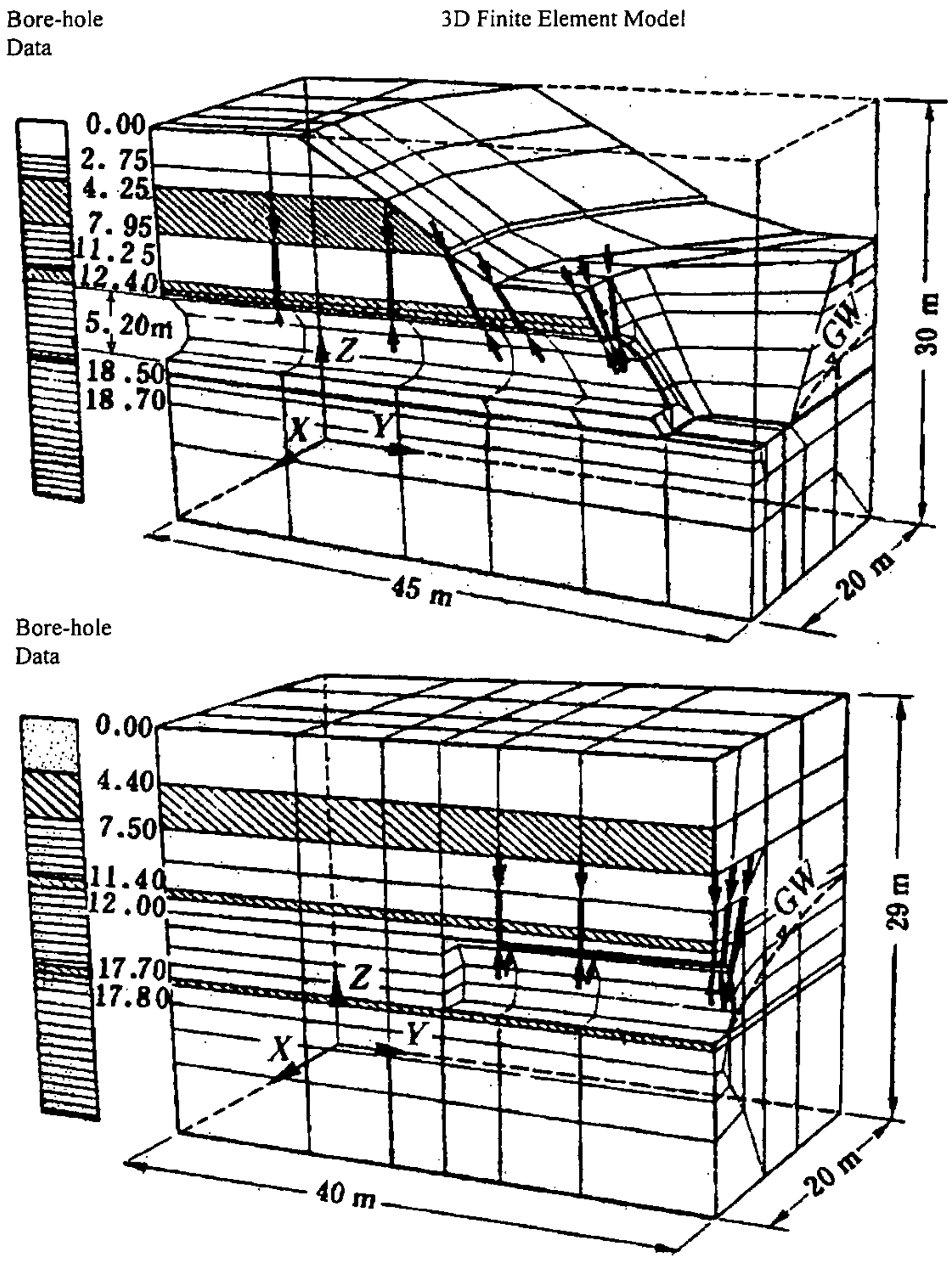


Figure 2.9 Examples of Finite Element Models generated from soil/ rock stratification data and tunnel geometry for structural analysis (Yi, 1997).

Performance standards governing the quality of detail surveying and drafting for construction projects can be found in the following documents:

1. Survey & Mapping Office (1995b). *Basic Mapping System Technical Manual for the Updating of the Building Polygon, Site Polygon and Related Textual Databases.* Lands Department, Hong Kong SAR.

2. Survey & Mapping Office(1997). *Topographic Survey Specification for Architectural Services Department.* Lands Department, Hong Kong SAR.

3. Hong Kong Mass Transit Railway Corporation (1995). *Drawing and CADD Manual.*

4. *GB50026-93 Code of Practice for Engineering Surveying* (in Chinese). People's Republic of China.

5. *JTJ063 Code of Practice for Surveying of Highway Tunnels* (in Chinese). Ministry of Transportation, People's Republic of China.

2.4 Setting-out and As-built Surveying

One of the survey operations of site surveyors is to set-out the position of structural elements, TBM(Tunnel Boring Machine), robotic machines, laser guidance systems and formwork during the construction phase of a tunnel project. Depending on the type of structural element, method of construction and available instruments, different survey methods are applied in setting-out operations. The points to be staked are usually coordinated so that construction layout from randomly located control points is feasible with the use of modern total stations. In order to expedite maximum performance in setting-out, precise geometric modeling systems are under development together with TAS(Tunnel Alignment Survey)®. These geometric modeling systems are suitable for setting-out of different types of laser guided machines (e.g. TUNNPLAN, Tamrock Jumbo Drills, RoboFOR, etc.), TBMs and precast structural elements in modern practice. Details of their applications in setting-out operations are given in Chapter 4.

As-built survey is required on the completion of a construction project for the purpose of re-establishing the principal horizontal and vertical control points and to locate the positions of all structures and improvements. These control points may also be used to monitor any deformation occurring on the structures. Depending on surveying on ground surface or underground, GPS, total station systems and photogrammetric systems can be used in the establishment of control points and the acquisition of data that define the as-built facilities. These systems permit acquisition of data in data collectors and on film or as digitized images for transfer to a GIS for subsequent reduction, processing, retrieval, review, analysis, plotting and production of final reports.

As-built surveys are carried out in completed tunnels to determine clearances available for the installation of pipelines, lighting, ventilation, etc. The surveys provide a record of existing structures and the as-constructed condition of the tunnel. As-built survey of a tunnel should be implemented in two steps. The first step is to survey the finished tunnel before and after the breakthrough. The second step is to check if existing tunnels have been built to within allowable tolerances, and if the design tolerances are exceeded, to see if it is possible to realign the tunnel without remedial work to the existing structures. Methodology, instrumentation and details of their applications in as-built surveying of highway tunnels are given in Chapter 4.

Table 2.3 provides the overall tolerances allowed in respect of the departure of any point on the internal profile of the structure from its established centre-line. Allowable tolerances for the manufacture of precast tunnel segments are also given in (The British Tunneling Society and the Institution of Civil Engineers, 1997). The allowable tolerances given in Table 2.3 are found most likely based upon the past experience in tunnel construction. Geometric tolerances should also be considered to provide an overall picture of the as-built results. Therefore, findings on geometric tolerance for tunnel construction are given in Chapter 9. These tolerances are numerical constraints that describe the allowable errors in design or production, and eventually determine the accuracy, quality, and cost of the tunnel.

Table 2.3 Allowable errors for setting-out of tunnels (The British Tunneling Society and the Institution of Civil Engineers, 1997, Table 4)

			Tunnel Diameter	
			< 5 m	> 5 m
1	Expanded segmental linings:	Line and Level	± 25 mm	± 40 mm
2	Grouted segmental lining:	Line and Level	± 35 mm	± 50 mm
3	Cast In-situ concrete lining:	Line and Level	± 35 mm	± 50 mm
4	Cast In-situ hydraulic invert:	Line	± 35 mm	± 50 mm
		Level	± 10 mm	± 10 mm
5	Shotcrete lining:	Line and Level	± 30 mm	± 75 mm
6	Pipejacking:	Line	± 50 mm	-
		Level	± 35 mm	-

Accuracy standards governing the setting-out and as-built surveying of highway tunnels can be found in the following publications:

1. British Tunneling Society and the Institution of Civil Engineers (1997). *Model Specification for Tunneling.* Thomas Telford.

2. ISO 3443 (1979). *Tolerances for building.* Parts 1 to 8. International Organization for Standardization.

3. Ballast D. K. (1994). *Handbook of construction tolerances.* McGraw-Hill.

Performance standards governing the setting-out and as-built surveying can be found in the following standards and codes of practice:

1. *JTJ042-94 Technical Specifications for Construction of Highway Tunnel* (in Chinese). Ministry of Transportation, People's Republic of China.

2. *JTJ063 Code of Practice for Surveying of Highway Tunnels* (in Chinese). Ministry of Transportation, People's Republic of China.

3. *GB50026-93 Code of Practice for Engineering Surveying* (in Chinese). People's Republic of China.

4. ISO 4463 (1989). *Measurement methods for building – Setting-out and measurement.* Parts 1 to 3. International Organization for Standardization.

5. ISO 7077 (1981). *Measurement methods for building – General principles and procedures for the verification of dimensional compliance.* International Organization for Standardization.

6. ISO 7737 (1986). *Tolerances for building - Presentation of dimensional accuracy data.* International Organization for Standardization.

7. ISO 7976 (1989). *Tolerances for building – Methods of measurement of buildings and building products.* Parts 1 and 2. International Organization for Standardization.

8. ISO 8322 (1995). *Building construction – Measuring instruments – Procedures for determining accuracy in use.* Parts 1 to 10. International Organization for Standardization.

An enormous amount of geo-spatial data and design drawings will be collected and managed inside the geographic information system (GIS) of the project. The different layers of GIS data include information on lot boundaries, buildings, roads, utilities, topography, street directory maps, geological maps and memoirs, rainfall records, ground water conditions, etc. These data will be used to demarcate cadastral boundaries and site limits; to locate the properties owned or occupied by petitioners; to assess the environmental impact and disruption that may be caused by construction works; to identify surface properties that are likely to be affected by settlement or other displacements during tunnel construction; to analyze obstructions, such as piled foundations of existing buildings and tunnels on or near the new tunnel alignments; to divert public utilities that are encroaching the tunnels; and to expedite CAD/CAPP/CAM of the tunnel project.

Having found the precision required of all surveying operations in tunnel construction as stipulated in the standards and codes of practice, we are able to identify the precise geometric models required of highway tunnels in the following chapters.

CHAPTER 3

GEOMETRIC MODELING SCHEMES FOR HIGHWAY TUNNELS

3.1 Coördinate Referencing Systems for the Design and Construction of Highway Tunnels

Today, geometric models are designed in an electronic space which is defined in terms of 3D Cartesian (rectangular) coordinates inside computer systems. The 3D modeling space or work space has at least one permanent coordinate system known as the global or world coordinate system. For specific tasks, local or auxiliary coordinate systems may be defined relative to the main axes of an object or the global coordinate system. Therefore, for practical aspects of a construction project, it is necessary to create a rectangular grid coordinate system most suited to the project area so that location, alignments and geometric models of all the building structures for the works can be designed and set out with minimum complication.

This orthogonal projection system will provide a one-to-one correspondence between points on the surface of the Earth and points on the plane surface, and allows spatial coordinates to be used. The conversion between geodetic and plane coordinates can be expressed in terms of mathematical formulas that permit numerical computation to any predetermined accuracy for the result. In addition, a central meridian will be chosen passing through the center of the project area so that the need for applying scale factor and (t – T) direction corrections for all sight lines could be excluded in plane computations except for very long surveyed lines, where

T is the projected grid azimuth of the arc and t is the plane azimuth of the chord for a projected line of sight in plane computations. The design of such a plane surveying system for construction projects is best illustrated by the local Grid Plane Coordinate System in Hong Kong (Figure 3.1).

During the past 30 years, massive infrastructure projects including the new twin runway International Airport, railways, tunnels, highways, bridges and other associated structures were constructed in Hong Kong. As shown in Figure 3.1, a false origin (800,000.000mN, 800,000.000mE) has been designated at the southwest corner of the grid system so that all the plane coordinates are positive. All heights, levels or vertical elevations on land refer to the Principal Datum (reduced level = 0.000 m) which is approximately 1.23 m below the mean sea level of Hong Kong. Over 200 main horizontal control points and about 1400 level benchmarks have been established to facilitate all surveying operations in Hong Kong (Survey & Mapping Office, 1995c). Some of the ground-based positioning techniques are described in (Lam and Chen, 2000) for such a coordinate referencing system.

Figure 3.2 illustrates the three-dimensional Cartesian coordinate system normally adopted by tunnel projects. In this coordinate system, positions of objects along a route are expressed by the NEZ(Northing, Easting, Elevation) system and the COZ(Chainage, Offset, Elevation) system. The NEZ coordinate system facilitates geometric design, coordinate-geometry (cogo) computations and quick setting-out in the field using modern surveying instruments such as hand-held computers, electronic total stations and GPS.

In the COZ coordinate system, reference lines are chosen to facilitate geometric design of site formation and structural elements. Common reference lines are road centre-lines or other alignments of main structural features which are parallel to the geometric forms of the tunnel route. The position of an entity is then defined by its chainage which is the distance from the start point on the reference line, its offset left or right from the reference line, and its elevation above or below the principal level datum. Facing increasing chainage, the offset on the left-hand-side is addressed as negative offset inside the computer system while the offset on the right-hand-side is regarded as positive offset.

In order to create 3D solid models from 2D geometry of cross-sections, a third coordinate system is also adopted to define the position (X, Y) of any point on the cross-section profile from the principal alignments and the tunnel centre. As shown in Figure 3.2, X-axis and Y-axis are the normal coordinated axes at the tunnel centre co-planning the cross-section and radial to the horizontal alignment and vertical alignment respectively at a particular chainage. Details of creating 3D models from 2D geometry are given in Section 3.5.

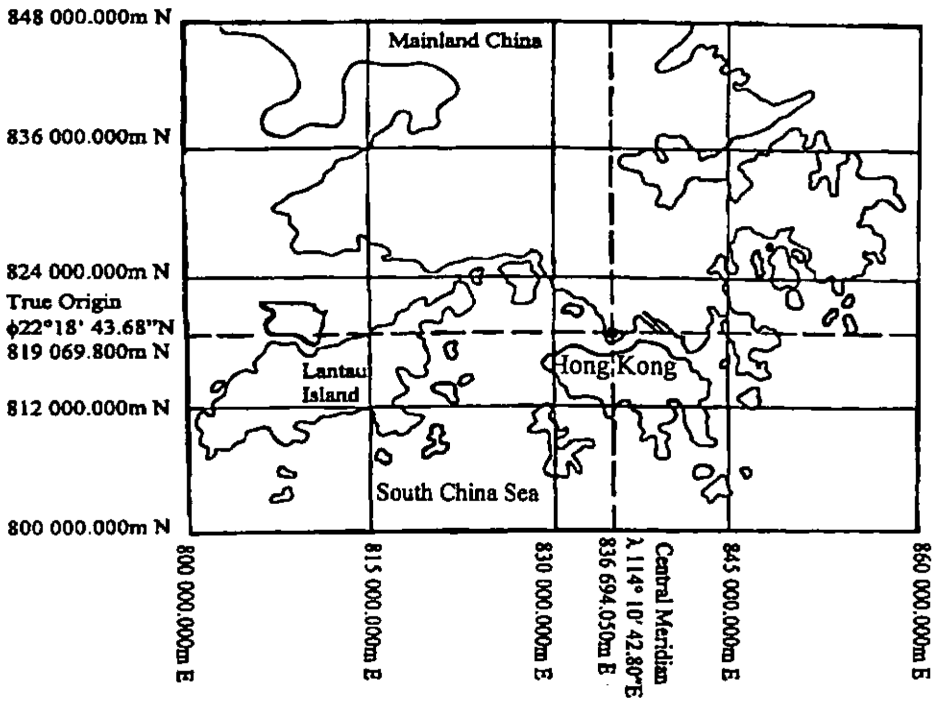


Figure 3.1 Hong Kong 1980 Grid Plane Coordinate System (Survey & Mapping Office, 1995c).

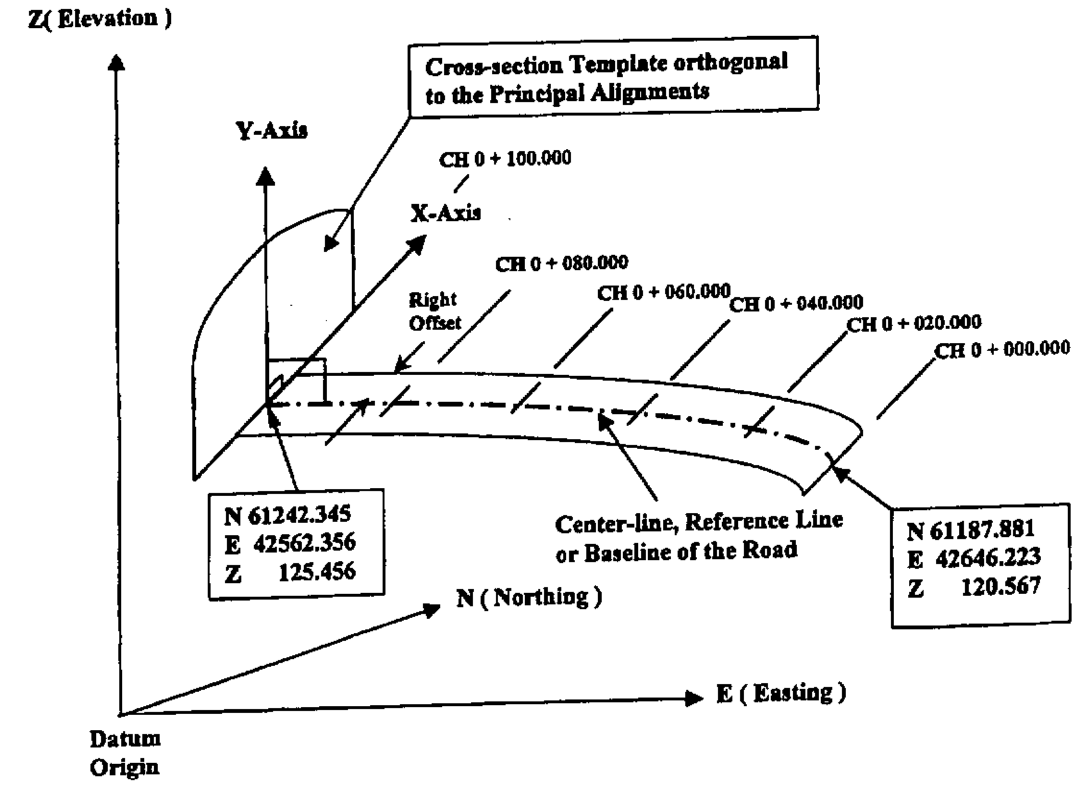


Figure 3.2 Three-dimensional cartesian coordinate system for construction surveying of highway tunnels.

3.2 Principal Alignments of Highway Tunnels

3.2.1 Horizontal Alignments

In transportation engineering, road alignments are designed on the vertical projection planes and the horizontal projection planes according to geometric design standards which can be found in:

1. *Transport Planning and Design Manual,* Volume 2 (Highway Design Characteristics). Transport Department, Hong Kong SAR.
2. *TD9/ 81 Road Layout and Geometry.* Department of Transport, U.K.
3. *Geometric Design Standards for Canadian Roads and Street.* Roads and Transportation Association of Canada.
4. *A Policy on Geometric Design of Rural Highways.* American Association of State Highway and Transportation Officials.
5. *JTJ011-84 Highway Code* (in Chinese). Ministry of Transportation, PR China

As shown in Figure 3.3, the following types of curves are common for horizontal alignments of road works:

1. straight lines of infinite radius,
2. circular curves,
3. transition (spiral) curves,
4. reverse curves, and
5. compound curves.

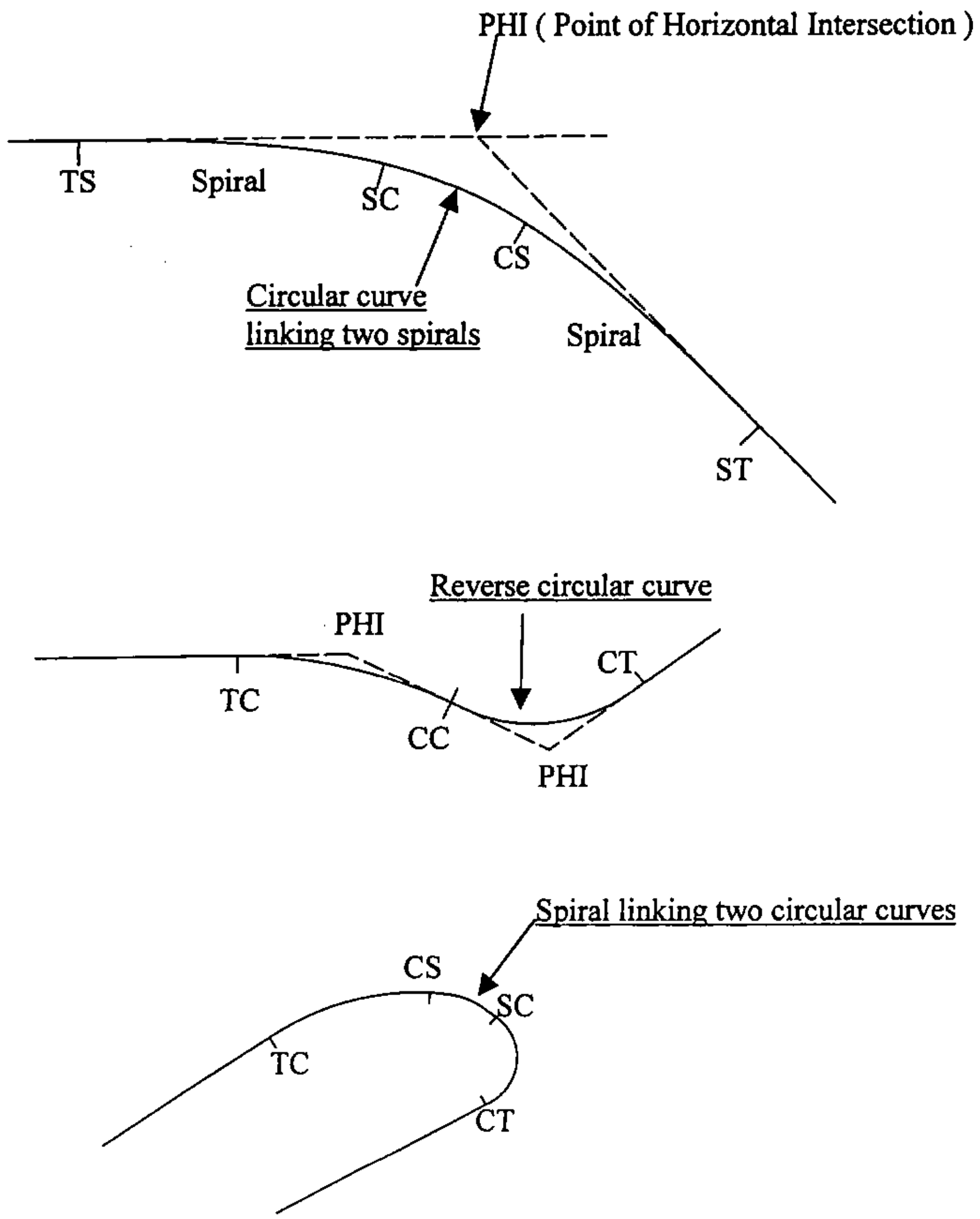
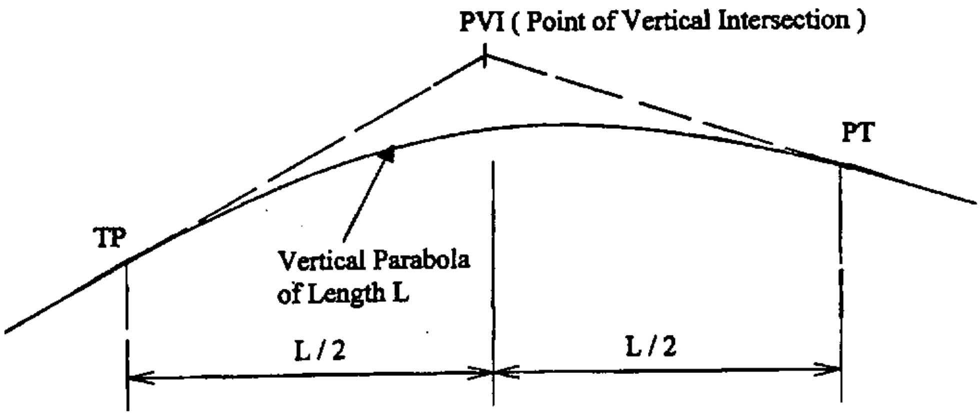


Figure 3.3 Curve elements of horizontal alignment.



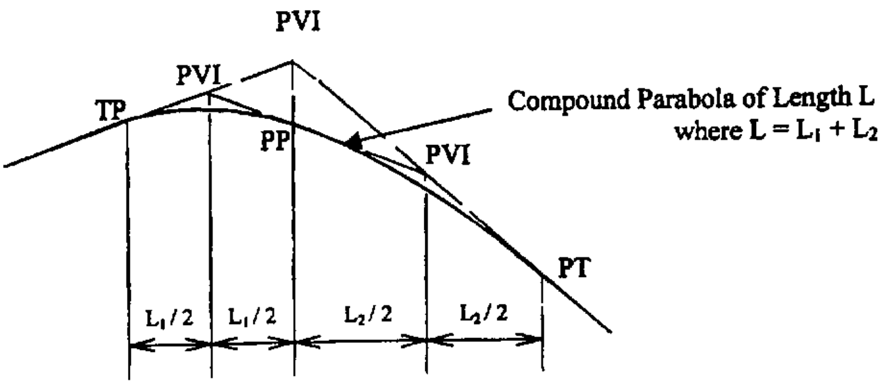


Figure 3.4 Curve elements of vertical alignment.

3.2.2 Vertical Alignments

Curve elements projected on the vertical plane of the vertical alignment include:

1. straight lines of infinitive radius,
2. parabolas (or vertical circular curves), and
3. compound parabolas.

Their combinations are illustrated in Figure 3.4. The vertical alignment lies on the vertical plane that is blended and is passing through the horizontal alignment. It is important to know that the principal alignment, a combination of both the vertical alignment and the horizontal alignment, is the center-line of the geometrical model of a highway tunnel.

Allan et al.(1973), Schofield (1993), Shepherd (1981), and Bickel et al. (1996) provide the detailed descriptions of the parametric models, mathematical formulas and curve computations for both vertical and horizontal alignments of highways and highway tunnels.

3.3 Principal Components of a Geometric Modeling System

Production or manufacturing systems can be classified into discrete-part production and continuous process production. The former refers to producing a product in which the product undergoes a finite number of assembly operations. The latter refers to the manufacturing of a product that undergoes continuous changes such as chemical reactions to transform raw materials into the final products. Construction of tunnels is a discrete-part manufacturing process. It relies on different resources such as people, machinery, and equipment that are constrained by building materials and information flow. In order to adapt rapid product change in view of functionality, geometric accuracy, structural requirements and cost requirements, Computer Integrated Manufacturing (CIM) Systems are becoming popular in the "manufacturing " of tunnels. A geometric modeling system is considered as the core of such a computer-integrated manufacturing system, and surveyors are responsible for the computation and set out of the precise geometric models of the physical parts of tunnels in the field.

Therefore, a successful geometric modeling system must possess a geometric representation scheme that provides shape models for a variety of generation, manipulation, display, and analysis functions as well as the support for applications such as finite-element modeling, construction planning and scheduling, cost estimation and analysis, and setting-out and as-built surveys. Principal components of a geometric modeling system for the construction of highway tunnels are shown in Figure 3.5. Only setting-out and as-built surveys associated with their applications will be discussed in this thesis. Other applications of geometric modeling systems such as FEA(Finite Element Analysis), construction scheduling, etc., are outside the scope of this research.

There are four main categories of geometric modeling systems, namely the Graphical models, Wireframe models, the Surface models and the Solid models.

Graphical models which comprise graphical primitives such as lines, arcs, cones, texts, and other symbols are needed to present engineering data and drawings in 2D or 3D. Each graphical primitive has graphical attribute(s) which determine how it is displayed or plotted. Application-specific information can be addressed with symbols for tasks such as bills-of-materials computations. Graphical entities are stored in layers containing basic geometry, construction components, dimension lines and other supporting notations. Major graphical components and database structures of a CAD drawing are given in Section 3.4.

Wireframe models represent the shape of objects by their characteristic lines and end points together with curve equations, coordinates of vertices and connectivity information for the shape's curves and points. Objects are thus represented by their edges. Because of their inherent visual problems and ambiguity of boundary surfaces, wireframe models are being replaced by surface models and solid models.

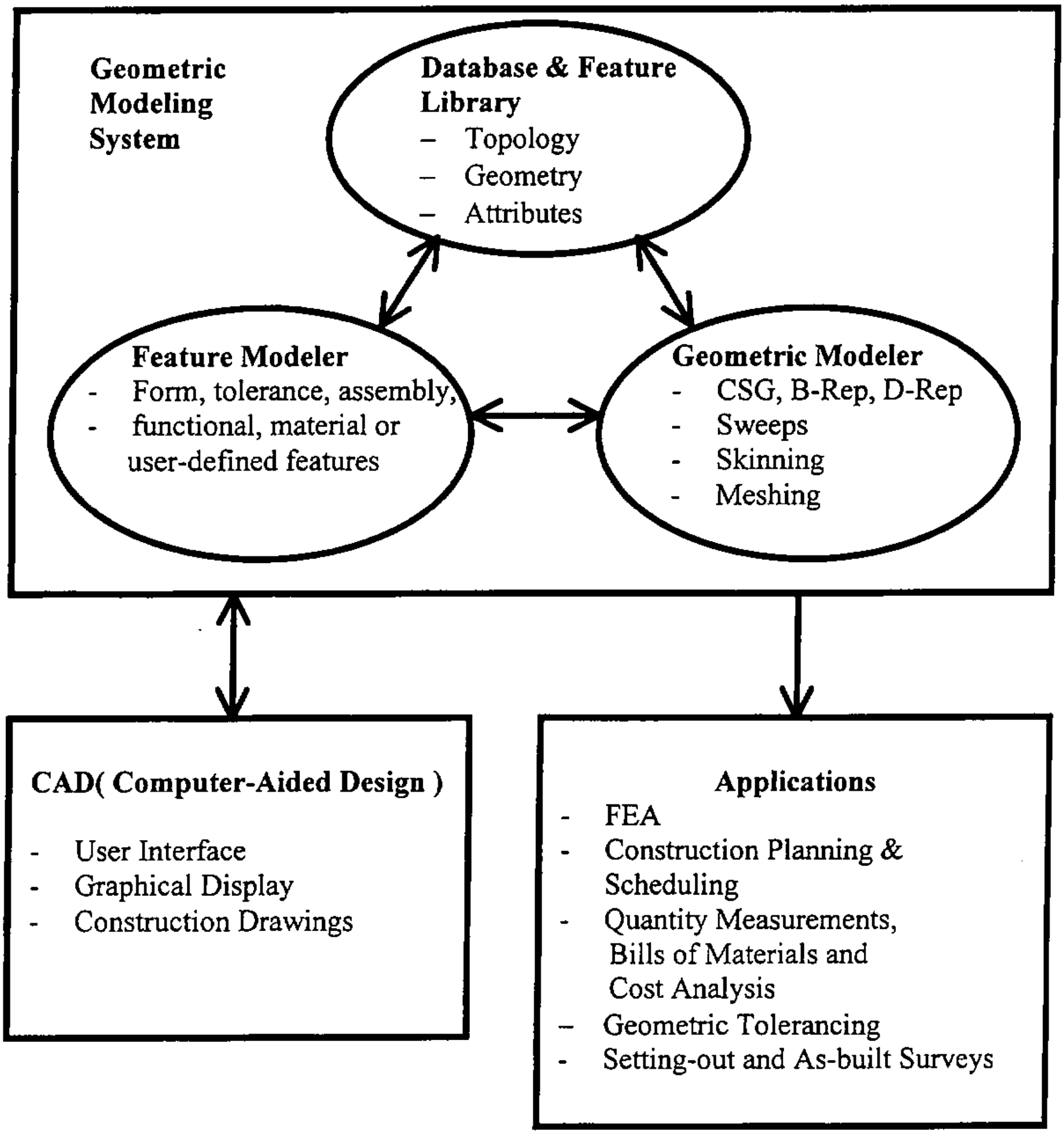


Figure 3.5 Principal components of a geometric modeling system for tunnel construction.

Surface models may be analytical surfaces or free-form surfaces. They are used to support the design and setting-out of complex sculptured surfaces in geometric modeling systems. Analytical or parametric surfaces, which are defined by curves and known parametric equations, are non-planar patches suitable to represent geometric surfaces of tunnel linings. Bicubic surfaces, Bezier surfaces, B-spline surfaces, Non-uniform Rational B-Spline (NURBS) surface, and ruled surfaces are some types of parametric surface patches. A free-form or sculptured surface is defined as a collection or sum of interconnected and bounded parametric patches together with blending and interpolation formulas. In the CAD/CAM industry, NURBS curves and NURBS surfaces are being applied mostly because they are able to represent both classical shapes (e.g. quadrics) and free-form complex surfaces of solid models.

Surface modelers store geometric information in addition to some topology but still can not solve the problems of model validity completely because they do not guarantee closure of the objects they described. The capabilities of surface models to represent the precise digital geometry of objects by themselves alone remain uncertain but they are still useful to represent complex surfaces of solid models.

Solids are volumes created by rotational sweeps, well-defined surface enclosures, or analytic solid objects such as cubes, spheroids, cones, toroids, right-circular cylinders, etc. They provide 3D geometry of a solid physical object or complex geometric models to higher levels of functionality and automation than the other types of geometric models. They are able to address more information (

geometry and topology) than wire-frame and surface models (geometry only). They produce accurate designs, provide complete three-dimensional definition of tunnel objects, improve visualization and quality of the design and have potential for functional automation and integration for the construction process, making them least abstract and most realistic among the three types of geometric models for construction surveying of highway tunnels.

Solid modeling systems are also capable of providing automatic finite element meshing and interactive loads and boundary condition definition in finite element analysis. Finite element analysis is outside the scope of construction surveying and therefore will not be included in this thesis. Because of the large memory and extensive computations necessary to produce, render and store solid models, the development of solid modelers are still confined to expensive computer systems.

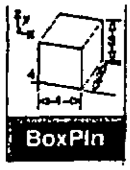
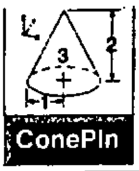
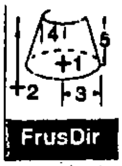
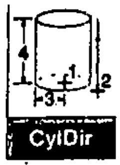
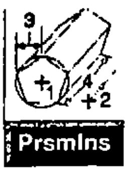
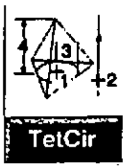
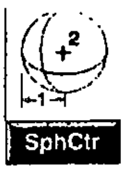
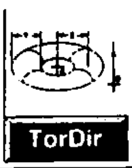
There are six different types of solid representation schemes that are suitable for representing tunnel objects namely Sweep models, Skinning models, Constructive Solid Geometry (CSG) models, Boundary Representation (B-Rep) models, hybrids models which are combinations of CSG and B-Rep models, and Decomposition Representation (D-Rep) models.

The kind of Sweep model which is defined by a 2D cross-sectional area swept along a curved trajectory is most suitable for construction surveying of highway tunnels, the curved trajectory being the combination of the vertical and horizontal alignments of the tunnel. The Sweep models are adopted by all commercial software for tunnel surveying because the models are easy to program with existing compilers and PC. Their practicality will be demonstrated in Chapter 4 and Chapter 5.

A CSG model is formed by combining a set of simple solid primitives with Boolean operators (UNION, INTERSECTION and DIFFERENCE). Samples of solid primitives for CSG modeling are given in Table 3.1 along with their input requirements. CSG models are further assembled with other combinations to form more complex shapes. The representation is in the form of a binary tree (the CSG graph). The terminal nodes of the tree are the solid primitives with the desired values for parameters and spatial transformation. The intermediate nodes address the Boolean operators. Alternately, spatial transformations can be represented parametrically in the terminal nodes with the above intermediate nodes addressing the transformation operations.

Thus, changes of primitives, Boolean operations and transformation are easy because they involve only tree-node building. In addition, CSG models require considerably less storage to store solid definitions than other geometric representations such as B-Rep and D-Rep.

Table 3.1 Sample of primitives for CSG modeling
(LaCourse et al., 1995, Table 6.1).

Primitive	Description	Typical input required
	**Box** A box is a right rectangular hexahedron. That is, it has six rectangular faces.	**Box** Length, width, height, and location. The center point and orthogonal edge vectors as well as two diagonally opposite corners are specified with some systems.
	**Cone** A cone has a base circle, a curved exterior surface tapering to a point, and an axis of revolution normal to the base circle. All lines on the curved exterior surface between the base circumference and the apex are linear.	**Cone** Base radius, height or length, and the base center point as a location.
	**Frustrum** A frustum is typically defined as the portion of a cone that lies between two parallel intersecting planes.	**Frustrum** Bottom center point for location, an axial direction, bottom radius, top radius, and length.
	**Cylinder** Cylinders are defined by a constant diameter bounded on each end by right-angular, parallel circles of equal radius. The axis is normal to the ends.	**Cylinder** Direction, base point or location, radius, length.
	**Prism** A prism is similar to a right rectangular box, except that it has more faces.	**Prism** Base point or location, directional vector, the radius of the defining circle, and length. Prisms may be inscribed or circumscribed about the defining circle. Some systems also allow the number of equilateral edges or facets on its base to be specified.
	**Tetrahedron** A tetrahedron has an equilateral triangular base and three triangular sides.	**Tetrahedron** Base point or location, directional vector, the radius of a defining circle, and length or height. The base may be inscribed or circumscribed about the defining circle. A variation is known as a *pyramid*, defined by four sides and a rectangular base.
	**Sphere** A sphere is the volume generated by a semicircle revolved about an axis passing through its end points.	**Sphere** Spherical radius and the center or polar point.
	**Torus** A torus is generated by revolving a circle about an axis in the plane of the circle. The axis must not pass through the center of the circle, and must lie outside the circle in most SM systems.	**Torus** Radius of the circle, the radius from the center of the circle to the axis of revolution, and the direction of the axis must be defined. A hollow tube is created when two concentric circles of differing radii are revolved.

Sculptured surfaces, which are essential geometric configurations of structural elements in many construction cases, are difficult to incorporate into CSG models. Besides, pure CSG models are classified as unevaluated volume objects because they lack setting-out data of faces, edges and vertices, and are not suitable for construction surveying of tunnels.

A B-Rep model comprises discrete bounding surfaces, curves and vertices of the solid together with the adjacency relationship (topology) between the geometric entities. It is an evaluated representation scheme by which elements of a shape are explicitly held in the model with edges and faces readily available for display or other applications. It is applied effectively in the modeling of swept objects. As we need to continually access the vertices, edges and faces of tunnel objects for setting-out data in construction surveying, solid modelers which adopt B-Rep for storing both the geometry and topology are more precise and useful than unevaluated ones. However, direct entry of geometric entities into a pure B-Reps modeler would cause inconvenience in CAD and very often results in invalid objects. In addition, maintaining an evaluated database may be difficult for B-Rep modelers in terms of system complexity, storage requirements and performance.

Therefore, in considering the pros and cons of applying CSGs and B-Reps in solid modeling, most solid modelers, which support high-quality graphics and accurate shape adopt a combined CSG primitives and B-Reps, allow faster solid generation and accurate curved surfaces. However, the combined CSG and B-Rep geometric modeling schemes need to store huge amounts of data in order to maintain the two databases simultaneously during operations. Therefore, the schemes are intensive in computer memory and may not be suitable for representing complex objects. Algorithms and data structures of the combined models, which are suitable for the representation of tunnel objects in computer systems, are presented in Chapter 6.

In geometric modeling, a solid object can be represented approximately by decomposing its volume into smaller cubes which are contiguous and not interpenetrate. Nearly all kinds of objects can be represented by D-Rep models which can be generated by the cellular decomposition schemes, the spatial occupancy enumeration schemes and the octree decomposition schemes. In view of geometric accuracy, D-Reps produce only approximations of solid objects and are suitable for modeling irregular natural objects, geological features and finite elements in site investigation of tunnel projects. Unless high-speed computers with large memory storage can be afforded, D-Reps are not able to provide the uniqueness and accuracy required of a precise tunnel representation. Since these approximate models are currently unable to achieve sub-centimeter levels of accuracy for use with microcomputer systems, they are not cost-effective for geometric representation and setting-out of tunnel construction. Thus, D-Reps will not be further discussed in this thesis.

Since solid modelers have been proved successful by CAD/CAM researchers as the technological solution to automating and integrating design and manufacturing functions, the geometric modeling systems presented in the following chapters will be related to solid models that are applicable in tunnel projects.

Ordinary geometric models are lacking engineering meaning and function requirements of the designer, and time-consuming in editing an object. In recent years, feature-based parametric modelers are becoming popular among CAD/CAM software. A feature is a geometric entity which defines the attributes of an object's shape, size, geometry, topology, and includes specific operations and constraints to produce these attributes in a computerized solid model. Features impart not only geometry to a design but a set of associative, non-geometric attributes which aid in communicating the design to the manufacturing process. A feature-based geometric modeling system is able to store and provide the following range of information (Shah and Mantyla, 1995):

1. Generic shape (topology and/ or geometry);
2. Dimension parameters (independent parameters);
3. Constrained parameters and constraint relations;
4. Default values for parameters;
5. Location or attachment method;
6. Location parameters;
7. Orientation method;
8. Orientation parameters;
9. Constraints relating dimensions, location, and orientation, possibly of several neighboring features;
10. Tolerances;

11. Construction procedure for geometric model;
12. Recognition algorithm;
13. Parameters computed on the basis of other features;
14. Inheritance rules or procedures;
15. Validation rules or procedures; and
16. Non-geometric attributes (part number, function, etc.).

Parametric design functions are also provided by this kind of geometric modeling system to allow predefined objects to be created only once and edited, if required, by revising the parameters that define them. Although feature-based parametric solid modeling systems are ideal systems for tunnel construction processes, most microcomputers do not have sufficient memory or processing speed to meet the demands in a satisfactory way.

Ordinary modeling techniques have difficulty representing irregular surfaces and surface intersections at certain construction stages of a highway tunnel. For example, tunnel surfaces formed by drill-and-blast methods during excavation have irregular surfaces. These surfaces of the geometric models can be represented by meshes of 3D TIN(Triangular Irregular Network) or 3D grids. Automatic mesh generation processes are required to achieve desired mesh density distribution and well-shaped elements. It is a process that uses both geometry and topology of a solid model and particular mesh rules allow computerized generation of the mesh model. Details of these models as applied in tunnel construction are presented in Chapter 6 and Chapter 7.

3.4 Geometric Data, Topological Data and Geometric Operations for Geometric Modeling of Tunnels

A successful geometric modeling system for tunnel construction relies on a sophisticated and efficient database structure. The requirements of these database structures are examined in view of their geometric data, topological data and geometric operations. Together with other general components in computer programming such as data types (e.g. texts, graphics, symbols.), data structures (e.g. arrays, linked lists, trees.), data structure operations (e.g. searching, sorting, inserting, deleting.), data storage, data management, and the complexity of the algorithms, they should fulfill the overall requirements of the system. In this section, we focus only on the principal items of the geometric data, topological data and geometric operations, which are suitable for the geometric modeling systems of tunnel construction.

Geometric data are the geometric parameters of objects that make up a model, such as points, lines, surfaces, etc. By referring to Part 42 (Geometric and Topological Representation) of ISO 10303 Standard and STEP, the geometric shape of a tunnel or an entity can be defined and represented by its geometric data and topological data in three-dimensional space. Although these standards are established to govern the exchange format of design data and manufacturing data in the manufacturing industries, some of their data elements have been identified by the author as being suitable for geometric modeling of tunnels. Geometric data that are appropriate to represent the precise geometry of a tunnel are given in Figure 3.6.

1. Cartesian Coordinate System
2. Transformation Operators
   - 2D Cartesian Transformation Operator
   - 3D Cartesian Transformation Operator
3. Point
   - Cartesian Point
   - Point on curve
   - Point on Surface
   - Point Replica
4. Vector
   - Direction
   - Vector with Magnitude
5. Curve
   - Line
   - Conic
     - Circle
     - Ellipse
     - Parabola
     - Hyperbola
   - Bounded Curve
     - Poly-Line
     - B-Spline Curve
     - Trimmed Curve
     - Composite Curve
   - Curve on Surface
     - Parametric Curve
     - Surface Curve
     - Intersection Curve
     - Composite Curve on Surface
   - Offset Curve
     - 2D Offset Curve
     - 3D Offset Curve
   - Curve Replica
6. Surface
   - Elementary Surface
     - Plane
     - Cylindrical Surface
     - Conical Surface
     - Spherical Surface
     - Toroidal Surface
   - Bounded Surface
     - B-Spline Surface
     - Rectangular-trimmed Surface
     - Curve-bounded Surface
     - Rectangular-composite Surface
   - Swept Surface
     - Surface of Revolution
     - Surface of Linear Extrusion
     - Offset Surface
   - Surface Replica

Figure 3.6 Geometric data for modeling of tunnels.

Topological data are required to connect individual elements or define the connectivity relationship of individual elements (vertices, edges, and surfaces) among geometric components. By referring to Part 42 of ISO 10303 Standard, types of topological data, which can be adopted by tunnel construction, are shown in Figure 3.7.

Geometric operations, or creation of the shape models, refer to the group of geometric modeling operations which include, but is not limited to, sweeps, skinning, revolves, blends, extrudes and fillets. Common geometric operations are given in Figure 3.8. The only requirement of the geometric operations for geometric modeling of highway tunnels is that its models must be unambiguous and valid solids. In other words, the system must realize which regions of space are solid and which regions are empty. Mathematically, this can be reduced to the determination of whether any given point is solid (part of the object), not solid (outside the object or inside the interior voids of the object), or on a surface. Some of these geometric operations which are suitable for construction surveying of highway tunnels will be presented together with their precise digital models in the following Chapters.

As shown in Figure 3.5, a successful geometric modeling system relies on a CAD system that is simple to use. Parallel to the levels of design, this CAD system is able to display the proper model and generate database information for the immediate design. Inside the geometric modeling system, the generations of CAD database from solid models to the production of CAD drawings are given hierarchically in Figure 3.9.

1. Topology
   - Connected Edge Set
   - Connected Face Set
   - Edge
     - Edge Curve
     - Oriented Edge
   - Face
     - Oriented Face
     - Face Surface
     - Sub-Face
   - Face Bound
     - Face Outer Bound
   - Loop
     - Edge Loop
     - Poly Loop
     - Vertex Loop
   - Path
     - Open Path
   - Shell
     - Closed Shell (Oriented)
     - Open Shell (Oriented)
     - Vertex Shell
     - Wire Shell
   - Vertex Point
2. Curve Logical Structure
3. Edge Logical Structure
4. Face Logical Structure
5. Loop Logical Structure
6. Shell Logical Structure
7. Surface Logical Structure

Figure 3.7 Topological data for geometric modeling of tunnels.

- 1. Wireframe Model
  - Shell-based Wireframe
  - Edge-based Wireframe
- 2. Surface Model
  - Shell-based Surface Model
  - Edge-based Surface Model
- 3. Geometric Set
  - 2D Geometric Set
  - 3D Geometric Set
  - 3D Geometric Curve Set
  - 3D Geometric Surface Set
  - Geometric Set Replica
- 4. Solid Model
  - Manifold Solid B-Rep
  - Facetted B-Rep
  - CSG Solid
  - CSG Primitives
    - Sphere
    - Primitives with one axis
      - Right Circular Cone
      - Right Circular Cylinder
      - Torus
    - Primitives with Axes
      - Block
      - Right Angular Wedge
  - Swept-Area Solid
    - Solid of Linear Extrusion
    - Solid of Revolution
  - Solid formed by Boolean Operations
    - Union
    - Intersection
    - Difference
  - Solid Replica

Figure 3.8 Geometric operations for precise shape modeling of tunnels.

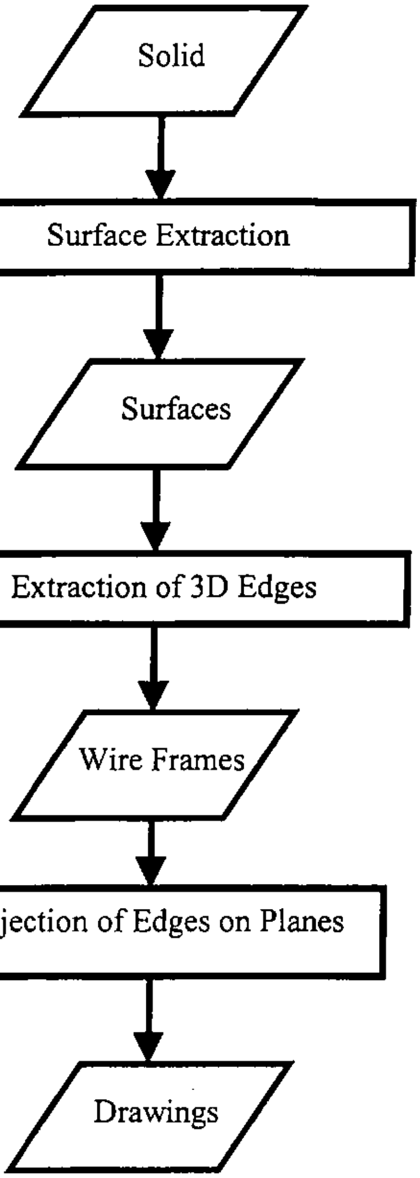


Figure 3.9 Hierarchical generations of CAD database in a geometric modeling system.

Major graphical components and database structures of a CAD Drawing are shown in Figure 3.10. Cavagna and Cugini (1977) presented a data structure for the description and management of engineering drawings. The data structure constitutes the graphic description of the shape of the piece and the specifications for production. The shape of the object is defined in space by finite contiguous surfaces. Each of these surfaces is a closed polygon. Technological processing specifications such as dimensions, dimensional tolerances, surface finish, type of material, functional details and manufacturing methods are addressed in the attributes of the database structures of the CAD system (Figure 3.11).

To ease data exchange between dissimilar systems, all CAD systems are organized to have the following key elements:

1. Layers or levels,
2. Texts including types of fonts,
3. Symbols including blocks or cells of entities,
4. Line-types and line-widths,
5. Plotting scale and layout,
6. Colours to identify objects, and
7. Reference library.

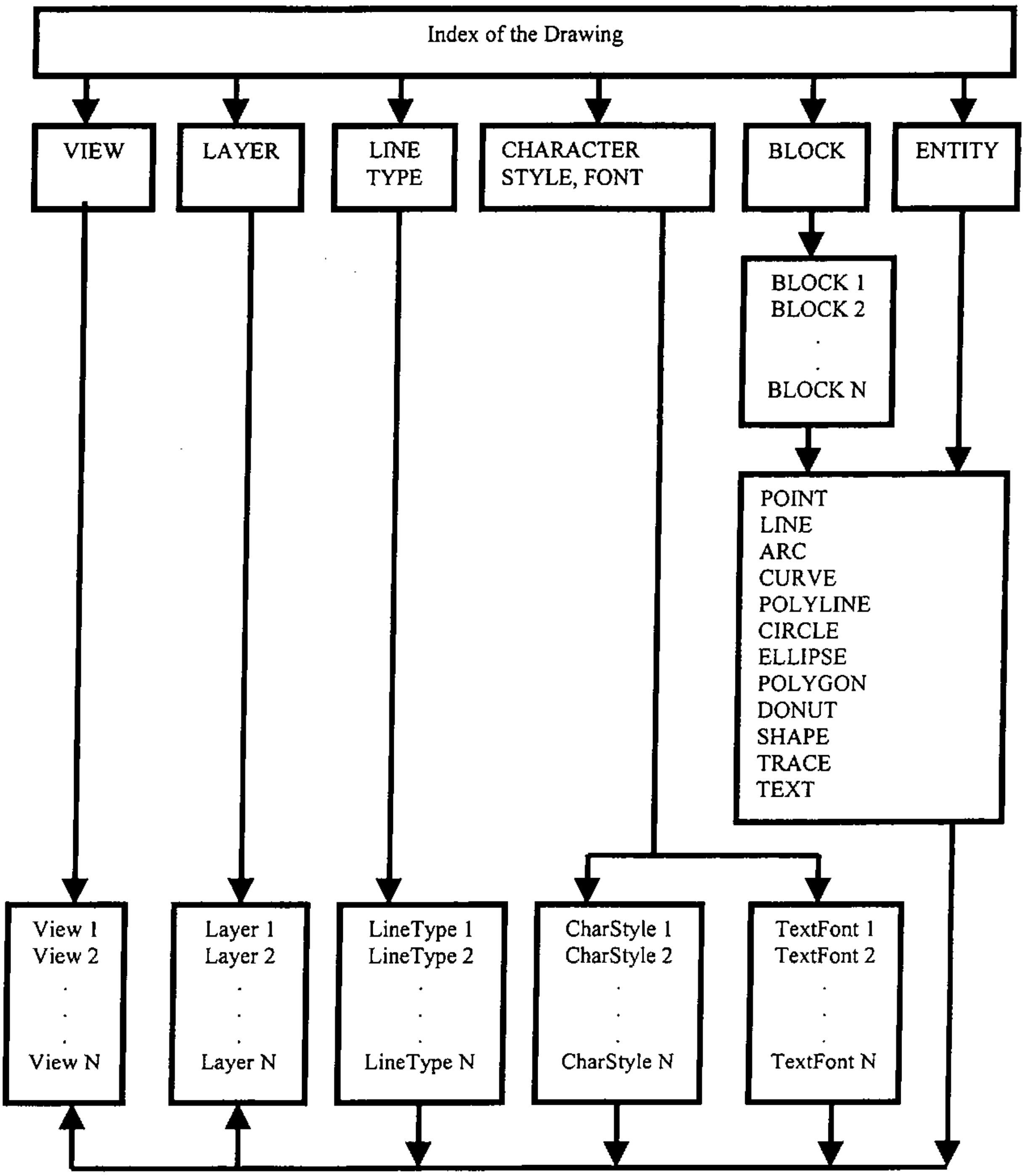


Figure 3.10 Major graphical components and database structures of a CAD drawing.

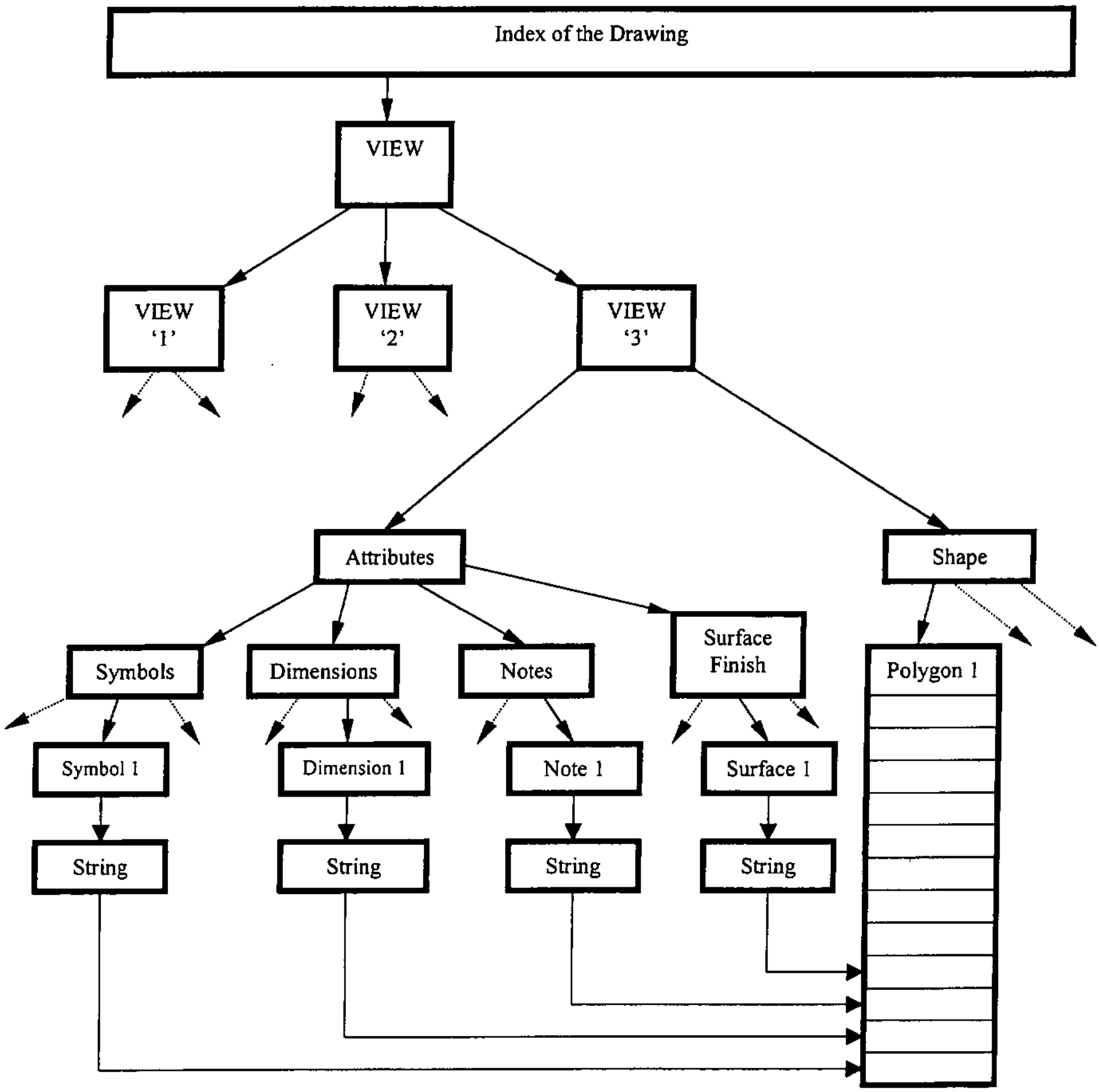


Figure 3.11 Data Structure for describing shapes and attributes of a CAD drawing.

Examples of common CAD data interchange standards are Drawing Interchange Format (DXF) of Autodesk Inc. and Standard Interchange Format (SIF) of Intergraph Corporation. Other CAD development and data standards published by ISO are:

1. ISO 128-21: General Principles for CAD.
2. ISO 3098-5: Lettering for CAD.
3. ISO 10127: CAD Techniques.
4. ISO 10623: Requirement for CAD
5. ISO 11442 (Parts 1 through 9): Regarding Product Documentation of CAD.
6. ISO 13567 (Parts 1, 2 and 3): Regarding Layering Standards for CAD.
7. ISO 16792 (Part 1): Requirements for 3D CAD Models.

Having identified different options of geometric data types, geometric operations and shape models for tunnel construction, we are now able to summarize the main data structure for generation and geometric representation of three-dimensional tunnel objects in Figure 3.12. These data are stored in the object files of the database in a compact form. All the necessary operations on three-dimensional geometric objects are then carried out by the geometric modeling system. When some operations of shape generation or modification are required, data are retrieved from the database, geometric operations are performed, and processed data are properly stored and addressed in the database. The database system should allow users access to every item, such as a face or an edge, in the object data structure.

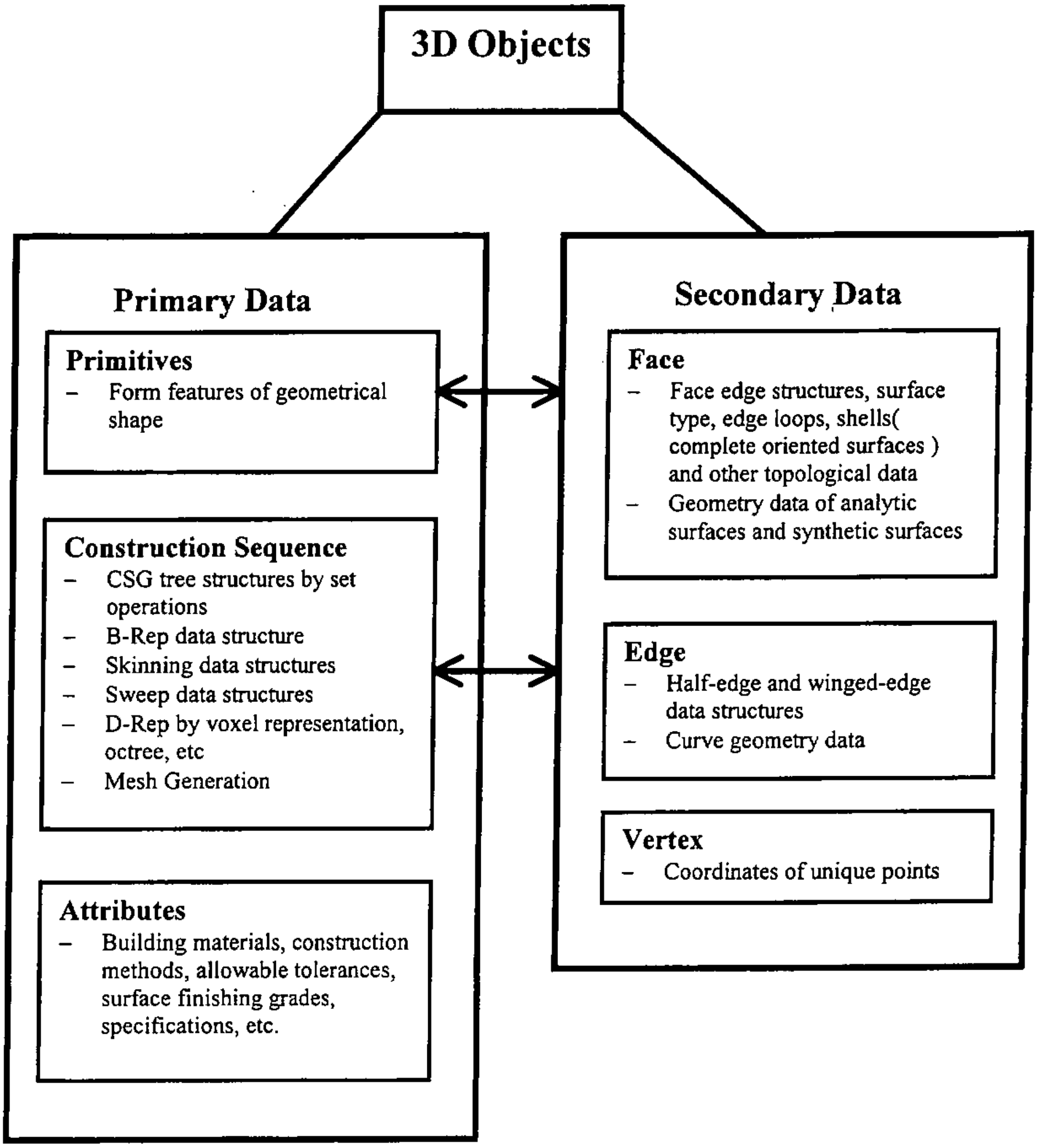


Figure 3.12 Main data structure for generation and geometric representation of three-dimensional objects in tunnel construction.

In order to integrate with the actual construction process, it is essential to establish relationships between geometric objects and technical information attributes such as tolerances, material types and surface finishing grades. Attributes are mainly textual information associated with CAD geometry and they are assigned to objects for applications such as creating bills of materials. These attributes are attached to or expressed on construction drawings by special symbols or descriptions for better understanding among construction workers. Necessary data to select tools, to determine the construction method or the process sequence can be obtained in the production team by the use of these attributes. These relationships can be automatically coded and stored in attribute file together with the corresponding face, edge, or vertex designations of the tunnel objects, and developed towards an ideal feature-based parametric modeling system.

3.5 Create 3D Geometric Models from 2D Geometry

Traditionally, all 3D geometric models of highway tunnels must be created from 2D geometry because of three main reasons. Firstly, all highway alignments must be designed on two-dimensional projection planes in order to comply with geometric design standards of transportation engineering by applying the data given in these standards and codes of practice. These standards are given in Section 3.2. Secondly, the drafting systems carry out all the design procedures based on two-dimensional geometry. Although modern geometric modeling systems allow the construction of objects in 3D space, designers interact with the systems through a monitor screen, pointing device and keyboard which are often working on two-dimensional construction planes. Thirdly, the design of structural elements by FEM or the conventional moment distribution methods involves solving two-dimensional continuum problems (Zienkiewicz and Taylor, 2000; Smith and Griffiths, 1998).

Therefore, in current practice, the positions of points and tunnel entities are designed on construction planes with respect to the center-line of the tunnel. The center-line of a tunnel is a combination of both vertical and horizontal alignments in the three-dimensional space (see Figure 4.5 and Figure 4.6). The construction and modification of 3D geometric models are also facilitated by creating and activating 2D auxiliary planes during the construction process. As shown in Figure 3.13, a construction plane is an X-Y projection plane of an auxiliary system. Entities projected on the construction planes can be combined to form precise 3D models and transformed (translated, rotated and scaled) from their individual auxiliary coordinate system into the site coordinate system for setting-out in the field.

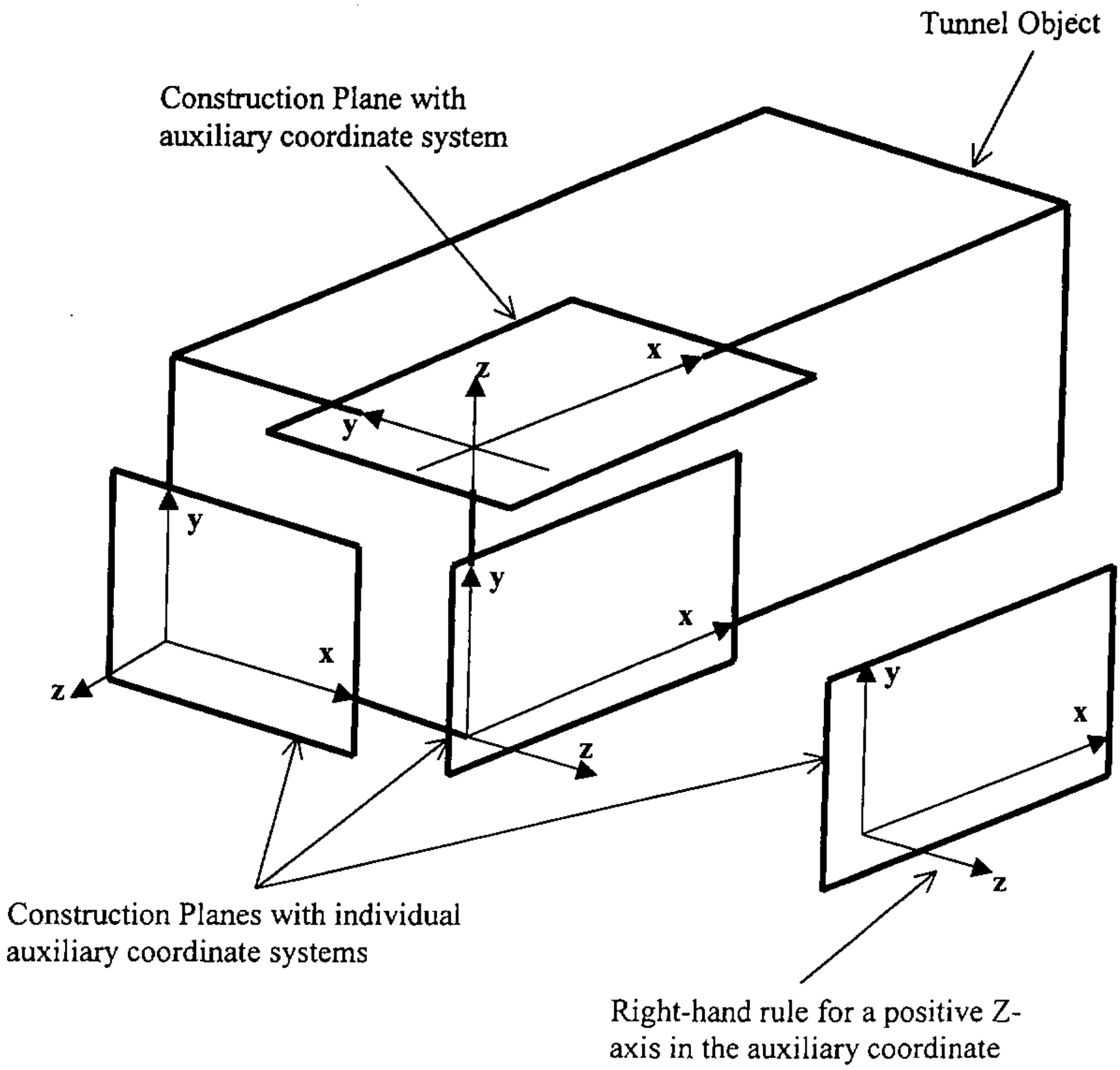


Figure 3.13 Construction planes displayed at different positions for the design of 3D geometric models from 2D geometry.

Precise three-dimensional models of tunnels are often generated from two-dimensional geometry by sweeping a 2D cross-sectional plane along the axis of the principal alignment which is a combination of the curve elements from both vertical and horizontal alignments (Figure 3.14). In this example, the cross-section template is the generator face designed on a 2D construction plane. Practical sweep algorithms for the construction of highway tunnels are given in Chapter 4. A lofting algorithm is given in Chapter 7 for the construction of solid model from 2D cross-sections.

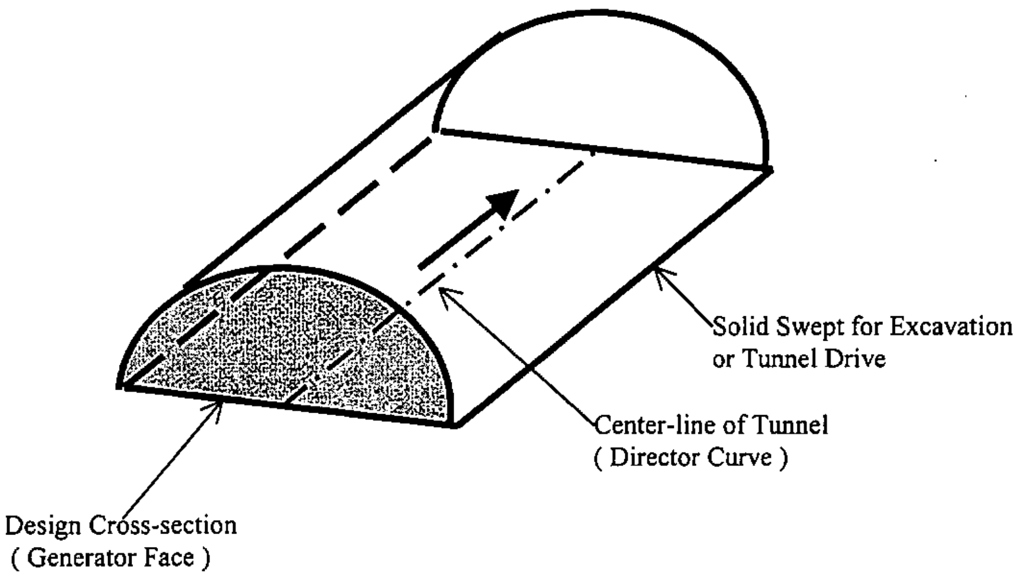


Figure 3.14 Tunnel generated by translational sweeping of a 2D cross-sectional plane.

Based on the work in (Idesawa, 1973; Sakuri and Gossard, 1983; Kaining et al., 1986; Aldefeld, 1983; Chen and Perng, 1988; Nagasamy, 1989), the generation of 3D geometric models from 2D geometry is summarized in the flowchart of Figure 3.15. The modeling begins with points, through forming surfaces and progresses to a closed solid volume. The algorithm places no restrictions on the order of input, but it needs three complete projections of the object.

In the flowchart, a vertex is one of the two points which separate an edge from the remainder of a line or curve. A vertex is shared by at least three edges. An edge is a finite segment of a three-dimensional line or curve which is part of the boundary between a face and the remainder of the surface. An edge, which is at the intersection of two faces, must be shared by at least two faces. A face is defined as the closure of a non-empty, bounded, connected, coplanar, open (in the relative topology) subset of the three-dimensional Euclidean space whose boundary is the union of a finite number of line segments (Markowsky and Wesley, 1980). Thus, a face is a closed cycle of edges. An object is defined as the closure of a non-empty, bounded, open subset of the three-dimensional Euclidean space whose boundary is the union of a finite number of faces segments (Markowsky and Wesley, 1980).

Wesley and Markowsky (1981, 1984) presented algorithms for searching for all possible solutions of polyhedral objects with a given B-Rep (having 3D edges and vertices) or a given set of 2D projections.

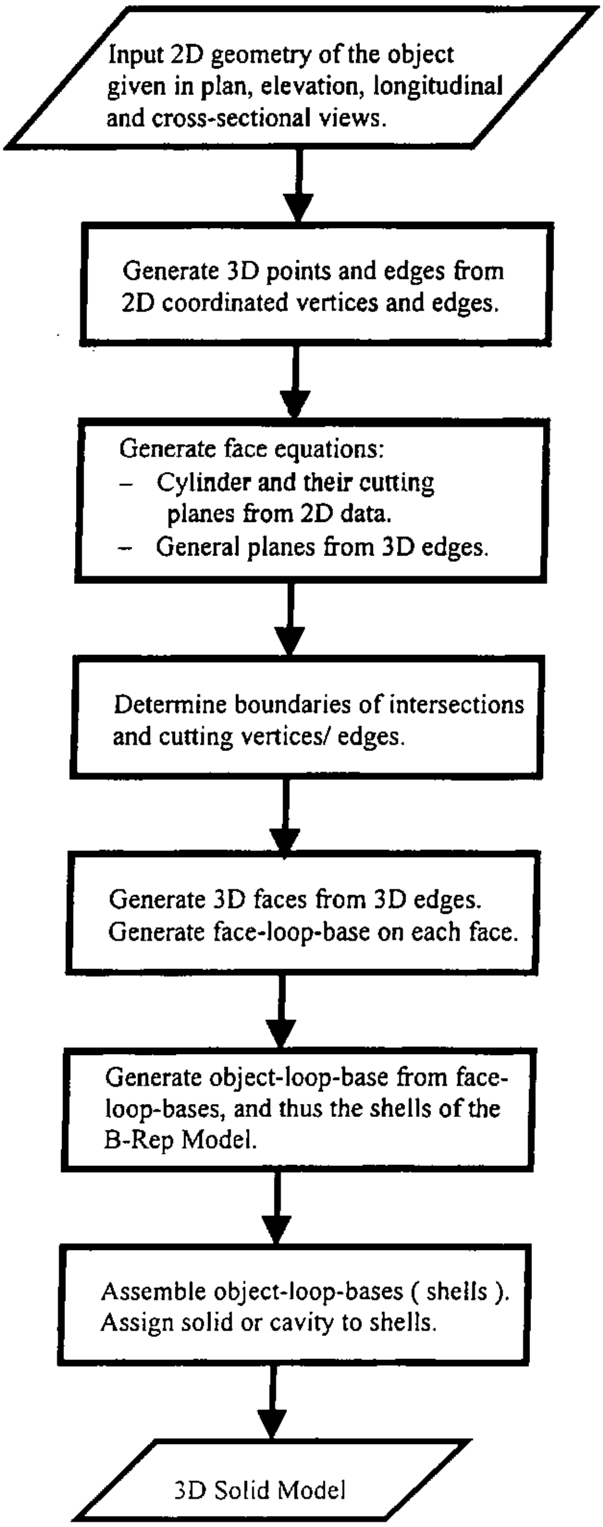


Figure 3.15 Flowchart of 3D geometric model generated from 2D geometry.

Bin (1986) presented a method to construct a CSG representation from 2D orthographic views by inputting 2D primitives. Five types of primitives (cuboid, pyramid, cylinder, cone and sphere) can be chosen, and are defined to have their axes (or height) perpendicular to one of the projection planes or oblique to two of the projection planes. Three coordinated points for the base and two coordinated points for the height are needed for the input of each primitive. If a primitive is a solid one, it is designated as positive. If a primitive is a hole or void, it is designated as negative. The positive and negative signs correspond to the Boolean operators, union and difference respectively, of the CSG method.

Not all modeling operations require the use of a 2D construction plane. Once a continuous baseline has been established precisely within the geometric modeling system, construction of objects in 3D model space can be produced more efficiently by CSG solid primitives (boxes, cones, spheres, cylinders, wedges, etc.) because they can be created with a minimum of steps and are always valid in solid modeling. As mentioned in Section 3.3, CSG must be combined with B-Rep to form more efficient geometric modeling systems for the construction of highway tunnels. The integration of CSG and B-Rep for tunnel construction will be discussed in Chapter 8.

CHAPTER 4

TUNNEL MODELS FORMED BY SWEEPS

4.1 Types of Sweeps for Modeling Highway Tunnels

Sweeping is a geometric modeling function with which a planar closed domain is translated or revolved to form a solid. There are three main kinds of Sweep model. The simplest kind is known as translational sweep or extrusion which is defined by a 2D planar area along a single linear path normal to the plane of the area to create a solid volume (Figure 3.14). The closed planar cross-section does not rotate about the extrude line but generate prismatic surfaces. This model may not be suitable for the construction of highway tunnels because the tunnel alignment is a continuous combination of both vertical and horizontal alignments of the highway in a 3D space.

The second kind of Sweep model is known as rotational sweep which is defined by rotating an arbitrary planar cross-section about an axis (Figure 4.1). Rotational sweep is suitable for geometric modeling of vertical utility shafts of highway tunnels. During the construction of the model, it can be edited by re-orienting the generator surface, changing the cross-section shape, or changing the direction of revolution. Rotational sweep can be replaced by extruding a horizontal plane vertically along the vertical axis or center-line of the shaft. Another alternative to represent this solid model is to apply the cylinder primitives of the CSG functions, if they are available in the geometric modeling system, to represent the external face and internal face of the shaft set out for excavation and subsequent erection of concrete formwork for placing concrete. CSG models will be discussed in Chapter 8.

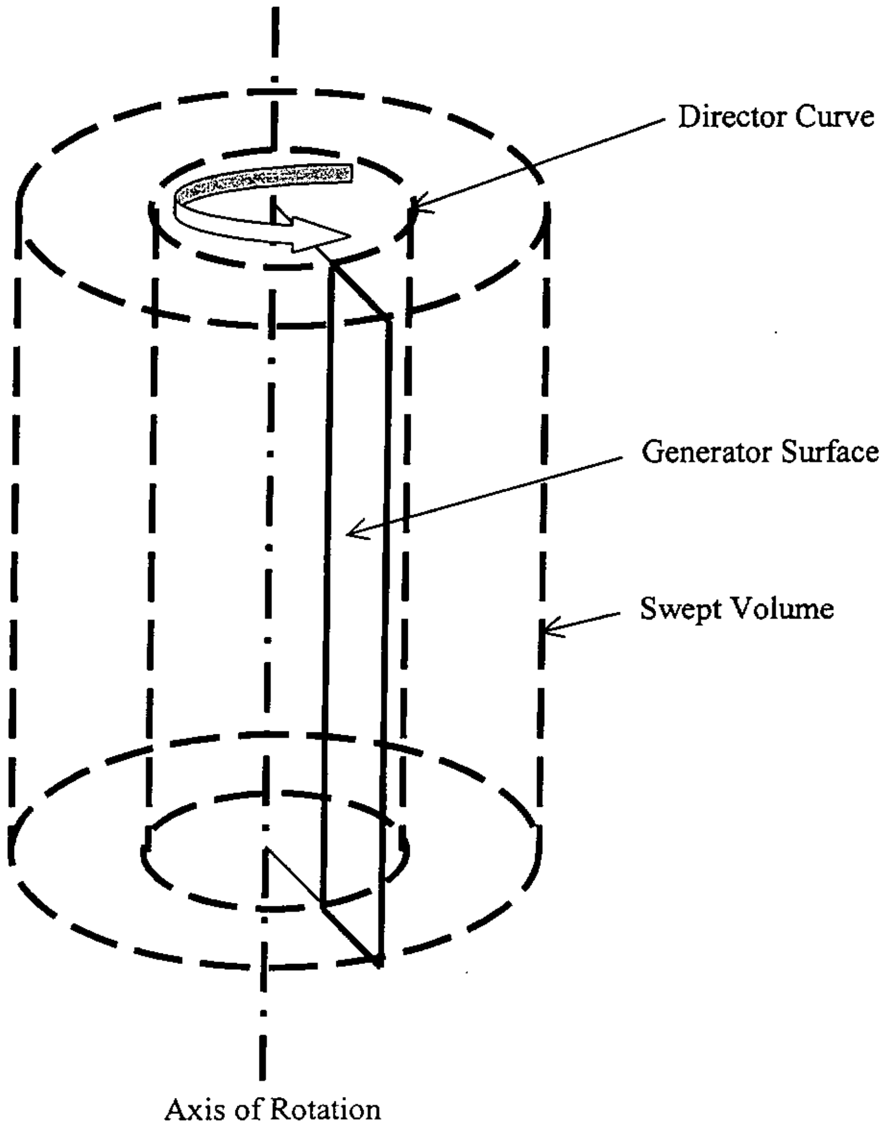


Figure 4.1 A vertical shaft formed by rotational sweep in tunnel construction.

The third kind is known as generalized sweep whose generating area changes in size, shape, or orientation as they follow an arbitrary curve. The cross-section should be a closed planar profile orthogonal to the principal alignment, and does not rotate about the principal alignment during construction. This kind of sweep is most suitable for tunnel construction. The curved trajectory of the sweep is the tunnel's centre-line which is a continuous combination of its both vertical and horizontal alignments in the 3D space (Figure 4.2). The cross-sections between specified chainages can be designed to comply with the geometry provided by the assessment results of structural engineering analysis of the tunnel. In normal cases, the cross-section should not cross the sweep axis. In many cases, the sweep axis may be defined as a distance offset from the principal alignment for proper operations with automatic tunneling machines.

A generalized sweep can be edited, in the case of tunnel construction, by reorienting the cross-section, changing the cross-section shape, replacing the cross-section with another, or by replacing or modifying the principal alignment in order to comply with geometric design standards or new design. The geometric modeling of generalized sweeps and their applications will be demonstrated by Tunnel Alignment Survey (TAS®) system in the following section. This computer system is being developed by the author for tunnel construction projects in Hong Kong, Canada and the United States. More theory on generalized sweeps can be found in (Mortenson, 1997; Lossing and Eshleman, 1974; Choi and Lee, 1990; Martin and Stephenson, 1990).

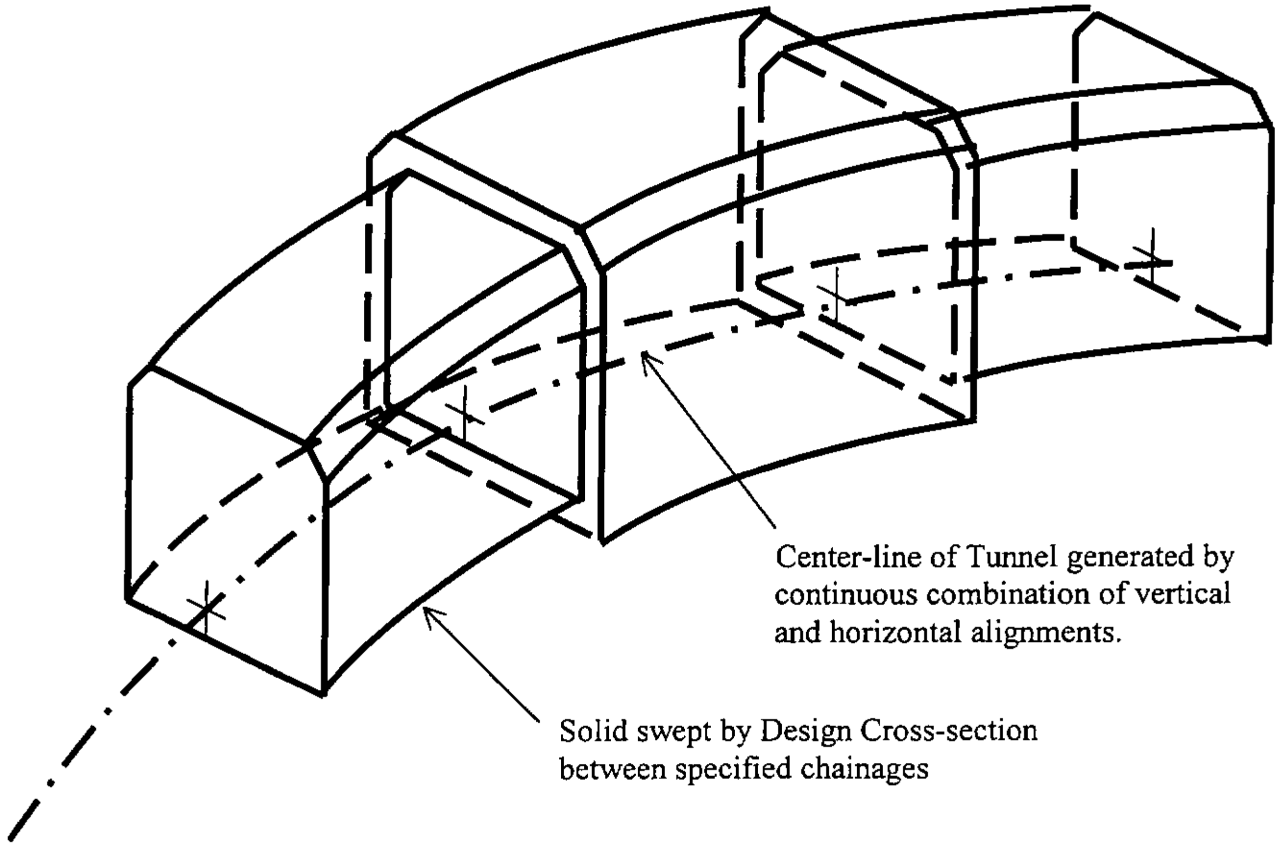


Figure 4.2 A generalized sweep for tunnel construction.

4.2 Development of TAS for Tunnel Construction

Algorithms of a generalized sweep and its database structure are demonstrated by TAS. TAS is a civil engineering software package designed by the author for alignment storage, geometric design, setting-out and as-built surveying of highway tunnels and railway tunnels. The hierarchical structure of its main functional modules is shown in Figure 4.3.

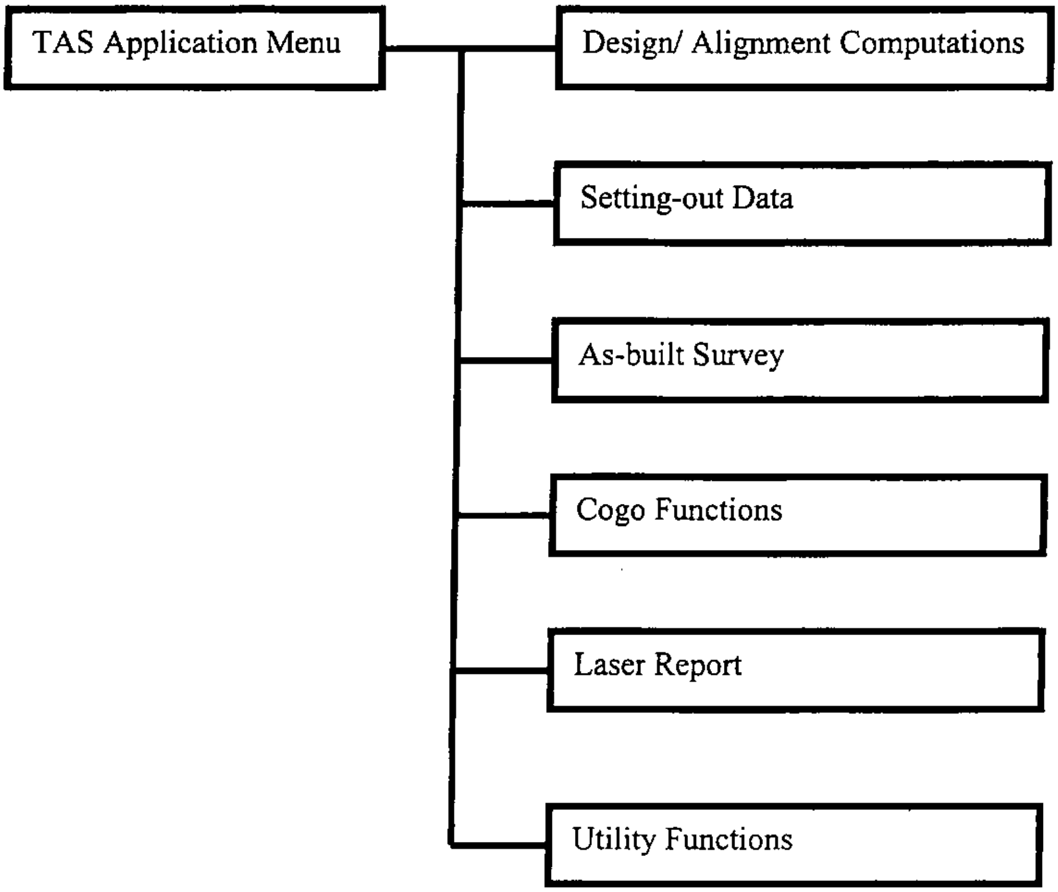


Figure 4.3. Main Functional Modules of TAS.

It is developed as an integral part of ISO 9000 Quality Assurance Program for the design and construction of the tunnels and their associated structures. Data bank of the system is given in Figure 4.4.

Inside TAS, the trajectory curve of the swept object is the principal alignment which is a continuous combination of both the vertical and horizontal alignments in 3D space. Coordinate referencing systems and principal alignments are described in Sections 3.1 and 3.2 respectively. In order to achieve precise digital models for construction surveying of highway tunnels, TAS has a parametric sweep modeling system by which the designer models a shape by applying geometric constraints and dimension data on its elements.

Inside TAS, a tunnel shape is constructed parametrically in the following steps:

1. Input geometric constraints, dimensional data and curve data from the horizontal and vertical alignments.
2. Input two-dimensional templates for tunnel cross-sections.
3. Repeat steps 1 and 2, modifying the geometric constraints and/ or dimensional data until the desired model is obtained.
4. Create a three-dimensional shape by sweeping the two-dimensional cross-section along the principal alignment of the tunnel.

In this kind of parametric modeling, parameters in the form of mathematical formulas or information must be used in the creation of, or extracted from, a geometric entity. As shown in Figure 4.5, curve data of the principal alignment are coordinates of Point of Horizontal Intersections (PHI), circular radii, spiral lengths, coordinates of Point of Vertical Intersections (PVI) and vertical curve length. It should be noted that the PHIs and PVIs are geometric constraints, not parameters.

A system of combination codes (Figure 4.6) is designed for the inputs of curve elements so that the system is able to process any combination of curve elements precisely to create a continuous center-line for the 3D model, and that each curve element will become a mathematically defined parametric curve. Printout of the final coordinated alignment of a center-line is given in Figure 4.7.

A typical cross-section of a highway tunnel in Hong Kong is given in Figure 4.8. Cross-section templates are categorized into box, circular, horse-shoe, and irregular in configuration to suit the design. Examples of these design templates are given in Figures 4.9, 4.10, 4.11 and 4.12. When the principal alignment and design templates are available, we are able to generate a swept volume for the tunnel.

DATA BANK
A route directory is designated to address the whole length of a tunnel. 6 data files are stored in each route directory as follows : (1) DESIGN.DAT which stores positions of PHIs, PVIs, curve parameters, etc., of the baseline, (2) COGEOM.DAT which stores the coordinted geometry of both vertical and horizontal elements of the 3D model, (3) AS_BUILT.DAT which stores coordinates of existing structure(s) for checking against TEMPLATE.DAT, (4) TEMPLATE.DAT which stores the design template of tunnel cross-section, (5) TABLES.DAT which stores offsets X and Y of the tunnel centre from the baseline at particular cross-section chainage, (6) CONTROL.PTS which stores the control points for stakeout and cogo computations. During data processing, the following output files or reports are created : DESIGN.RPT, COGEOM.RPT, STAKEOUT.RPT, AS_BUILT.RPT, LASER.RPT, XS.DXF, HOR.DXF and VERT.DXF.

Route Directory	Description
EDMREG_E	Edmonton to Regina (East Bound) Tunnel
EDMREG_W	Edmonton to Regina (West Bound) Tunnel
EDMRED_N	Edmonton to Regd Deer (North Bound) Tunnel
EDMRED_S	Edmonton to Regd Deer (South Bound) Tunnel
etc.	

Figure 4.4 Data Bank of Tunnel Alignment Survey System.

```
ROUTE : AL4

*******************************************************************
**                                                               **
**          DESIGN DATA OF HORIZONTAL ALIGNMENT                  **
**                                                               **
*******************************************************************

PHI     CHAINAGE   NORTHING       EASTING       CURVE  SPIRAL   SPIRAL   RADIUS
                                                CODE    (IN)    (OUT)

START  51,032.500 149,404.2290 193,992.9260                                0.000

  1               149,359.1290 188,455.9020 TT    0.000    0.000  50000.000

  2               149,321.1020 183,226.8960 TT  300.000  300.000   1430.000

END               150,318.6120 182,773.5890                                0.000

*******************************************************************
**                                                               **
**          DESIGN DATA OF VERTICAL ALIGNMENT                    **
**                                                               **
*******************************************************************

PVI      CHAINAGE     ELEVATION    VERTICAL CURVE LENGTH


START  50,918.590      337.960

  1    51,168.590      337.210        500.000

  2    53,250.000      295.580        500.000

  3    54,611.820      314.650        500.000

  4    56,697.560      320.910        460.000

  5    59,000.000      314.000        400.000

  6    60,183.180      314.000        400.000

  7    60,861.610      304.500        520.000

END    62,681.390      309.964
```

Figure 4.5 Computer printout of design elements of the horizontal and vertical alignments.

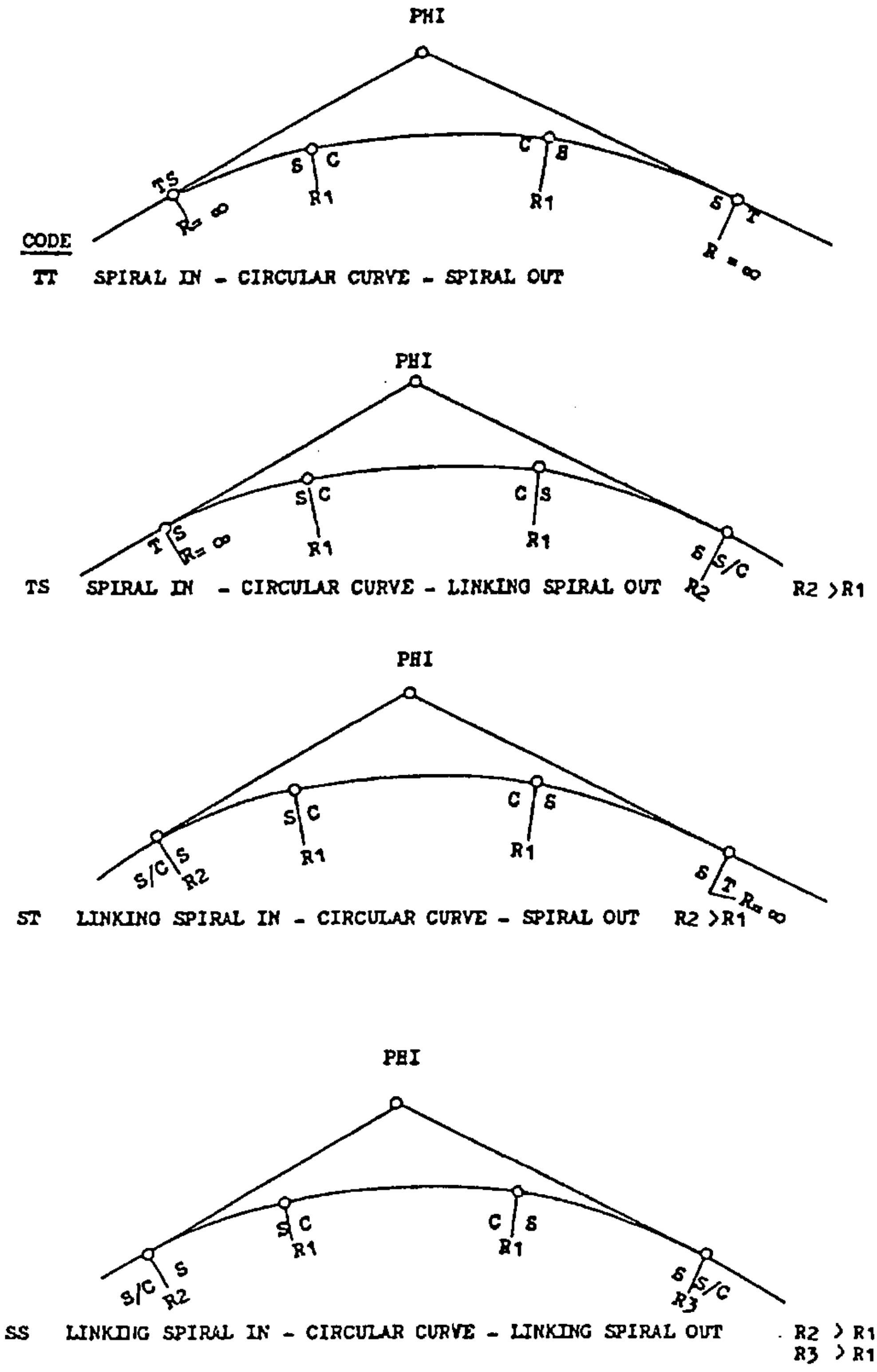


Figure 4.6 Curve combination codes for computing the principal alignment.

ROUTE : AL4

```
******************************************************************
**                                                              **
**              FINAL HORIZONTAL ALIGNMENT                      **
**                                                              **
******************************************************************
```

CURVE NO.	CHAINAGE	CURVE CODE	NORTHING	EASTING	RADIUS	RIGHT/LEFT TURN CURVE
1	51,032.500	T	149,404.2290	193,992.9260	0.000	
2	56,547.888	C	149,359.3067	188,477.7212	50,000.000	RTC
3	56,591.528	T	149,358.9703	188,434.0826	0.000	
4	60,718.947	S	149,328.9552	184,306.7729	0.000	RTC
5	61,018.947	C	149,337.2570	184,007.0345	1,430.000	RTC
6	62,365.634	S	150,035.7670	182,913.6374	1,430.000	RTC
7	62,665.634	T	150,304.2513	182,780.1151	0.000	
8	62,681.408	T	150,318.6120	182,773.5890	0.000	

```
******************************************************************
**                                                              **
**              FINAL VERTICAL ALIGNMENT                        **
**                                                              **
******************************************************************
```

CURVE NO.	CHAINAGE	CURVE CODE	ELEVATION	GRADIENT %
1	50,918.590	P	337.960	-0.30
2	51,418.590	T	332.210	-2.00
3	53,000.000	P	300.580	-2.00
4	53,500.000	T	299.081	1.40
5	54,361.820	P	311.149	1.40
6	54,861.820	T	315.400	0.30
7	56,467.560	P	320.220	0.30
8	56,927.560	T	320.220	-0.30
9	58,800.000	P	314.600	-0.30
10	59,200.000	T	314.000	0.00
11	59,983.180	P	314.000	0.00
12	60,383.180	T	311.199	-1.40
13	60,601.610	P	308.141	-1.40
14	61,121.610	T	305.281	0.30
15	62,681.390	T	309.964	0.30

Figure 4.7 Computer printout of the principal coordinated alignment.

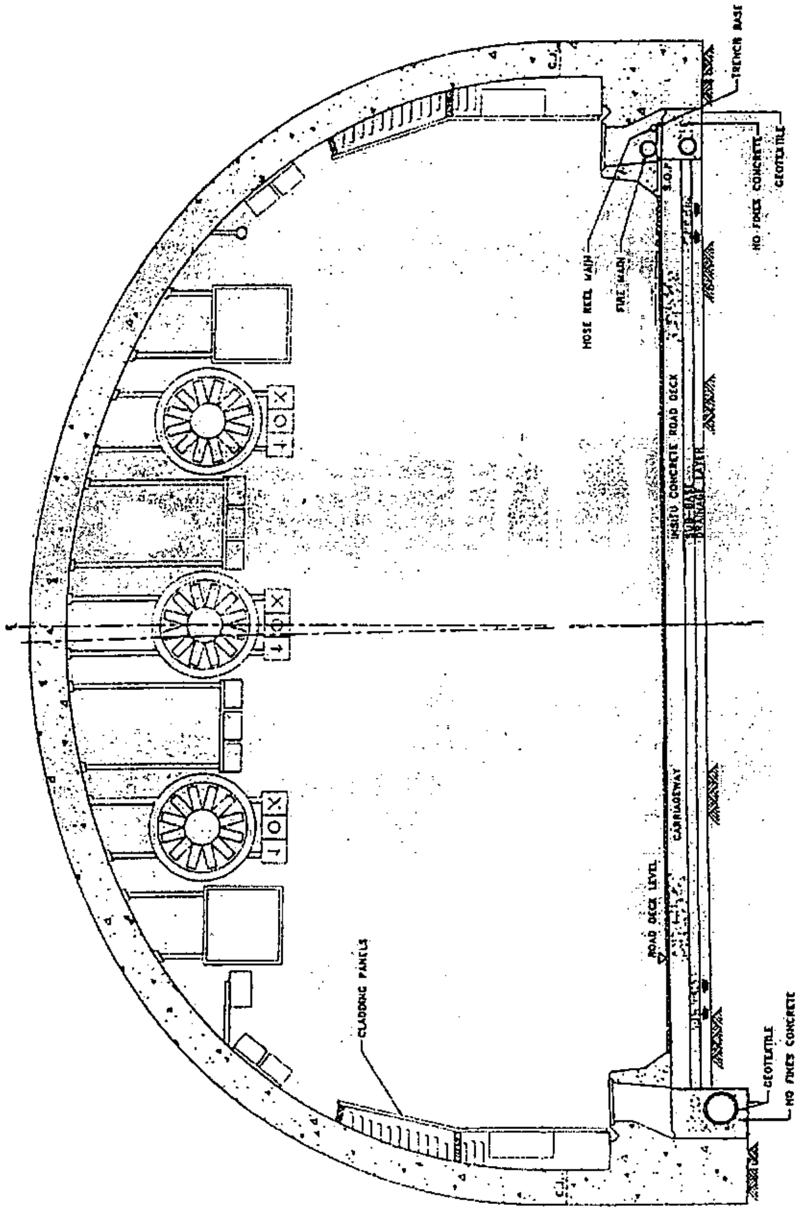
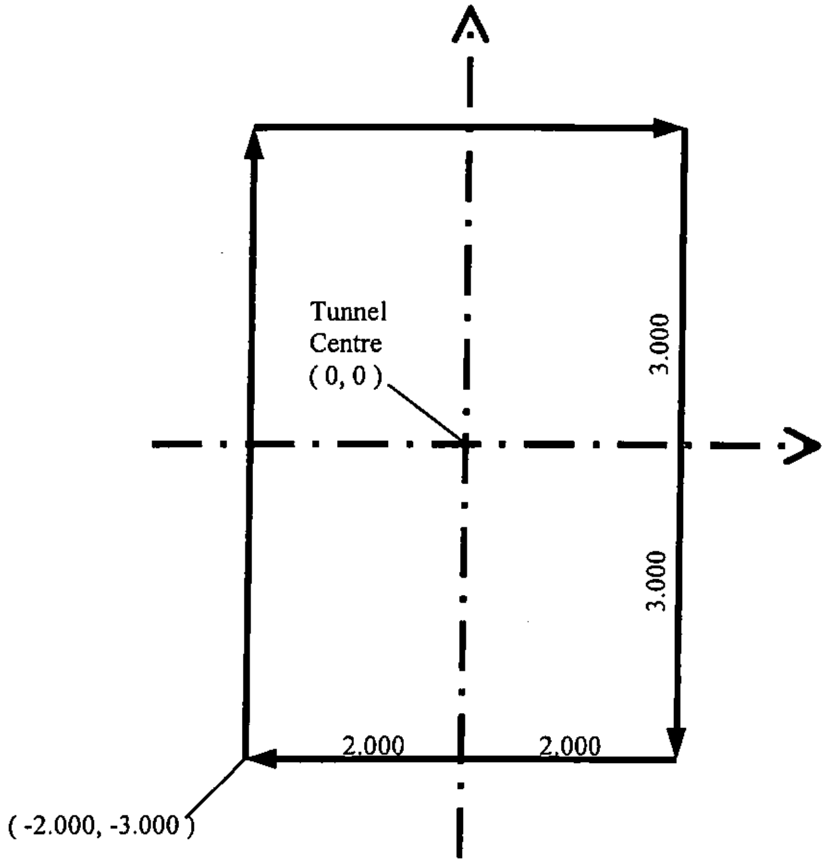


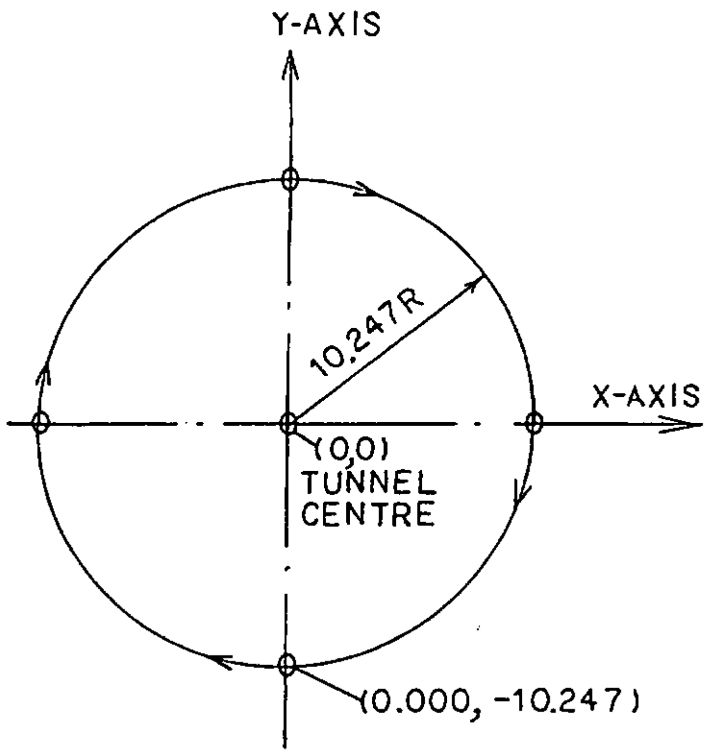
Figure 4.8 Typical cross-section of a highway tunnel
(Source: Highways Department, Hong Kong SAR).



File TEMPLATE.DAT

X	Y	R
-2.000	-3.000	
-2.000	3.000	
2.000	3.000	
2.000	-3.000	
-2.000	-3.000	

Figure 4.9 Example of box cross-section template.

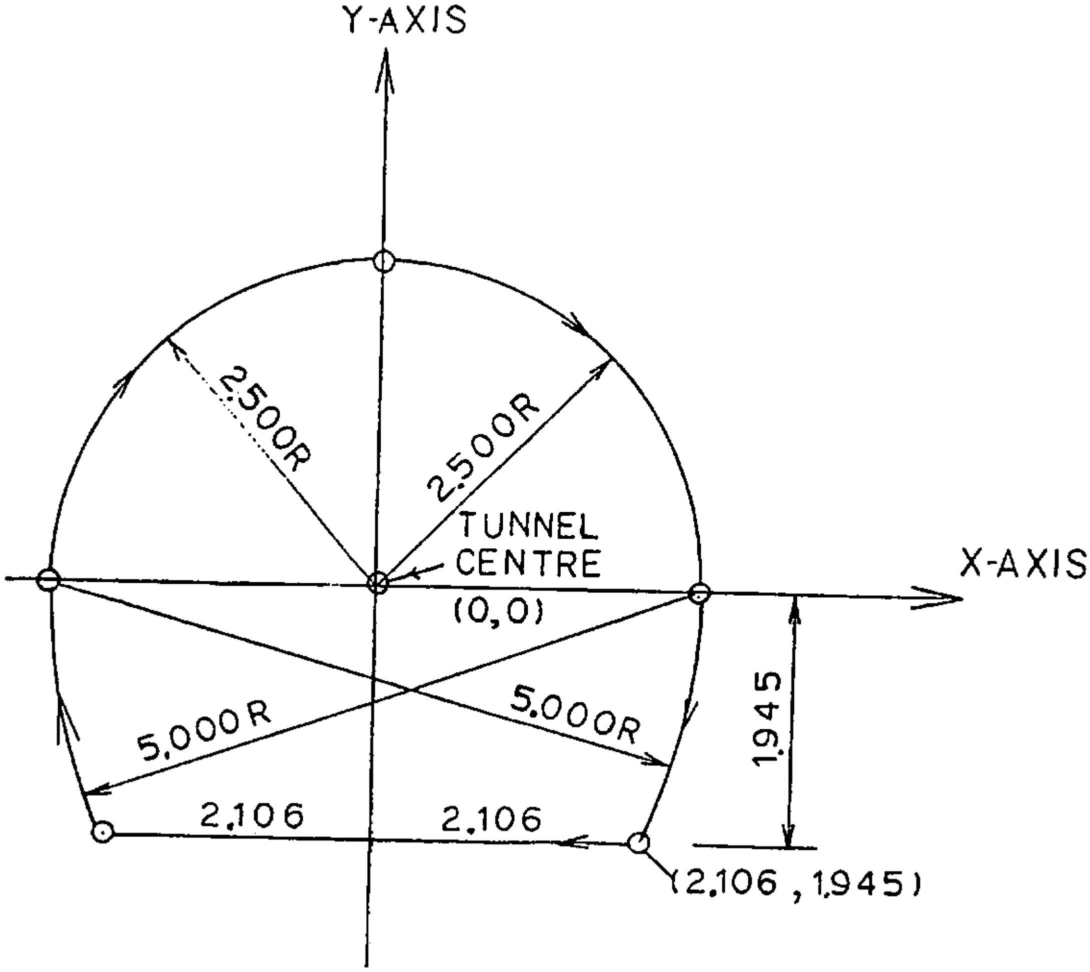


File TEMPLATE.DAT

X	Y	R
0.000	-10.247	10.247
-10.247	0.000	10.247
0.000	10.247	10.247
10.247	0.000	10.247
0.000	-10.247	

CIRCULAR CROSS-SECTION

Figure 4.10 Example of circular cross-section template.

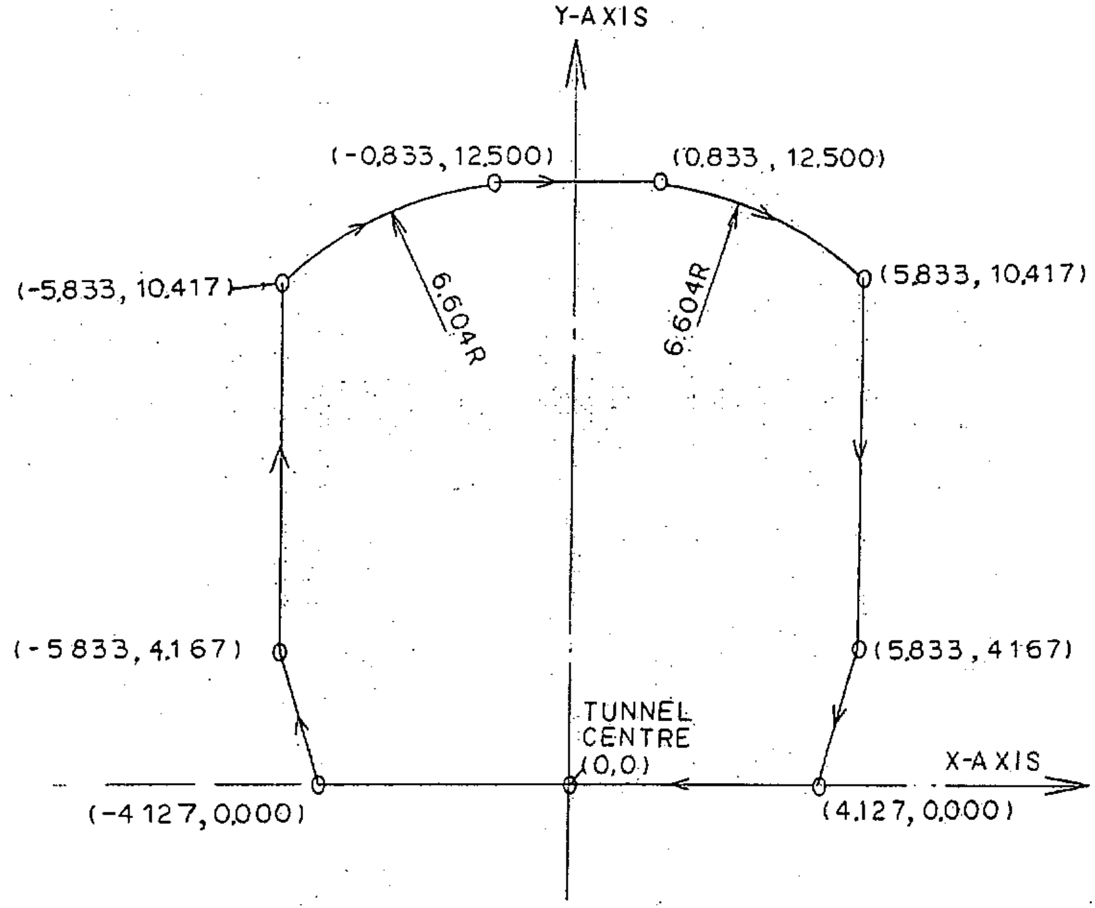


File TEMPLATE.DAT

X	Y	R
2.106	-1.945	
-2.106	-1.945	5.000
-2.500	0.000	2.500
0.000	2.500	2.500
2.500	0.000	5.000
2.106	-1.945	

HORSE-SHOE CROSS-SECTION

Figure 4.11 Example of horse-shoe cross-section template.



File TEMPLATE.DAT

X	Y	R
-4.127	0.000	
-5.833	4.167	
-5.833	10.417	6.604
-0.833	12.500	
0.833	12.500	6.604
5.833	10.417	
5.833	4.167	
4.127	0.000	
-4.127	0.000	

IRREGULAR CROSS-SECTION

Figure 4.12 Example of irregular cross-section template.

4.3 Applications in Setting-out Tunnels

At the time of writing, only a few software packages are capable of setting-out structural elements, TBMs, tunnel robotic machines and tunnel laser guidance systems. Popular computerized systems like TMS PROFILE (formerly known as AMT PROFILER®) and Geotronics Tunneling System are designed mainly for as-built surveying of tunnels. Therefore, TAS was developed to setout different types of laser guided machines (e.g. TUNNPLAN, Tamrock Jumbo Drills, RoboFOR, etc.), tunnel boring machines (TBMs), precast structural elements and other tunneling operations.

Depending on the geological features on site, highway tunnels are normally built by the drill-and-blast method or shield drive. In the drill-and-blast method of tunneling, laser guidance systems will be installed and set out by tunnel surveyors to position the tunnel direction in three-dimensional space. An example of a tunnel guidance system is given in Figure 4.13. It is the responsibility of the tunnel surveyor to compute offset position and chainage of the laser beam at one metre intervals with respect to the geometric model of the tunnel, and print the data into a Laser Line Report (Figure 4.14).

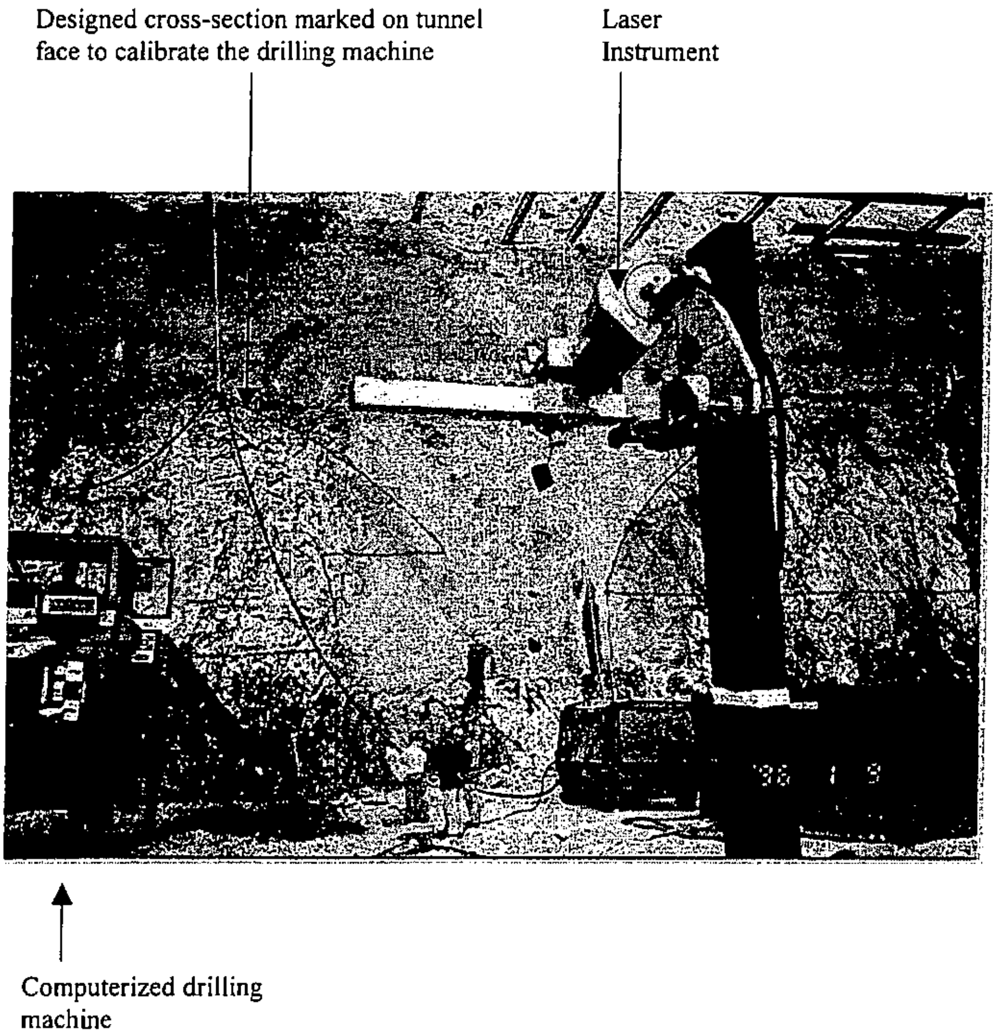


Figure 4.13 A laser guidance system for drill-and-blast construction method.

```
TUNNEL : South Bound Tunnel. ST20. Chainage from South Portal.

*********************************************************************
**                                                                 **
**                        LASER LINE REPORT                        **
**                                                                 **
*********************************************************************

SURVEYOR :                                        DATE  04-15-1996
                                                  TIME  16:59:48
TUNNEL HEAD CHAINAGE    :

   LASER LINE POSITION : Left Shoulder
               AZIMUTH : 314 deg. 26 min. 08 sec.
              GRADIENT :   -1.1429 %
           COORDINATES :
Chainage     Northing      Easting      Elev.   X-Offset  Y-Offset
 1001.641   826301.311   824943.619    91.613    -7.356     3.714
 1108.309   826376.453   824866.981    90.386    -5.888     3.714

*********************************************************************
**                                                                 **
**                       LASER OFFSET TABLE                        **
**                                                                 **
*********************************************************************

                  OFFSETS FROM TUNNEL CENTRE
                  HORIZONTAL       VERTICAL
        CHAINAGE  ( X-OFFSET )    ( Y-OFFSET )
        1109.000     -5.916          3.714
        1110.000     -5.957          3.714
        1111.000     -5.999          3.714
        1112.000     -6.042          3.714
        1113.000     -6.087          3.714
        1114.000     -6.132          3.714
        1115.000     -6.178          3.714
        1116.000     -6.225          3.714
        1117.000     -6.274          3.714
        1118.000     -6.323          3.714
        1119.000     -6.373          3.714
        1120.000     -6.425          3.714
```

Figure 4.14 A laser line report for setting-out tunnel excavation.

```
TUNNEL : South Bound Tunnel. ST20. Chainage from South Portal.

**********************************************************************
**                                                                  **
**                        LASER LINE REPORT                         **
**                                                                  **
**********************************************************************

SURVEYOR :                                          DATE  04-15-1996
                                                    TIME  16:59:48
TUNNEL HEAD CHAINAGE    :

   LASER LINE POSITION : Left Shoulder
               AZIMUTH : 314 deg. 26 min. 08 sec.
              GRADIENT :   -1.1429 %
           COORDINATES :
Chainage       Northing        Easting       Elev.   X-Offset  Y-Offset
1001.641     826301.311     824943.619     91.613    -7.356     3.714
1108.309     826376.453     824866.981     90.386    -5.888     3.714

**********************************************************************
**                                                                  **
**                       LASER OFFSET TABLE                         **
**                                                                  **
**********************************************************************

                     OFFSETS FROM TUNNEL CENTRE
                     HORIZONTAL          VERTICAL
         CHAINAGE   ( X-OFFSET )       ( Y-OFFSET )
         1109.000      -5.916             3.714
         1110.000      -5.957             3.714
         1111.000      -5.999             3.714
         1112.000      -6.042             3.714
         1113.000      -6.087             3.714
         1114.000      -6.132             3.714
         1115.000      -6.178             3.714
         1116.000      -6.225             3.714
         1117.000      -6.274             3.714
         1118.000      -6.323             3.714
         1119.000      -6.373             3.714
         1120.000      -6.425             3.714
```

Figure 4.14 A laser line report for setting-out tunnel excavation.

The principal alignment, the cross-section template, the laser offset table and the drill plan are then entered into the computer system of the drilling machine. The laser targets, usually two of them mounted on the drilling machine, are aligned onto the laser beam by the machine operator. Blasting holes are drilled automatically at precise positions and directions by the computerized machine. When drilling is completed, explosives are charged into the drill holes. Soils and rocks are then excavated from the tunnel by blasting and mucking. After scaling and rock-bolting of fragile surfaces, as-built surveying will be carried out by surveyors to ensure no under-break is found on the tunnel cross-sections.

On the completion of excavation, concrete liners will be installed or cast-in-situ. Their final positions will be surveyed by the tunnel surveyors and checked against the designed plans to the satisfaction of the engineers. Techniques of as-built surveying and reporting will be described in Section 4.4. To a certain extent, as-built data can be used for setting-out structural elements which have to be constructed in several stages from foundation to their completion. Therefore, the as-built function of TAS has been designed for both setting-out and as-built surveying of tunnels.

Other setting-out data may be required during each construction phase of the tunnel. Figure 4.15 illustrates data provided by TAS for setting-out points which are offset from the tunnel centre-line.

```
ROUTE : AL4

*****************************************************************
**                                                             **
**              SETTING-OUT DATA OF TUNNEL                     **
**                                                             **
*****************************************************************

        CONTROL POINT        NORTHING            EASTING

       AT :         62200     149,898.4280       183,006.0140

BACKSIGHT :         62600     150,244.5430       182,807.3690

             AZIMUTH BEARING = 330°08'50"   DISTANCE =    399.068

CENTRE-LINE OFFSET =      0.000

CHAINAGE     CURVE          TUNNEL-CENTRE COORDINATES                TANGENTIAL
             CODE     NORTHING          EASTING         ELEVATION    AZIMUTH

62,210.000    C     149,906.4242    183,000.0139      314.215    323°18'55"
             AZIMUTH BEARING = 323°06'59"   DISTANCE =    9.997
62,220.000    C     149,914.4618    182,994.0698      314.245    323°42'57"
             AZIMUTH BEARING = 323°18'58"   DISTANCE =    19.994
62,230.000    C     149,922.5408    182,988.1820      314.275    324°07'00"
             AZIMUTH BEARING = 323°30'58"   DISTANCE =    29.990
62,240.000    C     149,930.6607    182,982.3509      314.305    324°31'02"
             AZIMUTH BEARING = 323°42'59"   DISTANCE =    39.986
62,250.000    C     149,938.8212    182,976.5767      314.335    324°55'05"
             AZIMUTH BEARING = 323°55'00"   DISTANCE =    49.982
62,260.000    C     149,947.0219    182,970.8597      314.365    325°19'07"
             AZIMUTH BEARING = 324°07'01"   DISTANCE =    59.977
62,270.000    C     149,955.2624    182,965.2002      314.395    325°43'10"
             AZIMUTH BEARING = 324°19'02"   DISTANCE =    69.971
62,280.000    C     149,963.5423    182,959.5984      314.426    326°07'12"
             AZIMUTH BEARING = 324°31'03"   DISTANCE =    79.964
62,290.000    C     149,971.8611    182,954.0547      314.456    326°31'14"
             AZIMUTH BEARING = 324°43'04"   DISTANCE =    89.957
62,300.000    C     149,980.2185    182,948.5693      314.486    326°55'17"
             AZIMUTH BEARING = 324°55'05"   DISTANCE =    99.948
```

Figure 4.15 An example of setting-out data for tunnel construction.

When a tunnel is constructed by the shield drive, the following positional parameters are required to steer a TBM precisely:

1. Start and end chainages in the direction of the drive,
2. X-offset (offset left or right of the tunnel centre),
3. Y-offset (offset above or below the tunnel centre),
4. Lead (rotation about the vertical axis at the tunnel centre),
5. Tilt (deviation from the horizontal), and
6. Roll (rotation about the tunnel axis through its centre).

The most practical method of setting-out a TBM is by laser line and double target. The laser instrument is set to emit the laser beam through two control targets along the next predetermined (X, Y) position. The control targets are set between the laser instrument and the TBM. Each of the control targets has a hole just large enough for the laser beam to pass through. This will provide independent checks on the laser line, and detect any disturbance of the laser during construction. Total stations, computers and other accessories are used to set the laser and the control targets on site. The correct (X, Y) position of the laser instrument and control targets are set out by trial and error operation in which (N, E, Z) coordinates of points on the laser line are determined from known control points. The (N, E, Z) data are then entered into TAS's as-built function to determine their (X, Y) values (Figure 4.17) instantly for setting-out the laser instrument and the control targets in the field.

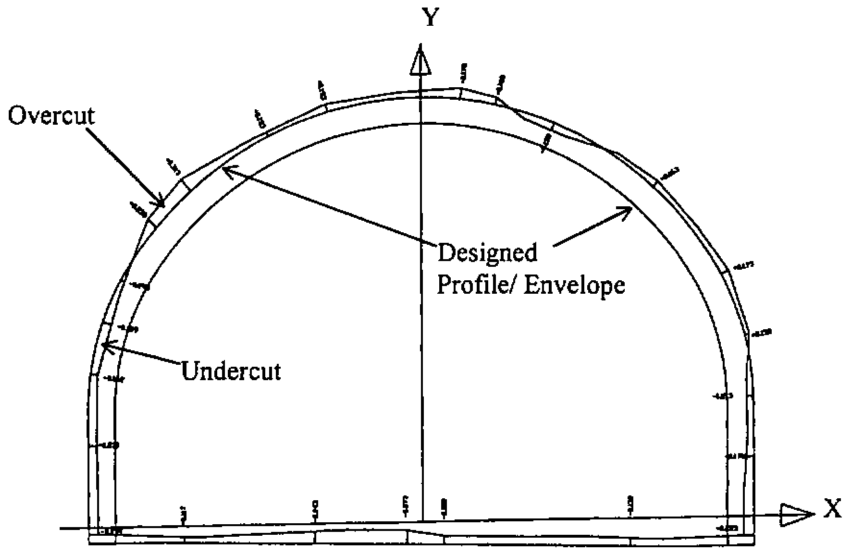
In the horizontal plane, the laser line is a chord line or a tangent to the tunnel centre-line. In the vertical plane, the laser line approximates the gradient of the tunnel centre-line. Depending on the size of the tunnel, two or four targets are mounted on front and rear ends of the TBM. The targets are installed at pre-determined offset positions (X, Y) and centered on a line parallel to the longitudinal axis of the TBM.

The theoretical position of intersection between laser beam and TBM targets at regular chainage intervals is computed by the surveyors and reported in the laser off-set table. These data are entered into the computer system of the TBM in advance for each drive. The machine will be steered so that the laser beam will pass through the center of the target when the TBM is travelling on a straight alignment, or through the computed offset from the centre of the target when it is driven along a curved alignment. After the TBM is driven to the end chainage of the laser offset table, the laser is moved forward to the next laser position.

4.4 Applications in As-built Surveying

The final routine operation in construction surveying is to measure the finished structures and check against their design dimensions and positions during construction phases. The surveys provide a record of existing structures and the as-constructed position of the tunnel. If existing structures exceed allowable tolerances, remedial work would be required. During excavation, as-built surveying is required to ensure no undercut is found on the tunnel profiles. An as-built report on a tunnel cross-section is shown in Figure 4.16. Before and after concreting of tunnel liners, position of formwork and completed concrete surfaces are also checked by as-built surveying. An as-built report on tunnel liners is shown in Figure 4.17. The general flow chart of the as-built module is given in Figure 4.18. In the report, position of the surveyed point from the tunnel centre and the designed cross-section (or envelope) are given to evaluate the quality of the structures and setting-out.

As-built surveys are also carried out on completed tunnels to determine if sufficient clearances are available for the installation of pipelines, lighting, ventilation, etc. They should be implemented in two steps. The first step is to survey the tunnel before the breakthrough from opposite drives. The second step is to check if existing tunnels have been built to within allowable tolerances, and if the design tolerances are exceeded, to see if it is possible to realign the tunnel without remedial work to the existing structures.



TUNNEL CENTRE		CROSS-SECTION AREAS (m^2)	
Slope Chainage:	1754.663	Theoretical:	132.995
Northing:	826957.058	Measured:	130.758
Easting:	824603.984	Overcut:	0.905
Elevation:	84.976	Undercut:	3.142
% Slope:	-1.15		

Figure 4.16 Report on a tunnel cross-section in an as-built survey.

AS-BUILT SURVEY OF TUNNEL

Route : AR2 Tunnel

Point No.	Chainage	Clear (+ve) Encroach (-ve)	From Envelope dX	dY	From Tunnel Centre X	Y
110008	45926.803	0.131	0.002	-0.131	0.182	-10.376
110009	45922.469	0.177	0.004	-0.177	0.229	-10.422
110010	45918.630	0.244	0.006	-0.244	0.263	-10.488
110011	45914.207	0.257	-0.016	-0.257	-0.638	-10.485
110012	45909.960	0.240	-0.015	-0.240	-0.644	-10.467
110013	45905.920	0.404	0.048	-0.401	1.268	-10.575
110014	45901.878	0.349	0.017	-0.348	0.503	-10.584
110017	45888.905	0.253	-0.001	-0.253	-0.052	-10.500
110018	45885.190	0.237	-0.001	-0.237	-0.055	-10.484
110019	45880.828	0.289	0.033	-0.287	1.218	-10.465
110020	45877.144	0.201	0.024	-0.200	1.229	-10.376

Figure 4.17 An as-built report on tunnel liners by TAS.

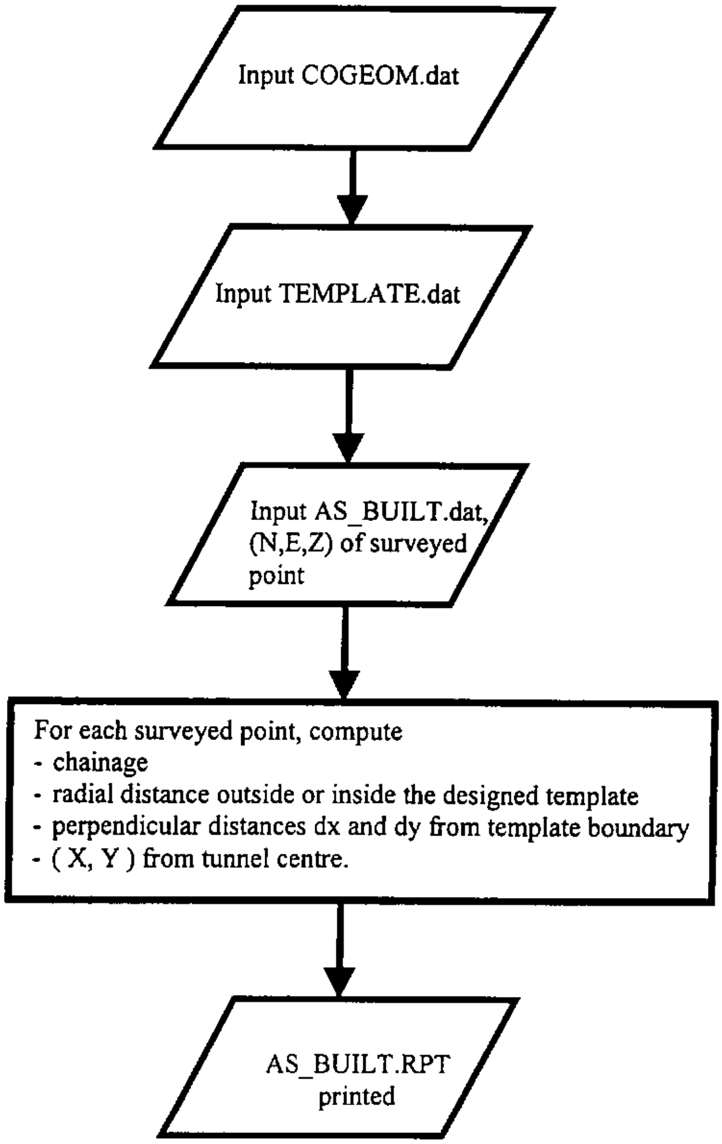


Figure 4.18 Flow chart of the as-built module of TAS.

It would be impractical to measure every finite element of the lining for checking their tolerances. In normal practice, cross-sections at regular intervals along the whole length of the tunnel are surveyed. Critical points around the lining on the plane of normal coordinated axes are recorded in a process known as tunnel profiling. Their surveyed positions are then computed or plotted for checking the clearance against the designed cross-section, the structure gauge or the kinematic envelope. Structure gauge is the profile coplaning the normal coordinated axes of the tunnel centre-line into which no part of any structure or fixed equipment may penetrate. Thus, should any part of the lining be encroaching into the boundary of the structure gauge, remedial work should be implemented either to reconstruct the lining or realign the highway tunnel so that the structure gauge can pass through. Kinematic envelope is the cross-section coplaning the normal coordinated axes of a highway alignment which covers the various parts of the vehicle(s), taking into account the most favorable positions, for safe running on the carriageway. Once an offending profile has been discovered, it is customary to survey adjoining profiles at closer chainage intervals in order to provide adequate information for remedial measures.

There are many methods of profiling being employed in checking the clearance of tunnels. They include:

1. Measuring offsets directly to a structure gauge being mounted on a trolley and driven along the tunnel.

2. The application of photogrammetric methods in which terrestrial photographs of cross-sections are taken [Richardus, 1984].
3. The application of cross-section tacheometer or gage [Richardus, 1984].
4. The use of reflector-less total stations by which coordinated points on the tunnel surface are automatically recorded, processed and analyzed by laptop computers in the field.

The first method usually requires a free tunnel. If the tunnel is designed for a single-lane road, it may be impractical to carry out the survey in the field during the construction. The second method and the third method can achieve certain levels of plotting accuracy. Their applications inside the tunnel are expensive and may require a free tunnel. Therefore, they are not applied in modern tunnel construction.

The last method using reflector-less total station with microcomputer systems is the most common one in as-built surveying of highway tunnels. It can be conducted sequentially with construction progress without obstructing normal passage of construction vehicles inside the tunnel, and adapted to measure all types of profile shape. Besides, all the field data are stored electronically in the form of 3D coordinates of the constructed tunnel inside a total station or directly recorded by a palm-top-computer for processing in the field. By comparison with other methods, the reflector-less total station method is less time-consuming and surveyors can be protected from flyrocks.

The range of reflector-less total stations is to some extent governed by the reflectivity and orientation of the measured surface. A bright surface whose orientation is perpendicular to the laser beam of the total station has a greater range and better accuracy than a dark surface with an oblique orientation. The presence of excess water and loose particles on the surfaces being measured can affect the laser measurement, effectively reducing the range and accuracy. Depending on the size of the cross-sections of the tunnel, accuracy of 5 – 10 mm could be achieved in the profile.

When the cross-section database of as-built surveys is available inside the computer system, volume of excavation and quantity of materials for construction are computed by applying the mean cross-sectional area method. Sample of a volume report for quantity measurement is given in Table 4.1.

As-built data of existing tunnels are important and useful in breakthrough procedures. At an appropriate distance, say 100 metres, from the pre-arranged meeting point, small adits will be headed from opposite sites. At the breakthrough, the two main control traverses will be accurately joined via the adit. Misclosure for chainage, lateral offset and level difference will be surveyed and analyzed together with the as-built data of existing tunnels. The alignment over the breakthrough section of the tunnel are then adjusted to produce a final smooth junction of the opposite drives without remedial works to existing structures.

Table 4.1 Sample of a volume report in an as-built surveying.

VOLUME REPORT									
Route: AR3 Tunnel (North Bound)								**Surveyor:** **Date:**	
		Theoretical		Overcut		Undercut		Measured	
Chainage (m)	Distance (m)	Area (m^2)	Volume (m^3)	Area (m^2)	Volume (m^3)	Area (m^2)	Volume (m^3)	Area (m^2)	Volume (m^3)
1813.215		132.995		0.250		- 3.142		130.103	
	5.120		680.93		1.34		- 16.27		666.00
1818.335		132.995		0.273		- 3.215		130.053	
	5.472		727.75		1.17		- 14.66		714.26
1823.807		132.995		0.155		- 2.142		131.008	
	5.613		746.50		0.46		- 10.37		736.59
1829.420		132.995		0.010		- 1.553		131.452	
	5.201		691.71		0.92		- 12.40		680.23
1834.621		132.995		0.345		- 3.217		130.123	
	5.215		693.57		2.34		- 14.91		681.00
1839.836		132.995		0.551		- 2.501		131.045	
	5.124		681.47		5.26		- 14.61		672.12
1844.960		132.995		1.501		- 3.201		131.295	
	5.005		665.64		10.15		- 13.40		662.39
1849.965		132.995		2.553		- 2.152		133.396	
	4.973		661.38		7.03		- 8.41		660.01
1854.938		132.995		0.276		- 1.230		132.041	
	5.133		682.66		4.96		- 8.73		678.89
1860.071		132.995		1.655		- 2.172		132.478	
	5.365		713.52		8.52		- 8.66		713.39
1865.436		132.995		1.523		- 1.055		133.463	
Total			**6945.13**		**42.15**		**- 122.42**		**6864.87**

CHAPTER 5

TUNNEL MODELS FORMED BY SKINNING

5.1 Skinning Function for Geometric Modeling of Tunnels

In Chapter 4, designed cross-sections are assumed to be identical between specified chainages of a highway tunnel. It is not unusual to have variable cross-sections. This is usually found at the junction or intersection of utility tunnels with the main tunnel.

Skinning, or blending as it can be called, is a modeling function used to form a closed volume or a solid by creating a skin surface over pre-specified cross-sectional planar surface and closed at the end faces. It is a solid transition of variable cross-section swept along the principal alignment of the tunnel. Thus, the swept has two or more closed planar cross-sections which are normal to the principal alignment with equal number of segments on the boundaries of the cross-sections. As shown in Figure 5.1, a horse-shoe cross-sectional profile blends into a rectangular cross-sectional profile along the trajectory curve. As each segment is blended in consecutive cross-sections, the number of segments per cross-section is preferably equal to expedite tunnel construction. Depending on the allowable tolerances, the design of tunnel formwork and the method of construction, arcs and lines of cross-sections may need to be subdivided for more segments so that better geometric accuracy of the tunnel model could be achieved. If additional cross-sections are added, a check for surface continuity between profiles is required in order to avoid waviness on the model.

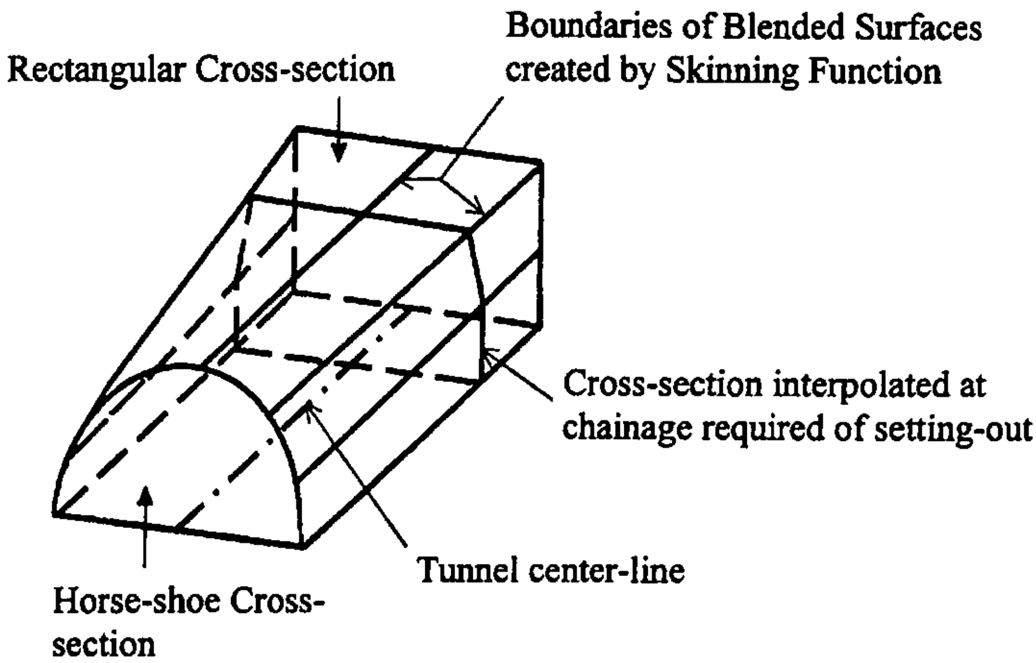


Figure 5.1 Tunnel model formed by skinning function.

5.2 Algorithms of the Skinning Function

The algorithms presented here are based on the assumption that cross-sectional boundaries are defined by an ordered set of coordinates (X, Y) as illustrated in Chapter 4. There are two practical algorithms to create a blend surface over planar cross-sections in tunnel construction namely the wire-frame method and 3D Delaunay Triangulation.

In the wire-frame method, a number of cross-sectional outlines are given. Pairs of defining points on two consecutive cross-sections are identified and connected by lines to form a wire-frame model (Figure 5.1) based upon the following algorithm developed by the author:

Step 1. Select the nearest pair of cross-sections.

Step 2. Divide the boundary of each cross-section with an equal number of segments.

Step 3. On each cross-section, join the tunnel centre to each point defining the cross-sectional boundary. Define each point by:

(a) If the line from the tunnel centre to the point crosses an odd number of boundaries, the point is labeled as an "n-point". If the line from the tunnel centre to the point crosses an even number of boundaries or does not cross a boundary , it is labeled as a "p-point". If designed cross-sections are regular and convex shapes, classification of n-point and p-point is not required.

(b) The direction of the line from the tunnel centre to the point, being the angle measured from the Y-axis.

Step 4. Join the defining points on the first cross-section by straight lines to those points on the second cross-section so that:

(a) P-point to p-point and n-point to n-point, and

(b) The direction of the point on the first cross-section is the closest to that of the point chosen on the second cross-section.

Step 5. A solid volume is then generated by the surfaces of the loops of connecting lines and the end faces.

The cross-section at a specified chainage can then be extracted by linear interpolation of the wire-frame model for setting-out and other construction operations. The centre line of a highway tunnel should be located on or inside the closed boundary of a cross-section. It is customary to check the sum of the angles subtended by the lines joining the tunnel centre to each boundary defining point. If the sum is equal to 360^0, the tunnel centre lies inside the cross-section. If the sum is equal to 0^0, the tunnel centre lies outside.

3D Delaunay Triangulation is another algorithm suitable for generating solid models of irregular surfaces between end cross-sections which are not identical in geometry (Figure 5.2). Its algorithm will be described in Chapter 6. These two algorithms were developed by the author and proved successful in the construction of tunnels having variable cross-sections.

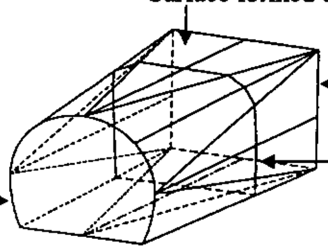


Figure 5.2 Cross-section interpolated from 3D TIN.

CHAPTER 6

COMPUTATIONAL GEOMETRY FOR IRREGULAR SURFACES AND TUNNEL INTERSECTIONS

6.1 TIN by Delaunay Triangulation for Irregular Surfaces

Ordinary solid modeling techniques are difficult to represent irregular surfaces and surface intersections at certain construction stages of a highway tunnel. For example, in the drill-and-blast method of tunnel excavation, tunnel surfaces are irregular in geometry after blasting. These irregular surfaces of the geometric models are usually represented by meshes of three-dimensional Triangular Irregular Network (TIN) in as-built surveying.

Figure 6.1 illustrates the tunnel intersection represented by a three-dimensional TIN model in as-built surveying during drill-and-blasting operations. Figure 6.2 illustrates a two-dimensional TIN model which represents the irregular surface of the tunnel after blasting. The model is developed on plan view in which undercuts greater than the allowable tolerance are plotted for site inspection and trimming processes.

Three-dimensional Delaunay triangulation is applied to generate TIN models of surfaces in a variety of applications in tunnel construction. From the knowledge and working experience of the author, it is perhaps the most efficient and popular method of generating triangles by connecting the coordinated points on a tunnel surface because it maximizes the sum of the smallest angles in all the triangles being generated (Delaunay, 1934; Watson, 1981, 1982, 1992; Tsai, 1993; Fang and Piegl, 1993, 1995).

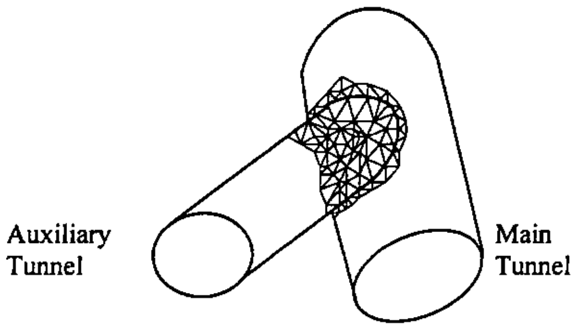


Figure 6.1 TIN model is applied to represent the irregular surface of a tunnel intersection in as-built surveying.

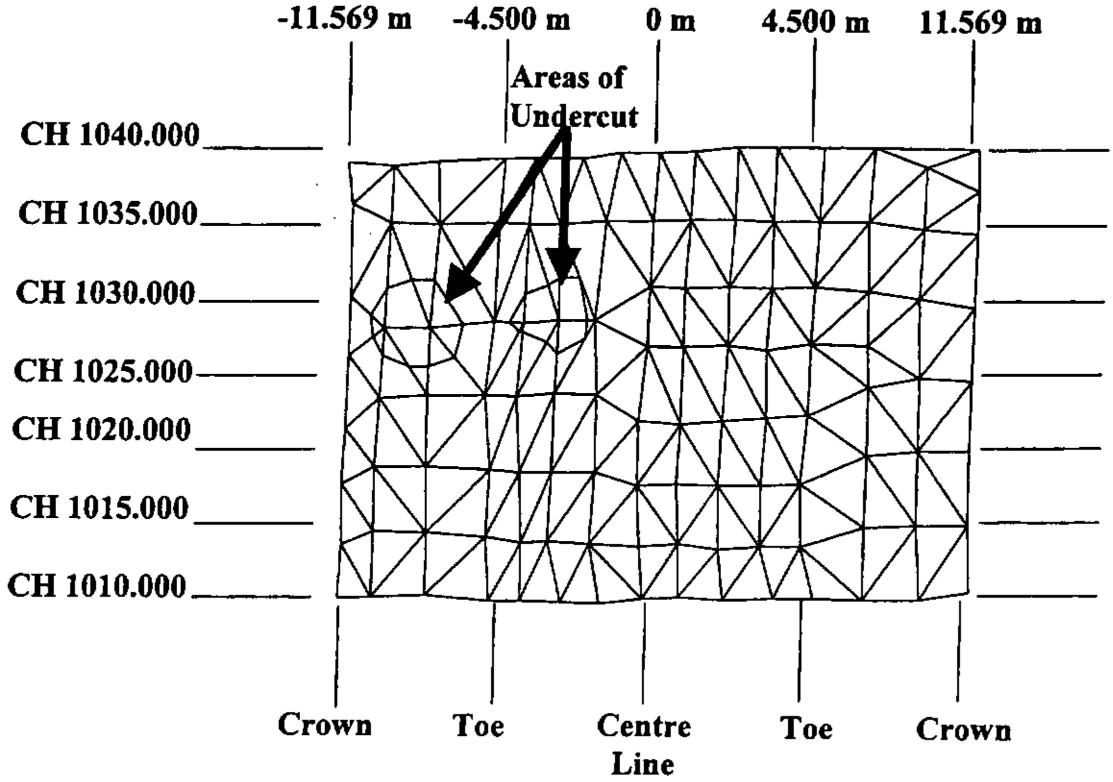


Figure 6.2 TIN surface developed on plan view for site inspection and removal of undercut areas in a construction project.

Delaunay algorithms are categorized according to their modeling methods as follows:

1. Divide-and-conquer methods given by Lee and Schachter (1980);
2. Incremental insertion methods given by Watson (1981, 1982, 1992), Sloan, (1987), Macedonio and Pareschi (1991) and Tsai (1993); and
3. Triangulation growth methods by having a radial sweep algorithm given by Mirante and Weingarten (1982) and Maus (1984).

Most of the Delaunay algorithms in software production apply the incremental insertion methods with a little variation in data structures and the setting of the initial Delaunay triangulation, which encompasses all of the data points, as either a super triangle or a rectangle.

Based on the concept given by Delaunay (1934) and Watson (1981, 1982, 1992), the following algorithm of 3D Delaunay triangulation is recommended by the author to represent irregular surfaces in tunnel construction:

Step 1. Create a super-triangle which circumscribes all the coordinated points between the chainages of the required tunnel section. The circumcenter must lie on the plane of the triangle and on the intersection of two perpendicularly bisecting planes of any two edges of the triangle.

Step 2. Construct the Delaunay triangulation (Figure 6.3) in the three-dimensional space by applying the following criteria:

(a) A triangle is formed from three non-collinear as well as non-coincident points when a sphere passing through the points, called the circumsphere of the triangle, does not include any other points.

(b) The circumcenter must lie on the plane of the triangle and on the intersection of two perpendicularly bisecting planes of any two edges of the triangle.

Step 3. Repeatedly insert other points and refine the existing Delaunay triangulation until all the coordinated points are addressed in the TIN model.

Step 4. Repeatedly insert breaklines and refine existing Delaunay triangulation until all the breaklines have been inserted in the TIN model. Breaklines are edges joining tunnel corners or changes of geometry in the design.

Step 5. Remove all the triangles that are within the internal exclusion boundaries or outside the external exclusion boundaries.

Topological data structures for the TIN model are given in Figure 6.4. This is also a skinning function and designed for generating solid models of irregular surfaces. The accuracy of the surveyed surface can be improved by increasing the number of points within the target area or by using higher order shape functions. The latter method of applying higher order facets is rarely applied in tunnel construction projects. Once the TIN model has been completed, the geometric model of the tunnel is ready for interpolation and extraction of cross-sections for setting-out, as-built surveying and volume calculations.

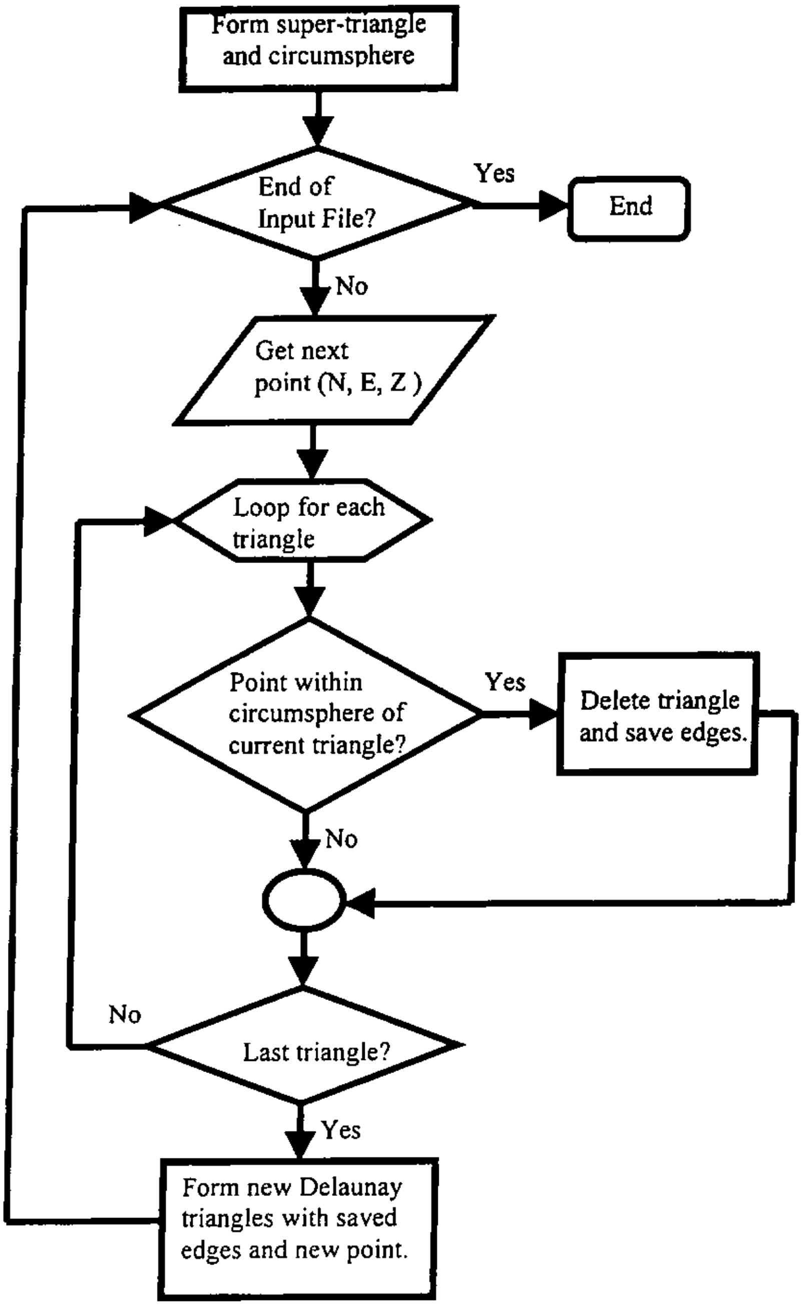


Figure 6.3 Flow-chart of three-dimensional Delaunay triangulation.

```
struct point {                          /* Mass data points                        */
        float   nez[ 3 ];               /* [ N, E, Z ] of points                   */
        long    next;                   /* Next point
};

struct edge {                           /* Edges in TINs                           */
        long    ft_nodes[ 2 ];          /* From_node and To_node                   */
        long    left_right_tin[ 2 ];    /* Left and Right TINs                     */
};

struct TIN {
        long    ed[ 3 ];                /* Indices of bounded edges                */
        long    at[ 3 ];                /* Indices of adjacent TINs                */
        float   csphere[ 3 ];           /* Center [ N,E, Z ] of circumsphere       */
        float   radius;                 /* Radius of circumsphere                  */
        long    next;                   /* Next TIN                                */
};

struct bline {                          /* Breaklines in TINs                      */
        long    ftbnodes[ 2 ];          /* From_break_node and To_break_node       */
};
```

Figure 6.4 Topological data structures in C language for 3D Delaunay triangulation on tunnel surface.

6.2 Computational Geometry for Tunnel Intersections

The precise digital model representing the surface intersection of tunnels, usually between the main tunnel and the auxiliary ones, is an important problem in geometric modeling of solid objects. The algorithm given in Section 6.1 is designed for modeling intersections of irregular surfaces surveyed in the field. If the designed data or the boundary segments of the surface joint are required for setting-out or as-built surveying of the intersection, the following surface-to-surface intersection algorithm is suggested:

Step 1. Compute the chainages of intersection on each tunnel by the horizontal alignments of the intersecting tunnels

Step 2. On the main tunnel surface, extract coordinated nodes from the principal alignment and the cross-section templates of the tunnel to generate triangular facets covering the region of the intersection.

Step 3. On the auxiliary tunnel surface, extract coordinated nodes from the principal alignment and the cross-section templates of the tunnel to generate triangular facets covering the region of the intersection.

Step 4. For each triangular facet of the main tunnel, carry out a bounding box (minimax) test with all the triangular facets of the auxiliary tunnel. If two bounding boxes overlap and the facets are not parallel, compute the segment of the two intersecting facets by solving the equations representing the two triangular facets.

Bounding boxes of a pair of facets from the two tunnels do not overlap if any one of the following inequalities is true:

1. Maximum N_{main} < Minimum $N_{auxiliary}$
2. Maximum $N_{auxiliary}$ < Minimum N_{main}
3. Maximum E_{main} < Minimum $E_{auxiliary}$
4. Maximum $E_{auxiliary}$ < Minimum E_{main}
5. Maximum Z_{main} < Minimum $Z_{auxiliary}$
6. Maximum $Z_{auxiliary}$ < Minimum Z_{main}

where (N_{main} , E_{main} , Z_{main}) are the maximum or minimum vertex coordinates of the facet from the main tunnel, and ($N_{auxiliary}$, $E_{auxiliary}$, $Z_{auxiliary}$) are the maximum or minimum vertex coordinates of the facet from the auxiliary tunnel.

Step 5. Segments of the intersecting facets are joined together to form a loop which is the intersecting boundary of the two tunnels. Replace any quadrilaterals, if existing, by Delaunay triangles.

Step 6. The final geometric model of the intersection is then completed by deleting the facets which are not forming the surface of the intersection.

Through the use of triangular facets, the boundary of the joint can be computed by surface-to-surface intersection. A designed surface joint of a tunnel intersection is illustrated in Figure 6.5. Accuracy of the geometric model at an intersection is governed by the geometry of both the cross-section templates and the principal alignments and of the intersecting tunnels. It can be raised by increasing the number of coordinated nodes, that is, more facets, being generated at closer intervals on the designed surfaces of the tunnels.

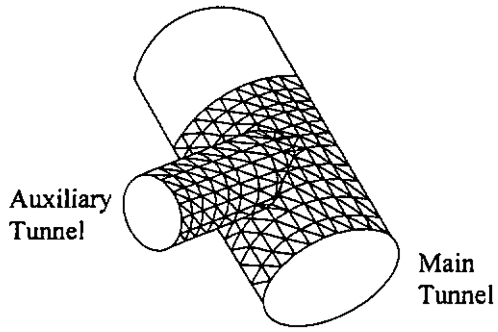


Figure 6.5 Designed surface joint of a tunnel intersection formed by TIN.

CHAPTER 7

TUNNEL MODELS FORMED BY MESH GENERATION

7.1 Purposes and Requirements of Mesh Models

A successful geometric modeling system, which adheres to a solid modeling system, must employ a representation scheme which provides general-purpose shape modeling for a variety of generation, manipulation, display and analysis functions as well as support for applications such as finite element modeling (FEM), finite element analysis (FEA) and numerical control (NC) machining. The FEM and FEA have been extensively used by all CAD/CAPP/CAM systems to solve structural, setting-out, fluid mechanics, and electromagnetic problems in engineering and construction because they are capable of handling complex shape (both geometry and topology), element type, material properties, physical properties (such as thickness), boundary conditions, loading conditions, deformation and displacement models, and other mesh attributes of various design cases.

FEM has been dominant in tunnel design practice because of its capability in analyzing structural and mechanical properties by computers. Figure 7.1 shows the procedure of finite element analysis in tunnel design.

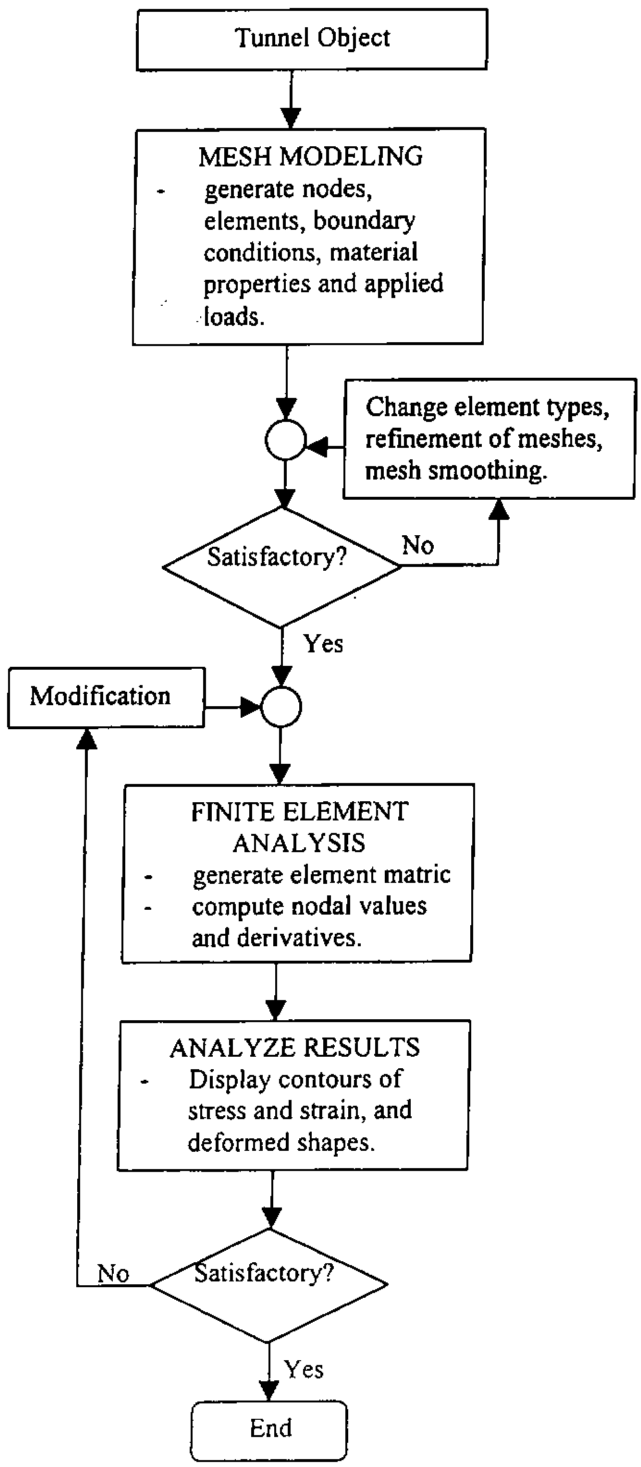


Figure 7.1 Procedure of finite element analysis in tunnel design.

An important step of FEM is the mesh generation based on boundary description of the tunnel object. Mesh generation, or finite element discretization, divides the interior of an object into simple elements of a type known to the analysis program. In practice, the discretization is performed using simplex elements such as quadrilaterals and triangles in two-dimensional space, or boxes, wedges and tetrahedra in three-dimensional space because they accommodate complex boundaries of the object. Examples of applying FEM in tunnel design are given in Figure 2.9.

Nodes at regular intervals or at changes of geometry are generated on the perimeter of each element. As a general rule, the larger the number of nodes and elements, the more accurate the meshed model in view of FEA and setting-out solution will be. This is probably at a sacrifice of computing time and memory storage among computer systems. The accuracy of the solution can also be improved by using higher order shape functions within each element. In this case, the number of nodes in each element can be increased to form higher order quadratic and cubic triangular elements or tetrahedral elements.

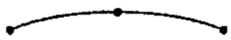
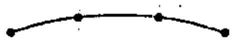
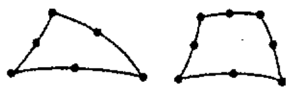
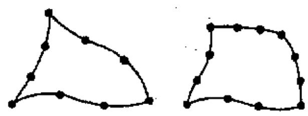
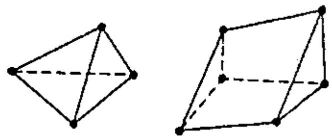
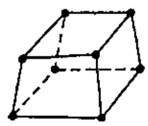
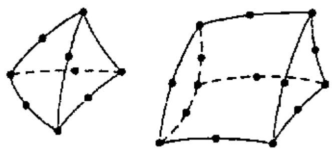
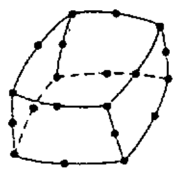
After the FEM has been generated, intersection process will be performed to delete or modify elements to produce the boundary model representing the precise geometrical configuration of the intersection. An intersection algorithm is given in Section 6.2. Thereafter, coordinated points on structural surfaces at particular chainages can be extracted by cross-sectioning the FEM vertically or perpendicular to the gradient of the principal alignments for setting-out operations in the field.

Fundamental requirements of a valid mesh model are summarized in the following items:

1. Nodes must lie inside or on the boundaries of the geometric model to be meshed.
2. A mesh element library must be provided in order to generate the dimension, degree, shape and element type required of the model. Typical mesh elements are given in Table 7.1 (LaCourse et al., 1995).
3. In order to ascertain the geometric accuracy of the model, it is required that mesh density (number of nodes and elements) should be increased around holes and sharp corners. Optimal mesh density variation is treated mainly as a function of topology, changes in topology and geometry of the boundary objects. Zeid (1991) recommended that the element aspect ratio be kept close to 1, that is, all sides of an element are approximately equal in length. However, in practice, mesh density controls should be applied on both edges and surfaces. An example of mesh density control is shown in Figure 7.2 (LaCourse et al., 1995).
4. It is desirable that a mesh of a given type of element can be easily converted to another mesh of a different element type.
5. Object and mesh topology should be consistent with each other in terms of orientation and matching in order to generate a precise mesh model for setting-out and FEA purposes (Figure 7.3).

6. A mesh generation must be compatible with the representation scheme whether it is a wireframe, surface or solid model.
7. In order to reduce the time and cost of FEM, it is important to optimize the mesh model by minimizing the number of nodes and elements and fulfilling the geometric accuracy and other requirements of the mesh generation.

Table 7.1 Typical mesh elements for finite element modeling
(LaCourse et al., 1995, Table 14.1).

Dimensions	Element degree	Element shape	Element type
1D (line)	Linear		Beam, truss
	Quadratic		Beam
	Cubic		Beam
2D (area)	Linear		Plane stress Plane strain Plate, shell*
	Quadratic		
	Cubic		
3D (volume)	Linear		
	Quadratic		

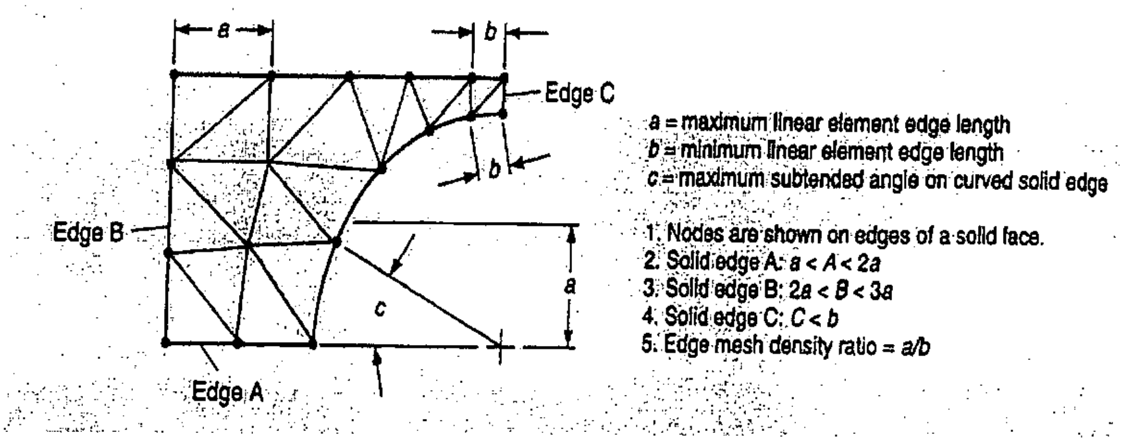
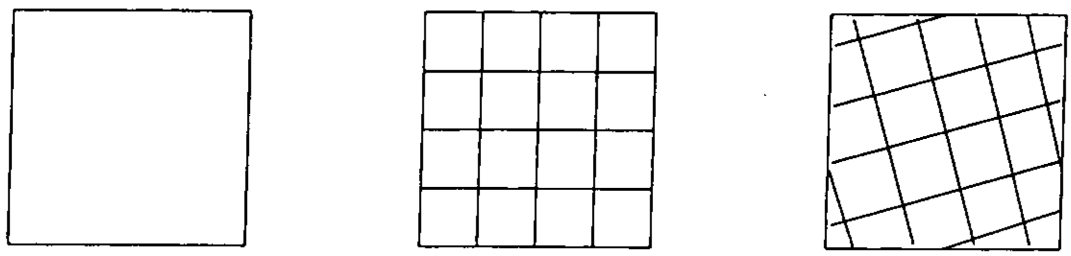


Figure 7.2 Example of mesh density controls on a surface and its edges (LaCourse et al., 1995, Figures 14.3 and 14.4).



(a) Object to be meshed.

(b) Mesh model is precise because object and mesh topology match each other.

(c) Mesh model is not precise because object and mesh topology do not match each other.

Figure 7.3 Basic requirement of topology for precise mesh models.

7.2 Mesh Generation Methods for Tunnel Construction

Mesh generation is a process that applies both the geometry and topology of a solid model and particular mesh rules to allow computerized generation of the mesh model. From the fundamental requirements of mesh models, the automatic mesh generation process must achieve a desired mesh density distribution and have well-shaped elements with boundaries precisely matching the geometry of the tunnel.

Mesh generation methods can be classified into the following groups according to Ho-Le (1988) and Lee (1999):

1. Node connection approach given by Cavendish et al. (1985, 1986), and, Shimada and Gossard (1992);
2. Topology decomposition approach given by Wordenweber (1984);
3. Geometry decomposition approach given by Bykat (1976);
4. Grid-based approach with octree data structure given by Yerry and Shepherd (1985); and
5. Mapped-element approach given by Zeid (1991).

They are further divided into semi-automatic or fully automatic ones. Some of them are suitable for the generation of mesh models for tunnel construction in view of geometric accuracy, current instrumentation and computers being used in tunnel surveying, and efficiency in programming their applications. However, none of them was experimented with in construction surveying of highway tunnels.

A mesh model of a highway tunnel generated by its principal alignments and 2D cross-sections is shown in Figure 7.4. Cross-sections are partitioned into simpler regions or subregions. Each subregion is partitioned into triangular or quadrilateral elements by transfinite mapping or the Delaunay triangulation method. The process is repeated until all the required cross-sections are designed and stored in the cross-section database. In the generation of the solid mesh model, each cross-sectional mesh is retrieved and positioned in the three-dimensional coordinate system with respect to the principal alignment of the tunnel. Each cross-section should be normal to the principal alignment, and transformed according to the required normal axis, the section scale factor and the angle of rotation (or angle of super-elevation) about its normal coordinated axes.

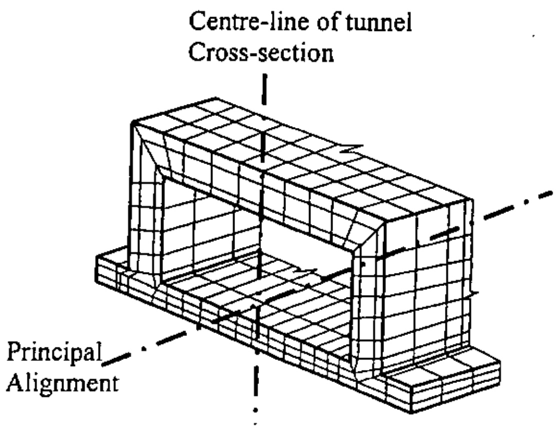


Figure 7.4 Example of a mesh model in tunnel design.

After positioning all the necessary cross-sections along the whole length of the principal alignment, specify the number of subsections or layers which will be interpolated between the specified cross-sections. A solid mesh model will then be generated in terms of parallel cross-sections or cross-sections normal to the principal alignment at chainage intervals. The solid mesh model can be edited by selecting different number of subsections or by creating different cross-sectional meshes. For changes of geometry among elements, relocate nodes, add or delete nodes and elements, and renumber nodes and elements. The meshing algorithm is represented schematically by the flowchart in Figure 7.5. As shown in the flowchart of Figure 7.1, editing of the attributes, boundary conditions, material properties and applied loads may be required before finite element analysis. When the mesh model is available, the designed cross-section at a specified chainage can then be extracted for setting-out and as-built surveying operations.

The accuracy of setting-out the finite element model depends very much on the quality of the geometric modeling system and its generated mesh. Therefore, the mesh generation process must achieve the desired mesh density distribution and have well-shaped elements with boundaries precisely matching the geometry of the tunnel. It can further be improved by increasing the number of meshes (or elements) or by applying higher order shape functions within each element.

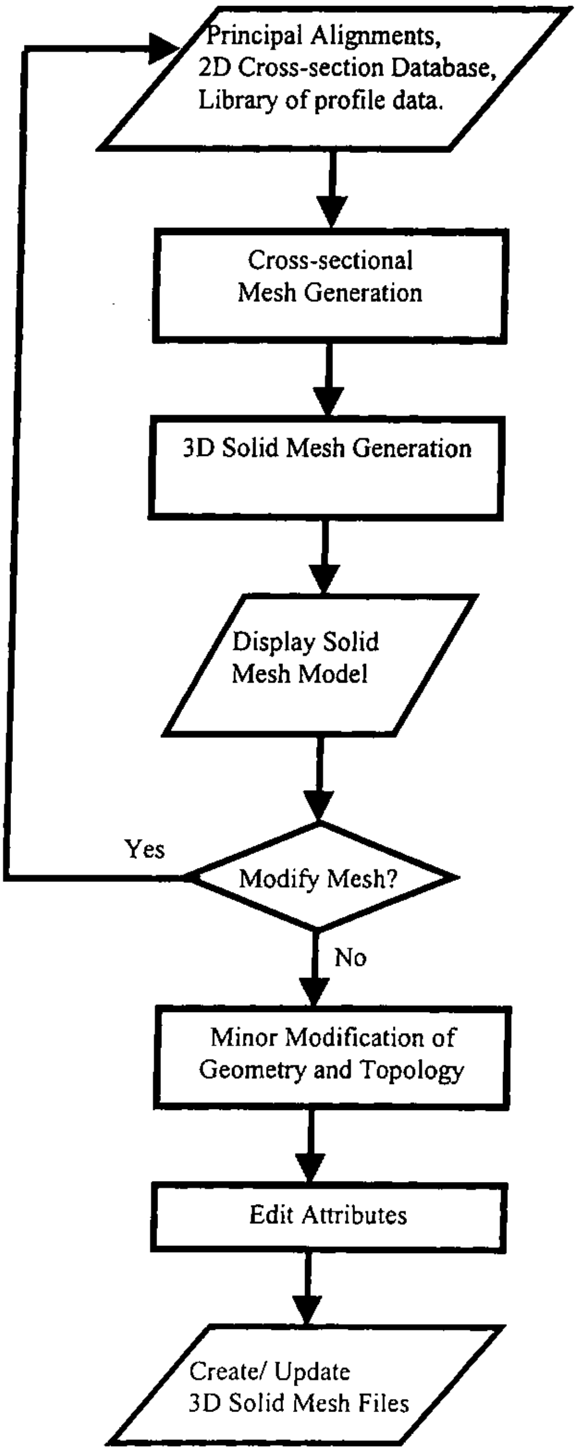


Figure 7.5 Flow-chart for creating and editing 3D solid finite element meshes in tunnel construction.

CHAPTER 8

COMBINED CONSTRUCTIVE SOLID GEOMETRY (CSG) AND BOUNDARY REPRESENTATION (B-Rep) MODEL

8.1 Data Structure of the Combined CSG and B-Rep Model for Tunnel Construction

This section describes some of the data structures of the combined CSG and B-Rep models which are suitable for tunnel construction. They are chosen by the author because of their proven capabilities and reliability in performing similar operations in the CAD/CAM industry.

Because of the inherent advantages and disadvantages of CSG models and B-Rep models (see Section 3.3), most of the geometric modeling systems for solid modeling on microcomputer platforms, for instance, AutoCAD, MicroStation, ProEngineer and Solidworks, are combined CSG and B-Rep modelers. These hybrid modelers support high-level CSG representation by an object-oriented approach (input of CSG primitives) and sweep operations as the basis for the user interface.

In these solid modeling systems, box, wedge, cone, cylinder, sphere and torus are the common predefined solid primitives being used to form complex solids. The primitives are assembled by Boolean operations to produce regular sets and form geometric models. Dangling faces, edges and vertices will be omitted during construction. The geometry stored in the database of a CSG model comprises the configuration parameters of its primitives and rigid motion and transformation.

Geometry of faces, edges and vertices are not addressed directly in a CSG model but transformed into B-Rep via boundary evaluation and merging algorithms like those given by Requicha and Voelcker (1985), Miller (1989), Rossignac and Voelcker (1989), and Hoffmann (1989). The conversion of data model from solid primitive to its B-Rep is given schematically in Figure 8.1.

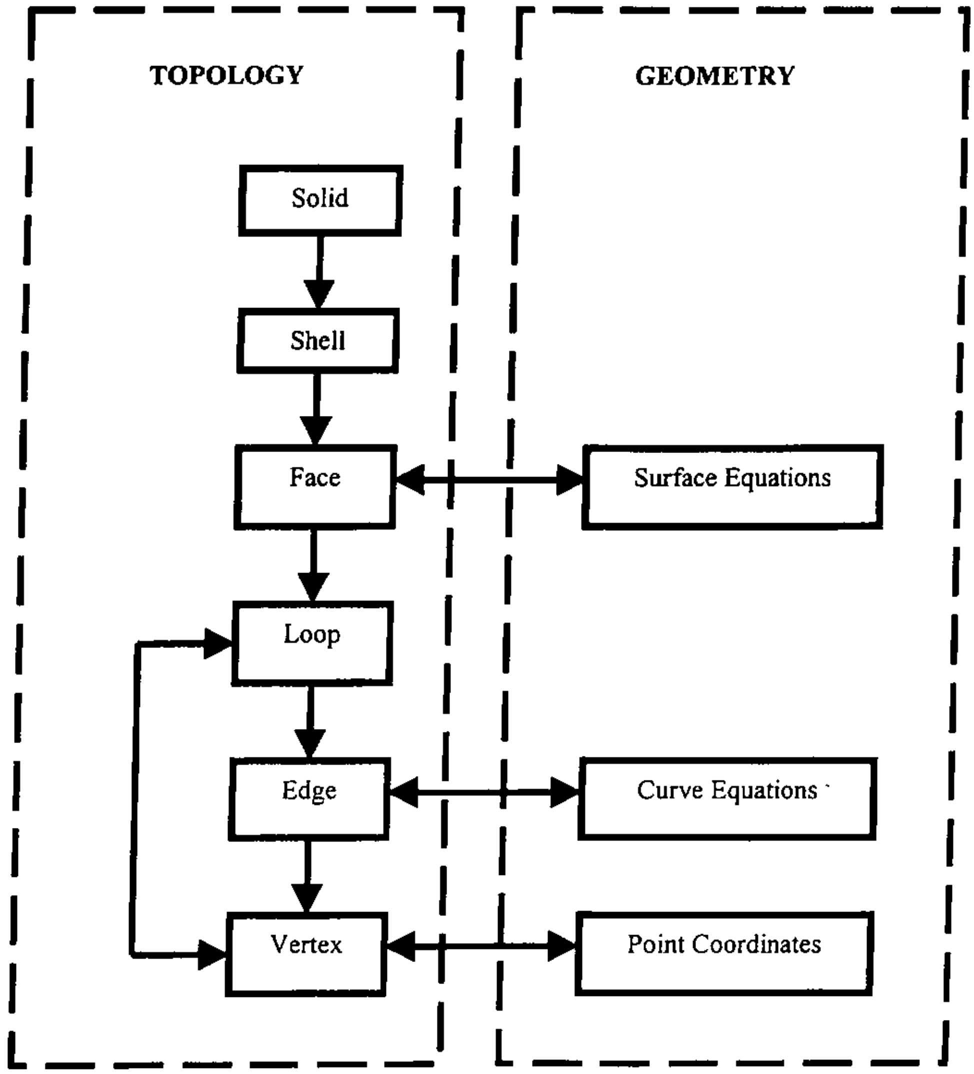


Figure 8.1 Schematic diagram for conversion of solid primitive into B-Rep model.

An example of a simple combined CSG and B-Rep model and its representations are given in Figure 8.2 and Figure 8.3. As shown in Figure 8.3, CSG representations of complex solids are ordered binary trees. Leaf nodes are primitive, and branch nodes are Boolean operators. Terminal nodes are used to change the location and orientation of an object or some part of an object represented by a sub-tree. Each sub-tree of a branch node represents a solid formed by the combining and transformation operations indicated below it. A CSG data structure suitable for modeling tunnels is given in Appendix I.

The algorithms required to implement CSG-based set-operations are the solid/solid intersection algorithms, the classification algorithms to compute the set membership classification functions, and the divide and conquer algorithms to process CSG trees. Set membership classification is a process by which various parts of a set (points, line segments or solid portions) are assigned or relative to the solid. To expedite computer programming, primitives of CSG models are converted to those that are defined by half spaces as shown in Figure 8.2. A half space is being defined as the space on one side of a surface which divides all of a defined space into two parts. Planes, natural quadrics and revolutions are the most commonly used half spaces for defining solid primitives.

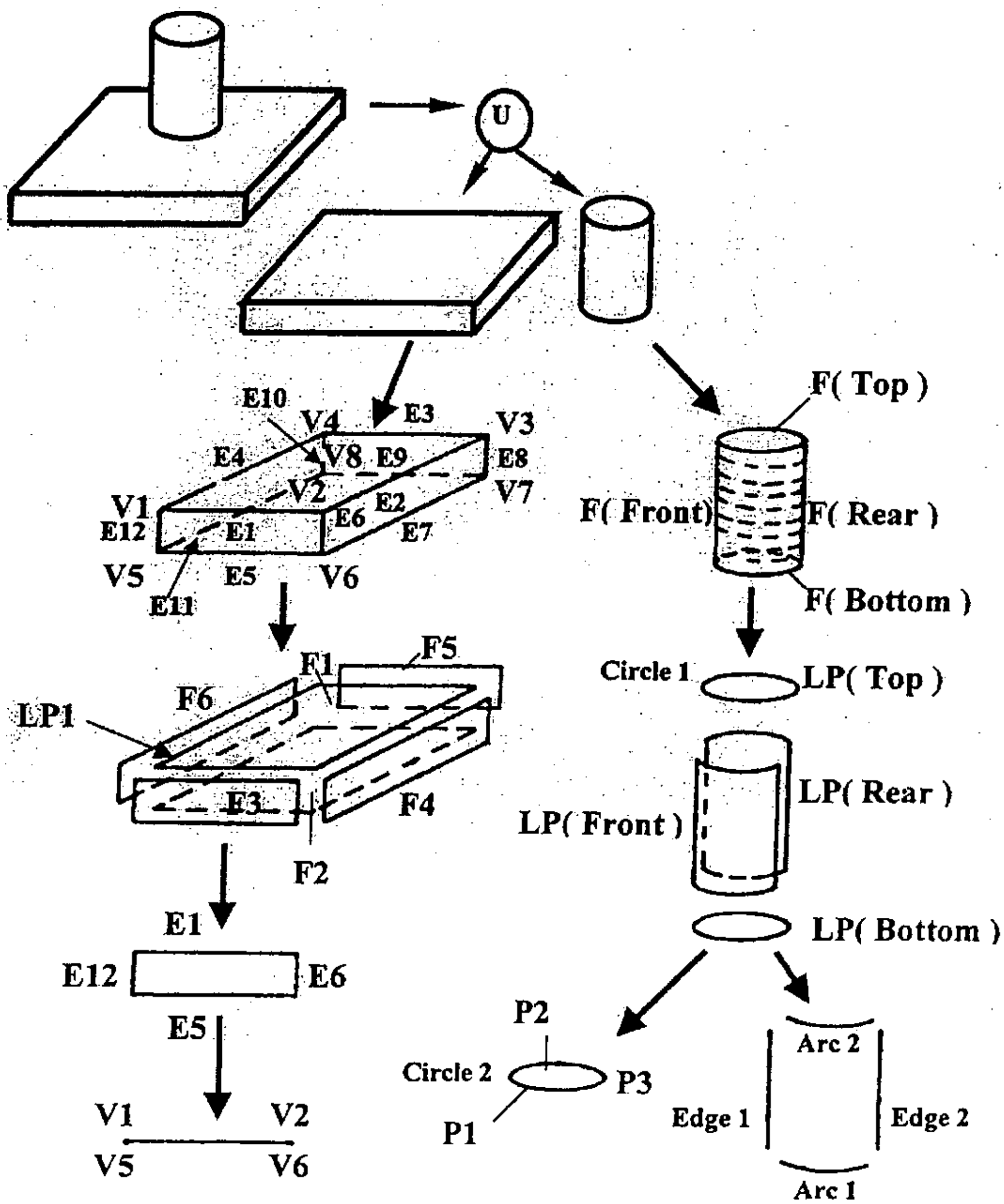


Figure 8.2 Example of a solid represented by a combined CSG and B-Rep model. Tree structure of the model is given in Figure 8.3.

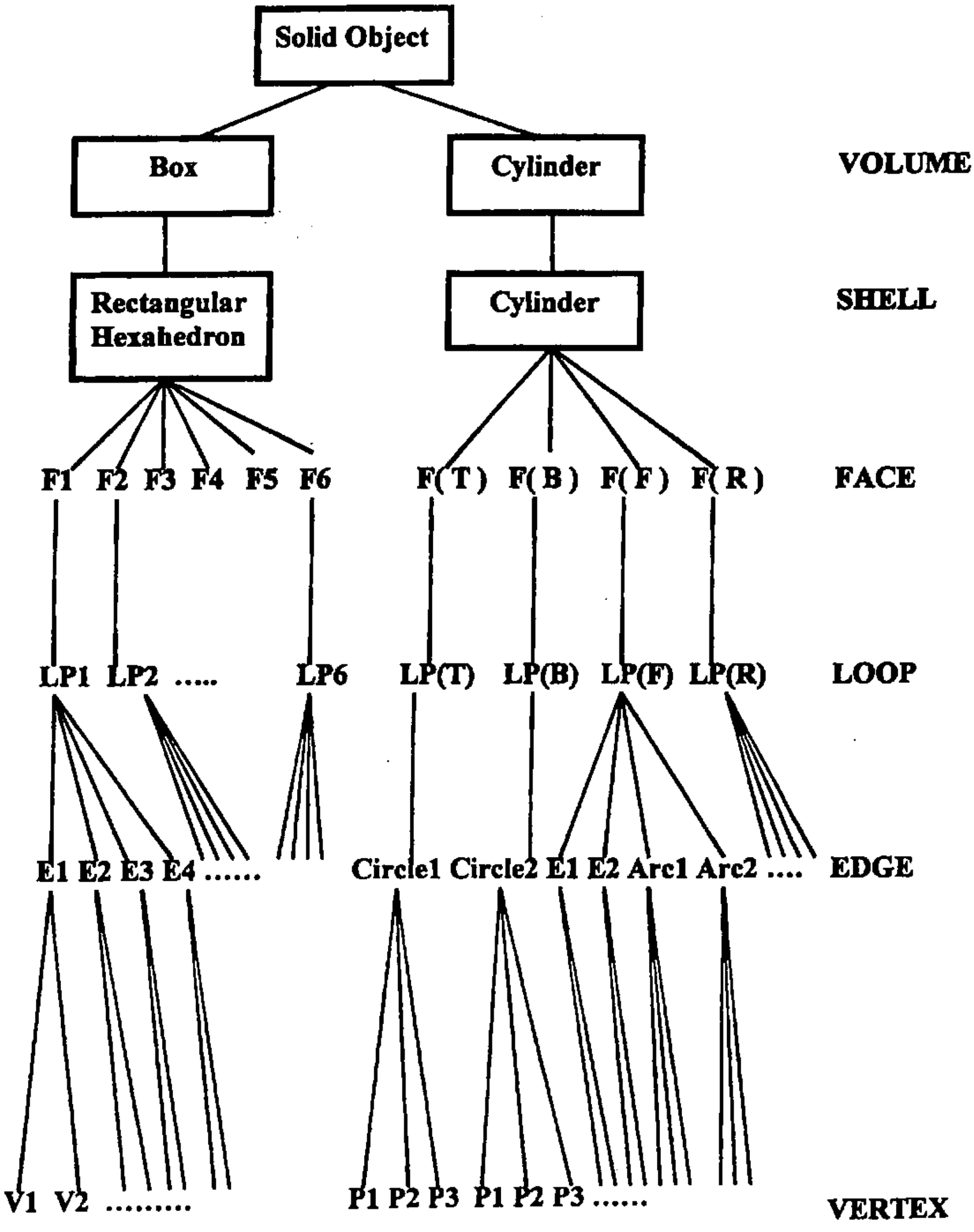


Figure 8.3 Tree structure of the combined CSG and B-Rep model

Boundary evaluation begins by generating the boundary of each CSG primitive. Selecting the boundary segments, which are the true edges of the solid generated by the method of classification and ordering of its curves and surfaces, is involved in order to construct the correct B-Rep model for the solid. These boundaries are then addressed in pairs to determine the intersections which generate the edges. These edges are then compared to those of the original CSG object to eliminate those which lie inside or outside the object. Thereafter, the remaining edges are topologically connected to form the boundary elements of a B-Rep object.

Boundary data have to be stored with neighborhood and orientation information to avoid ambiguities, and to facilitate storage and retrieval requirements. Two popular data structures are found suitable to address the B-Rep of a solid tunnel namely, the winged-edge data structure and the half-edge data structure. They are developed by Baumgart (1972) and Mantyla (1988) respectively. The adjacency relationship of a winged-edge model with hole loops is given in Figure 8.4. A winged-edge data structure similar to Fig. B.1 in (Lee, 1999) is given in Figure 8.5.

In the winged-edge data structure, an edge is adjacent exactly to two faces corresponding to two loops left and right of the edge. Each face points to its loop and the loop points to a hole loop if the face has a hole. The hole-loop points to another hole-loop if the face has multiple holes on it. The last hole-loop on the surface will be linked back to the parent loop as shown in Figure 8.4. Each loop also points to its parent face.

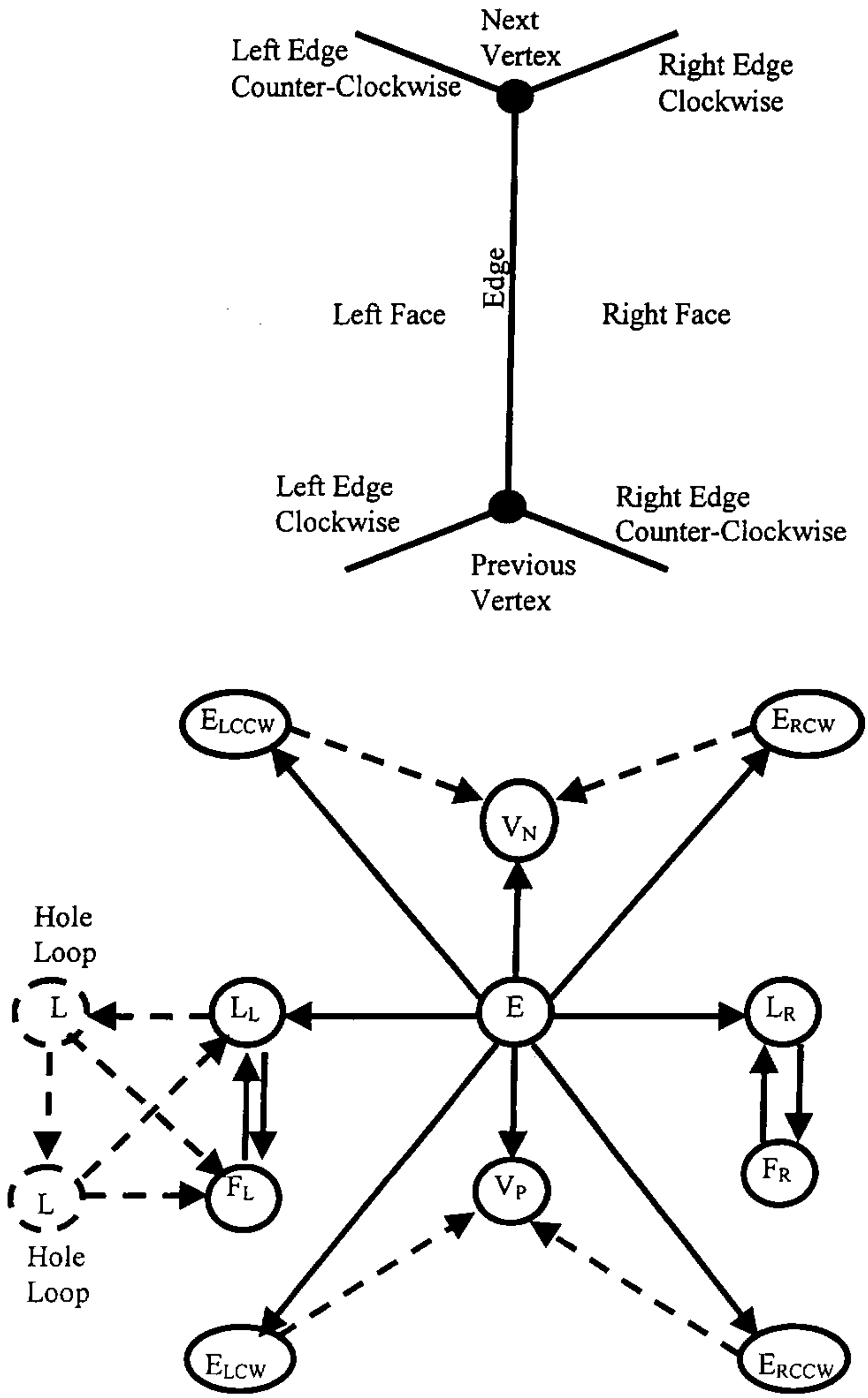


Figure 8.4 Adjacency relationship and pointers of the winged-edge data structure.

```
typedef  struct  tunnel_body      Body;
typedef  struct  tunnel_shell     Shell;
typedef  struct  tunnel_face      Face;
typedef  struct  tunnel_loop      Loop;
typedef  struct  tunnel_edge      Edge;
typedef  struct  tunnel_vertex    Vertex;
typedef  struct  tunnel_surface   Surface;
typedef  struct  tunnel_curve     Curve;
typedef  struct  tunnel_point     Point;

struct tunnel_body
{
          int    id;          /* body identifier       */
          Body   *next;       /* pointer to next body  */
          Shell  *shell;      /* pointer to shell      */
          char   *name;       /* pointer to body name */
};

struct tunnel_shell
{
          int    id;          /* shell identifier      */
          Body   *body;       /* pointer to body       */
          Shell  *next;       /* pointer to next shell */
          Face   *face;       /* pointer to face       */
};

struct tunnel_face
{
          int     id;         /* face identifier          */
          Shell   *shell;     /* pointer to shell         */
          Face    *next;      /* pointer to next face     */
          Loop    *loop;      /* pointer to loop          */
          Surface *surface;   /* pointer to geometry data */
};

struct tunnel_loop
{
          int    id;          /* loop identifier       */
          Face   *face;       /* pointer to face       */
          Loop   *next;       /* pointer to next loop  */
          Edge   *edge;       /* pointer to edge       */
          int    type;        /* loop type             */
};
```

Figure 8.5 A winged-edge data structure in C language

```
struct tunnel_edge
{
        int    id;              /* edge identifier                        */
        Loop   *left_loop;      /* pointer to left loop                   */
        Loop   *right_loop;     /* pointer to right loop                  */
        Edge   *left_arm;       /* pointer to left arm ( ccw left edge )  */
        Edge   *left_leg;       /* pointer to left leg ( cw left edge )   */
        Edge   *right_leg;      /* pointer to right leg ( ccw right edge ) */
        Edge   *right_arm;      /* pointer to right arm ( cw right edge ) */
        Vertex *tail_vertex;    /* pointer to tail vertex ( previous vertex ) */
        Vertex *head_vertex;    /* pointer to head vertex ( next vertex ) */
        Curve  *curve;          /* pointer to geometry data               */
};

struct tunnel_vertex
{
        int    id;              /* vertex identifier        */
        Edge   *edge;           /* pointer to edge          */
        Point  *point;          /* pointer to geometry data */
};
```

Figure 8.5 (continued)

According to Möbius' mathematical rule, the orientation or ordering of each surface of a B-Rep model helps identify neighborhood of edges or vertices, the presence of material (solid or cavity), and visibility of the face in the display of the solid model (Mortenson, 1997). As illustrated in Figure 8.6, an external well-formed face is defined by orienting its edges counter-clockwise with respect to the surface normal. An interior face of a cavity is defined by orienting its edges clockwise with respect to the surface normal. Or, the cavity (inside domain) of a face always resides on the left-hand side when the loop is traversed in its direction. A point on the face is visible if $\theta \leq 90^0$. Since $\cos(\theta) = (\mathbf{L} \bullet \mathbf{N}) / (|\mathbf{L}| \; |\mathbf{N}|)$, the face is visible if $\{ 0 \leq (\mathbf{L} \bullet \mathbf{N}) / (|\mathbf{L}| \; |\mathbf{N}|) \leq 1 \}$ where **N** is the outward-pointing vector and **L** is the line-of-sight vector.

If any geometric operation or a Boolean operation has been implemented inside a B-Rep model, the resulting B-Rep model must be proved to be topologically correct by the Euler operators using the following Euler-Poincare' s formula (Wilson, 1985; Mantyla, 1988; Lee, 1999):

$$V - E + F - H = 2 (S - P)$$

where V = number of vertices

E = number edges

F = number of faces or peripheral loops

H = number of hole loops

S = number of shells

P = number of passages through the holes of a solid

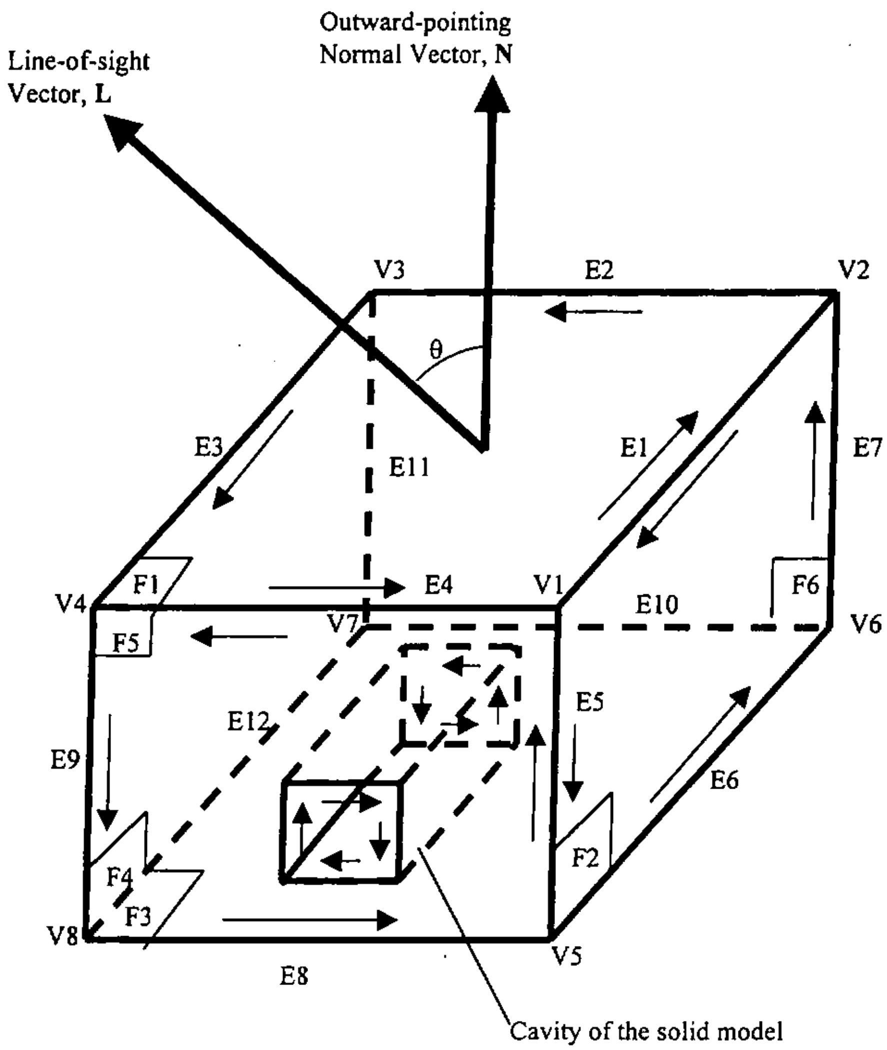


Figure 8.6 Well-formed surfaces of a B-Rep model.

To become a real solid, the Euler equation must also satisfy the following conditions:

1. V, E, F, H, S and P are all ≥ 0.
2. If V = E = F = H = 0, then P = S = 0.
3. If S > 0, then V ≥ S and F ≥ S.

These well-formed surfaces, which are closed, oriented, non-self-intersecting, bounding and connected, constitutes the tunnel model.

The half-edge data structure created by Mantyla (1988) is a face-based data structure capable of storing a list of faces for formation of a solid model. From the surface geometry, edge equations and vertex positions can be computed precisely. Hierarchical components and data structure of a half-edge model are given in Appendix II. In its data structure, each edge is designated into halves, called half-edges to facilitate the two adjacent faces sharing the original edge. Connectivity information for vertices, edges and faces are stored by the half-edges and loops, and adjacency information are derived for the connections. Each edge points to its two half-edges. Each half-edge points to its parent edge in order to maintain connectivity. The vertices, edges and faces point to the half-edges or loops, and the adjacency information for the half-edges and loops are readily available.

Based on the data structures of Baumgart (1972) and Mantyla (1988), a surface-based B-Rep data structure is under development to facilitate tunnel construction and setting-out operations. The data structure is given in Figure 8.7. It stores the topology separately from the geometric information and avoids storing any repeated topology more than once. Besides, it provides precise data of vertices, edges and well-formed surfaces for tunnel construction and setting-out operations.

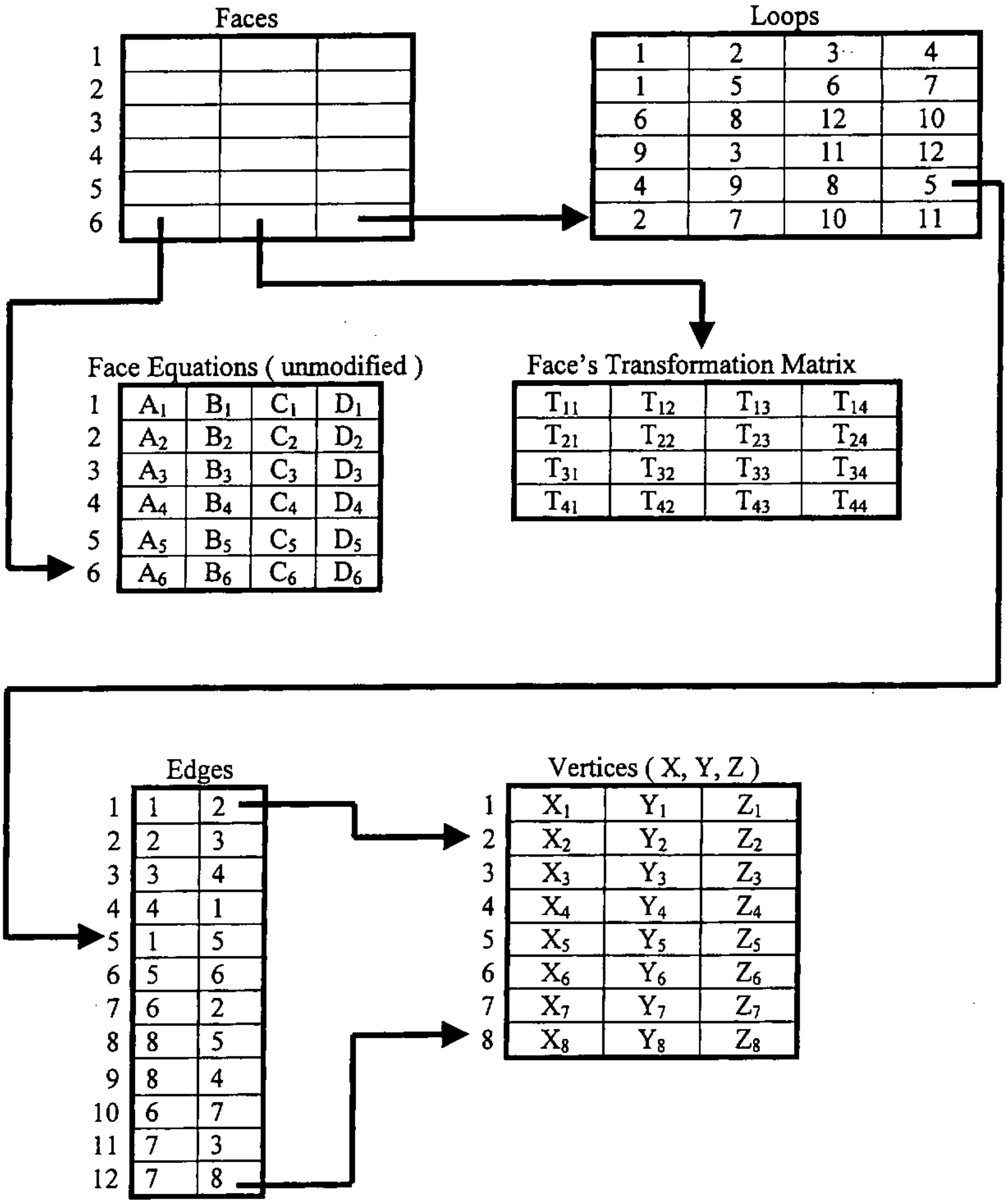


Figure 8.7 A surface-based data structure (refer Figure 8.6).

8.2 Application of Solid Modelers in Tunnel Construction

Existing solid modelers, such as AutoCAD, MicroStation, ProEngineer and Solidworks, are mainly designed for the CAD/CAM in manufacturing industries. Since combination of 2D highway curves is still being adopted in the design of highway tunnels under the codes of practice, none of the existing solid modelers is capable of being implemented for construction surveying of highway tunnels by itself. However, many tunnel engineers intend to use solid modelers in tunnel projects because of their powerful capabilities in CAD/CAPP/CAM. Therefore, in recent construction field environments, these solid modelers are under development or customized by engineers and surveyors to integrate them with 3D modeling and simulation, construction surveying, and other construction processes.

Among the solid modelers, AutoCAD has become the most popular PC-based solid modeling system in tunnel construction projects because of its open architecture and ease of customization. Setting-out information can be passed in and out of the program through attribute extraction, script files, ASCII and binary DXF files. New commands and functions can be written using interface programming languages of ARX(AutoCAD Runtime Extension in C), VBA(Visual BASIC for Application) and AutoLISP. A toolbar of the solid modeling system is shown in Figure 8.8.

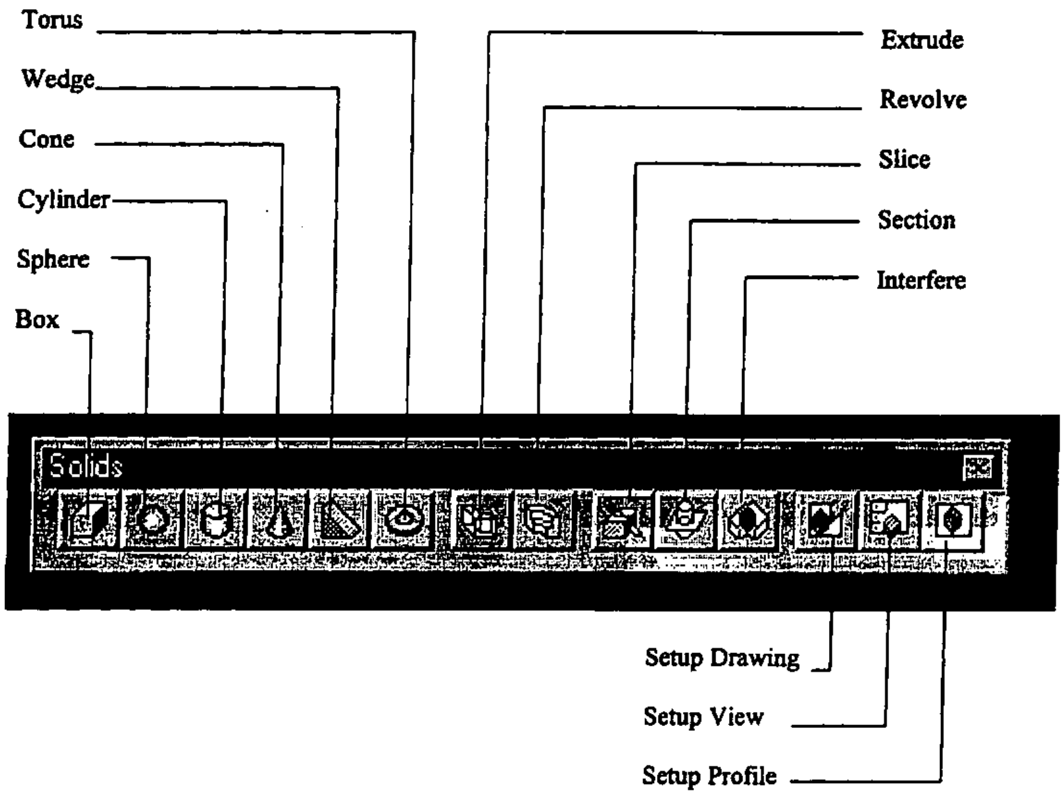


Figure 8.8 Toolbar of solid modeling functions inside AutoCAD®.

For use with AutoCAD®, TAS generates the principal alignment which is the combination of both vertical and horizontal alignments of the tunnel in DXF format. The 3D model of the principal alignment becomes the directrix along which the designed cross-sections are swept to generate the tunnel model inside the CAD system.

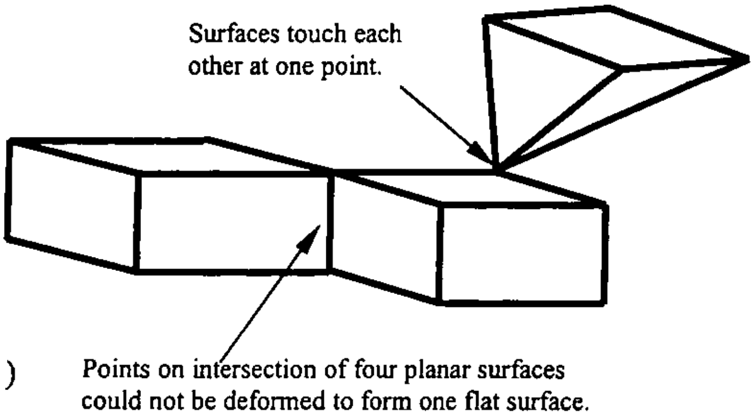
In this combined CSG and B-Rep solid modeling system of AutoCAD, six predefined solid primitives (box, wedge, cone, cylinder, sphere and torus) can be used to construct the solid model. During each entry, primitives are selected with parameters being configured to meet their desired shapes. Primitives having curved surfaces, cylinders and cones for examples, will be entered together with the number of tessellation lines or isolines designated by the user to generate a faceted B-Rep model of the primitive. The level of the approximation is controlled by the user, thereby allowing the best balance between the number of facets generated and the geometric accuracy required of the setting-out. If the number of tessellation lines is set too large, it will take significantly more time to convert the CSG into its B-Rep. Therefore, the number of tessellation lines for the B-Rep must be designated to comply with the allowable tolerances required of the construction.

These geometric modeling systems for the construction of highway tunnels only support manifold models because manifold models are manufacturable. However, in order to support a full representation scheme in which transitions between one-dimensional, two-dimensional and three-dimensional geometric entities are allowed in a design process together with a unified representation as mixtures of wireframes, surfaces and solids, non-manifold modeling systems are under development among CAD/CAM scientists.

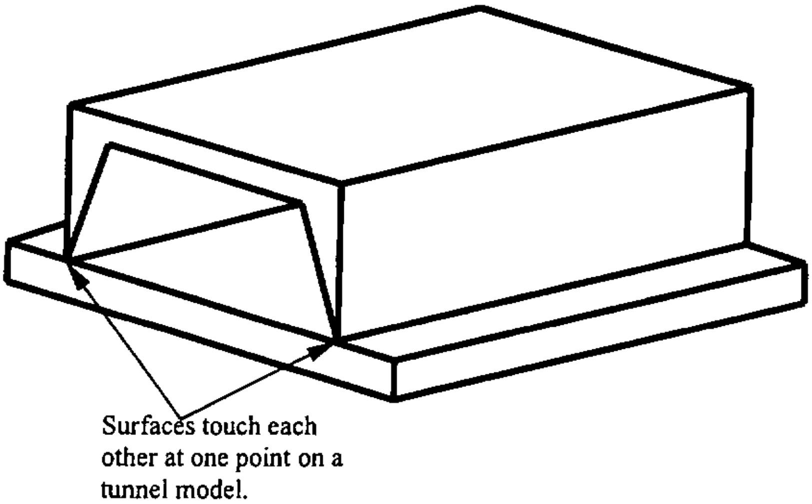
In a non-manifold model, a given point on the intersection of two or more topological planar surfaces could not be deformed to form a planar surface (Figure 8.9). This kind of model allows the modeling of finite element meshes in exactly the same form as the design models (Requicha and Rossignac, 1992).

Many of the combined CSG and B-Rep solid modeling systems have been extended beyond simple solids and encompass objects that are either dimensionally or materially inhomogeneous. For representing dimensionally and materially inhomogeneous objects such as structures built by composite materials, the half-edge model of Mantyla (1988) and the hybrid model of Kalay (1989) were applied.

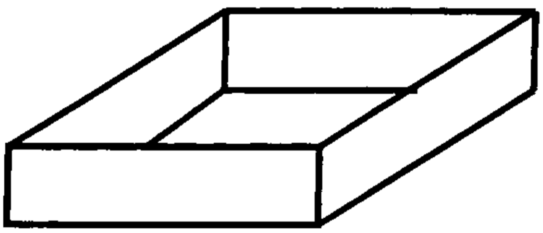
These are the major areas of CAD/CAM for tunnel researches in the development of the next generation of solid modelers. The data structure which is a modification of Baumgart (1972) by the author will pave the way for their creation. At present, we can only rely on customizing existing CAD/ CAM software for applying the combined CSG and B-Rep models in tunnel construction.



(a)



(b)



(c) An open box formed by five surfaces without considering surface thickness.

Figure 8.9 Examples of non-manifold models.

CHAPTER 9

GEOMETRIC ACCURACY AND ALLOWABLE TOLERANCES

9.1 Types of Construction Tolerances

It is impossible to construct a tunnel with exact dimensions or, without deviations from its designed shape. A number of limitations, such as geotechnical characteristics of soils and rocks, hardware accuracy, software accuracy, variation of material property, setting-out methodology and skill of construction workers during the construction processes, will cause geometrical deviations of the tunnel. Therefore, allowable tolerances are designated to each suitable dimension or for structural elements of the tunnel to facilitate the design process, construction planning and quality control. They are numerical constraints which describe the total permissible variation from design size, form or location of the structures under construction.

Geometrically, tolerance specifications are representations of variational classes of objects. They are the allowable variations in the size and shape from the nominal or desired geometry specified by the designer, and affect the buildability, cost and quality of a tunnel. When the allowable tolerances are too large, the appearance of the work piece would be impaired. If the allowable tolerances are set too small, it generally results in an increase in the costs. Therefore, tolerances should be chosen by the designer to ensure product quality standard at the lowest cost. If the size or shape of a part is not within the maximum and minimum limits as defined by the allowable tolerances, the part is not acceptable. In addition to cost consideration, tolerances are also specified to meet functional requirements of assemblies in tunnel construction. Therefore, allowable tolerances are essential information for the process planning of precast or prefabricated structures, assembly operations, and surveying and inspection of various structural elements from structural concrete, steelworks and masonry to finished components like architectural ceilings, and electrical and mechanical installations. They are important in fulfilling the desired functionality, geometric requirements and structural safety of the object under construction.

There are three main categories of tolerance namely conventional tolerances, geometric tolerances and statistical tolerances. Conventional tolerances are dimensional or coordinate tolerances presented traditionally in engineering designs and specified as plus or minus deviation from the length, angles and coordinates. Dimensional tolerances designated among dimensions of structural steel works but never applied in the dimensions of concrete structures. Linear or coordinate tolerances are usually found in the survey specifications of tunnel projects.

In the manufacturing industry, statistical tolerances specify a statistical distribution of tolerances for a dimension together with the property of distribution and values of mean or variance. The tolerance specification allows one to determine the probability that certain dimension(s) or size of the product is unacceptable. This probability will increase if the tolerances are relaxed. If the reduction in cost due to relaxed tolerances exceeds the increased cost due to unsatisfactory products, an overall saving can be achieved. Since they are only applied in the cost control and construction management of tunnel construction, it will not be further discussed in this thesis.

While conventional and statistical tolerances constrain particular dimensions, coordinates and costs of structural components in tunnel construction, geometrical tolerances constrain their geometry in specific regions of space known as tolerance zones. Geometric tolerances represent the variational conditions of shapes more accurately than conventional tolerances for proper assembly and function of parts and structural components. They are currently applied in tunnel design and construction processes among structural steel works and HVAC(Heating Ventilation and Air Conditioning) installations excluding concrete and wood structures.

In the CAD/CAM industry, the applications of geometric tolerances are standardized by the ISO 1101 Standard (or its equivalent, the ANSI Y14.5M Standard). Some of the principal elements of these standards are applicable to tunnel construction. Under the ISO 1101 Standard, geometric tolerances are classified into five categories namely form tolerance, orientation tolerance, location tolerance, runout tolerance and profile tolerance.

Form tolerance controls the straightness, flatness, circularity (roundness) and cylindricity of individual features. Orientation tolerance controls the angularity, perpendicularity and parallelism of related features. Location tolerance controls the position and concentricity of related features. Runout tolerance controls circular runout and total runout of related features. Runout is defined by a tolerance zone contained between two surfaces of revolution with respect to a specified datum axis or between two planes normal to the axis. Run-out tolerances may be circular radial, total radial, circular axial and total axial. It controls straightness, roundness and parallelism of surface features of axisymmetric parts, and is measured by rotating the form about its axis. Profile tolerance controls the profile of a line and the profile of a surface of undetermined features (individual or related features).

Associated with all five types of geometric tolerances, (ANSI Y14.5 M, 1982) classified geometrical features fall into three main types, namely individual features, related features and undetermined features. A feature is defined as a generic shape or part of a surface. Hole, slot, section face and planar face are examples of features. Individual features are single surface, edge, or size features, each of them has perfectly designed geometric form in the assessment of tolerances. Related features are single surface or element features which will be assessed with respect to a datum or datums for geometric tolerances. Undetermined features are single surface or edge features which they are not having designed geometric profiles. They may be checked with or without a datum(s) in tolerance assessment. The relationship between type of feature, type of tolerance and characteristics of geometric tolerances is summarized in Table 9.1.

Table 9.1 Types and characteristics of geometric tolerances (ANSI Y14.5 M, 1982).

Type of Feature	Type of Tolerance	Characteristic
Individual features	Form	Straightness
		Flatness
		Cylindricity
Related features	Orientation	Angularity
		Perpendicularity
		Parallelism
	Location	Position
		Concentricity
	Runout	Circular runout
		Total runout
Undetermined features	Profile	Profile of a line
		Profile of a surface

In the construction industry, tolerance information may be attached to geometric objects as attributes in CAD drawings of steel structures and machine parts of tunnels. Allowable tolerances of concrete structures are published separately in the contract documents.

Requicha (1986) treated tolerances as attributes of an object's features which are portions of the object's surface (topological boundary) in solid modelers based on CSG. VGraph (Variational Graph) is the database structures suggested for addressing features and attributes of variant information. An example of VGraph is given in Figure 9.1. In Figure 9.1, DatSys nodes represent datum systems governing the assessment of geometric tolerances with respect to the given specifications. They are the coordinate planes, axes, or three-plane coordinate systems constructed with ideal entities associated by mathematical rules with features of physical object. Each datum has an associated qualifier (Q), typically an MMC (maximum material condition) or RFS (regardless of feature size). Detailed description of datum systems is given in Section 9.3. FaceOp nodes and EdgeOp nodes are operations for faces and edges respectively. VFace nodes represent features and attributes. Each Vface points to four nodes: a solid it belongs to; a ClassOp node (node of membership classification operation that may be "in", "on", or "out"); an NFAce node (node of nominal face or half space of the primitive); and an attribute list.

More advanced feature-based tolerance representation schemes, based on combined CSG and B-Rep geometric modeling systems for the CAD/ CAM industry, are found in Roy and Fang (1996) and Roy et al.(1997).

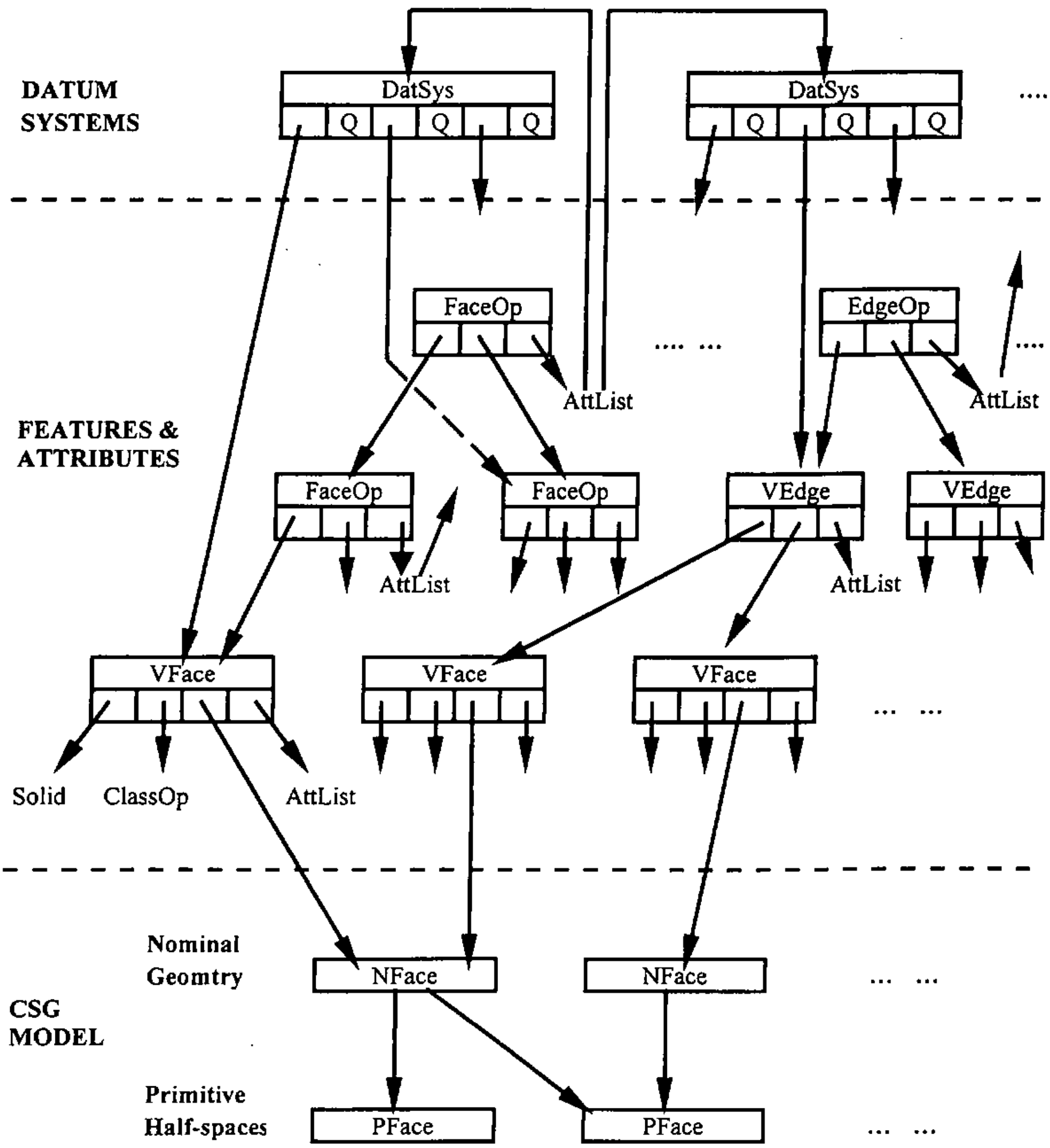


Figure 9.1 VGraph for representation of features, tolerances and other attributes in solid modelers (Requicha, 1986).

9.2 Determination of Allowable Tolerances for Tunnel Construction

Geometric dimensioning and tolerancing defined in ISO or ANSI standards for the CAD/CAM industry are not based on any explicit mathematical principles but codification of best practices based on working experience of practical people with artisan backgrounds (Voelcker, 1997).

Allowable tolerances, associated with survey instrumentation and measurements for tunnel construction, have existed over a long period of time. Current standards and allowable tolerances for control surveys, setting-out, as-built surveying and deformation monitoring in tunnel construction are given in Chapter 2. Some of them are considered standard practice based on the years of field experience on what is practical and readily achievable. Many are based on civil engineering and building construction standards that have been published and reflect what the construction industry agrees is reasonable as a balance among structural design safety, ease of construction, quality of materials and surface finishes, and cost. Others may be derived by optimization methods through applications of least squares models and operations research. During construction, these allowable tolerances will be further evaluated in the field by the attainable accuracy of construction machines, survey methodology and survey instrumentation.

In order to determine the geometric tolerance zones in as-built surveying of tunnels, current practice and formulation from the results of CAD/CAM research which are applicable to tunnel construction will be considered.

In computer-aided solid modeling, tolerance zones can be constructed by the parametric method of variational geometry (Requicha, 1986; Zeid, 1991). Variational geometry is a method of representing a solid model by a set of interrelated equations defining its shape and dimensions. In conventional geometric modelers, the designer creates the exact geometry and derives the dimensions from it. Any change of dimension requires editing of the geometric model. By applying variational geometry, the designer creates a set of dimensions, and the topology of parts (parameters) from which the exact geometry is derived. Thus, any change of dimension will result in automatic generation of the required geometric model. Specified tolerances are then applied to the dimensions or parameters of the geometric model being formed. The parametric tolerance zone will be defined between the largest and the smallest acceptable limits, called the maximum material condition (MMC) and the least material condition (LMC) respectively, to allow for the design of clearance fitting in manufacturing processes (Figure 9.2). The MMC is defined as the condition of the allowable tolerance under which the maximum amount of material is contained by the object. The LMC is defined as the condition of the allowable tolerance under which the least amount of material is contained by the object.

Light and Gossard (1982) and Lin et al. (1981) applied tolerances or variations to the coordinates of each vertex of the boundary model to generate a variational geometry (VG) model in computer-aided geometric design. The vertex coordinates are model variables which determine the faces and edges.

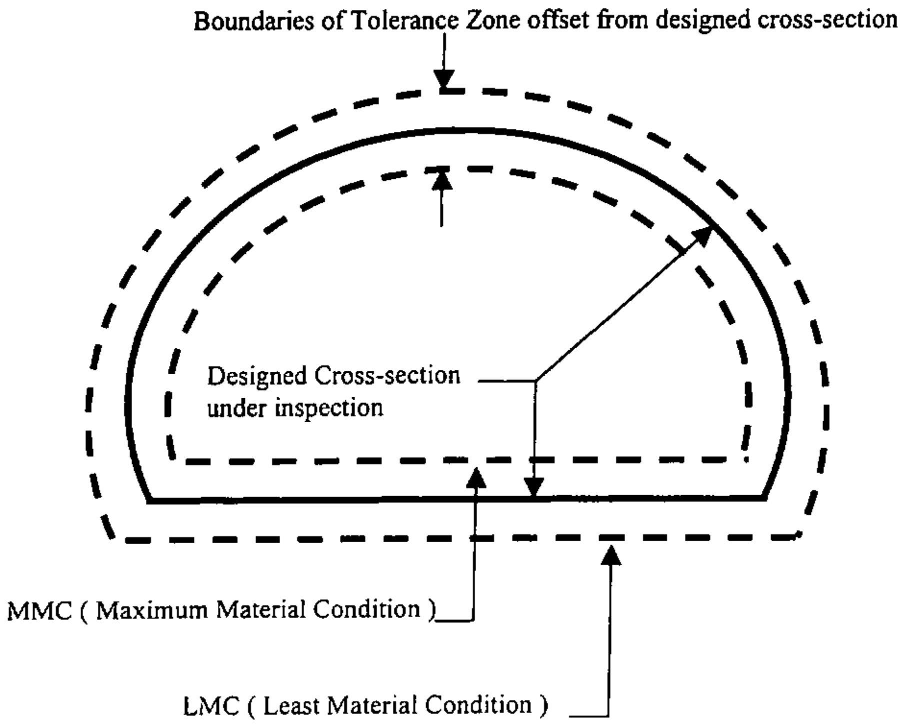


Figure 9.2 Tolerance zone of a tunnel cross-section under inspection.

Another method to generate allowable tolerance zones is the non-parametric method of offsetting. While the parametric methods depend on the nominal geometry of features and their parametric representation, non-parametric methods depend only on the features themselves. In offsetting operations, the boundary of the nominal part is offset by the amount of specified tolerance to generate the outer limits and the inner limits of the tolerance zones of the feature in the three-dimensional space. Thus, each offsetting zone corresponds to a tolerance zone. As mentioned in the previous chapters, the tolerances of existing tunnels are checked by slicing cross-sections within the surveyed area. Tolerance zones are allocated by offsetting the allowable tolerance from the theoretical cross-sections or profiles under inspection (Figure 9.1). The boundaries of a tolerance zone are the upper limit (LMC) and the lower limit (MMC) of variations. If the surveyed point is found within the boundary of the tolerance zones, the finished surface under inspection is acceptable in position known as in-tolerance. Other offsetting operations and their associated algorithms being applied in manufacturing processes which may be useful for tunnel construction are given by Requicha (1983), Rossignac and Requicha (1986), and Rossignac (1985).

Both the parametric and non-parametric methods of finding tolerance zones are useful for setting-out and as-built surveys in tunnel construction. They are also useful for tolerance analysis, clearance testing, modeling of coating processes, cutter paths of computerized machine tools, collision-free path analysis of robotic motions, and blending of geometric models.

9.3 Assessment of Tolerances in Tunnel Construction

During the course of construction, discrete points at changes of geometry on the object surfaces are surveyed for two main purposes: (1) to determine if the tunnel object meets the designed tolerance specifications, and (2) to provide information for improvement in the process control. These points are always surveyed with respect to one coordinate reference datum, for instance, the Hong Kong 1980 Grid Coordinate System, or the dimensions given in construction drawings. The operational model of such inspection is shown schematically in Figure 9.3. During inspection, the surveyed coordinates are checked against the allowable tolerances. If the surveyed tolerance exceeds the allowable tolerance or offset envelopes of a tunnel structure, remedial work is required together with preventive measures. This is the traditional practice of checking tolerances of finished structures.

In modern practice, geometric tolerances should also be surveyed with respect to local datum systems. These datum systems are references for measuring local features. They help define the orientation and/ or location of the tolerance zone. The establishment of these datum systems is important in the assessment of geometric tolerances because they are used as the basis of establishing the geometric relationship between related features of a tunnel structure. These datum systems include reference coordinate planes, axes or three-plane coordinate systems.

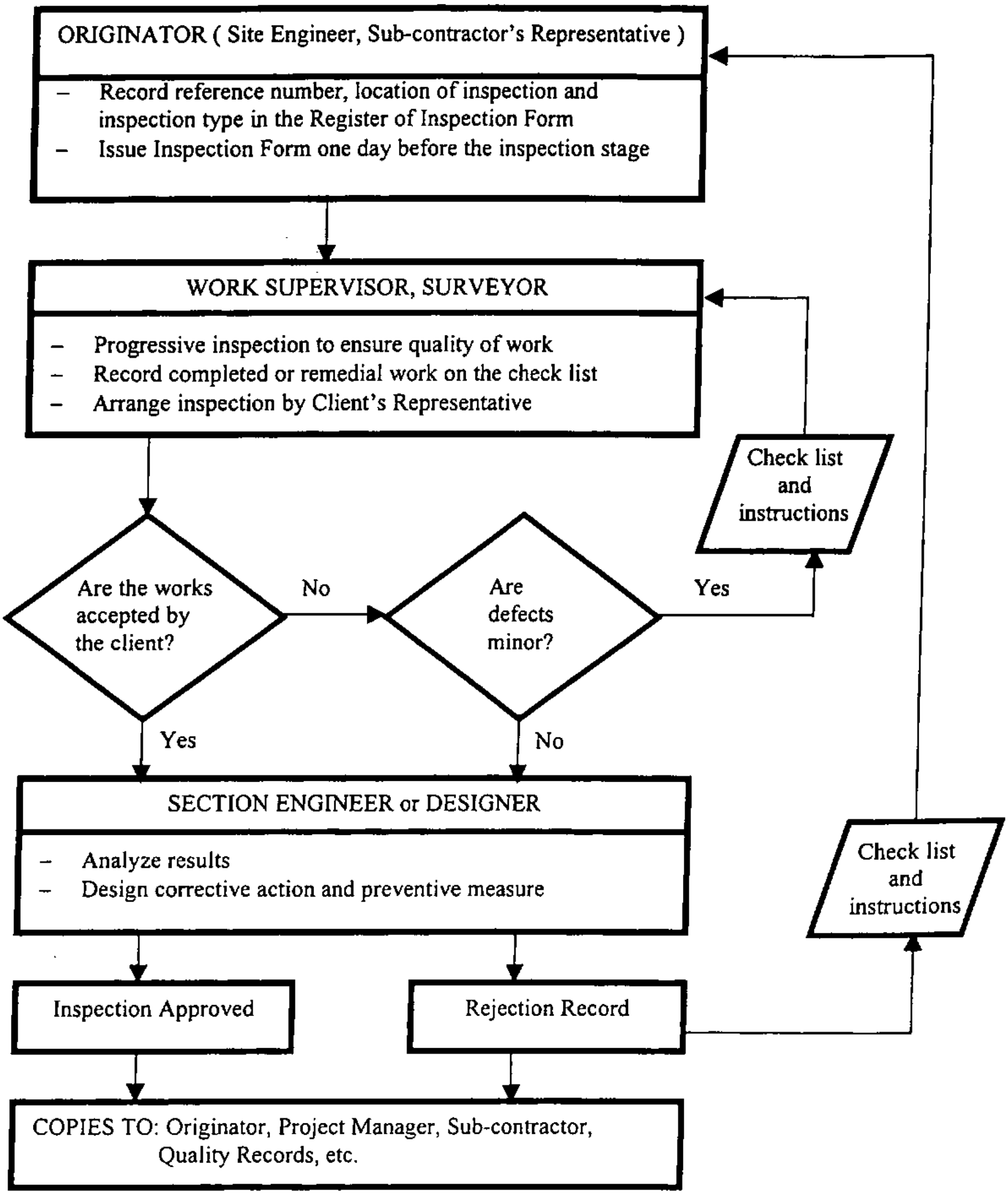


Figure 9.3 Flow chart for site inspection of works in construction projects (Lam and Tang, 2000).

If two or more datum systems are involved in the measurement of the same object, they will be designated into primary, secondary and tertiary datum systems and applied according to the orders of priority. An example of such an establishment for tunnel construction is given in Figure 9.4. The establishment of the datums follows the criteria published by Zhang and Roy (1993) and Henzold (1995) for the manufacturing industry but they are also applicable in tunnel construction.

In addition to planar surfaces, abstract geometric entities, such as the median plane of a pair of planar surfaces, an axis of a cylinder, etc., may also be used as tertiary datums for tolerance assessment of various tunnel structures. Examples of such tertiary datums are given in Figure 9.5 and Figure 9.6. In Figure 9.5, two nominally parallel surfaces are designed to determine the form deviation of an as-built surface with respect to a tertiary datum (a substitute element or a median plane), and in accordance with ISO 10360 Standard.

In Figure 9.6, straightness tolerance of a column axis is defined as a cylindrical zone. The as-built axis is surveyed by taking three points on each horizontal cross-section at regular intervals along the whole length of the column. The as-built axis of the column is then computed by the least squares model so that the effect of eccentricity from its designed position can be determined by the engineer. Another way to determine straightness tolerance of an axis is to project the surveyed axis in projected planes or between parallel planes in two-dimensional space. But the author believes that 2D tolerance data are less applicable than the 3D cylindrical ones in structural stress analysis.

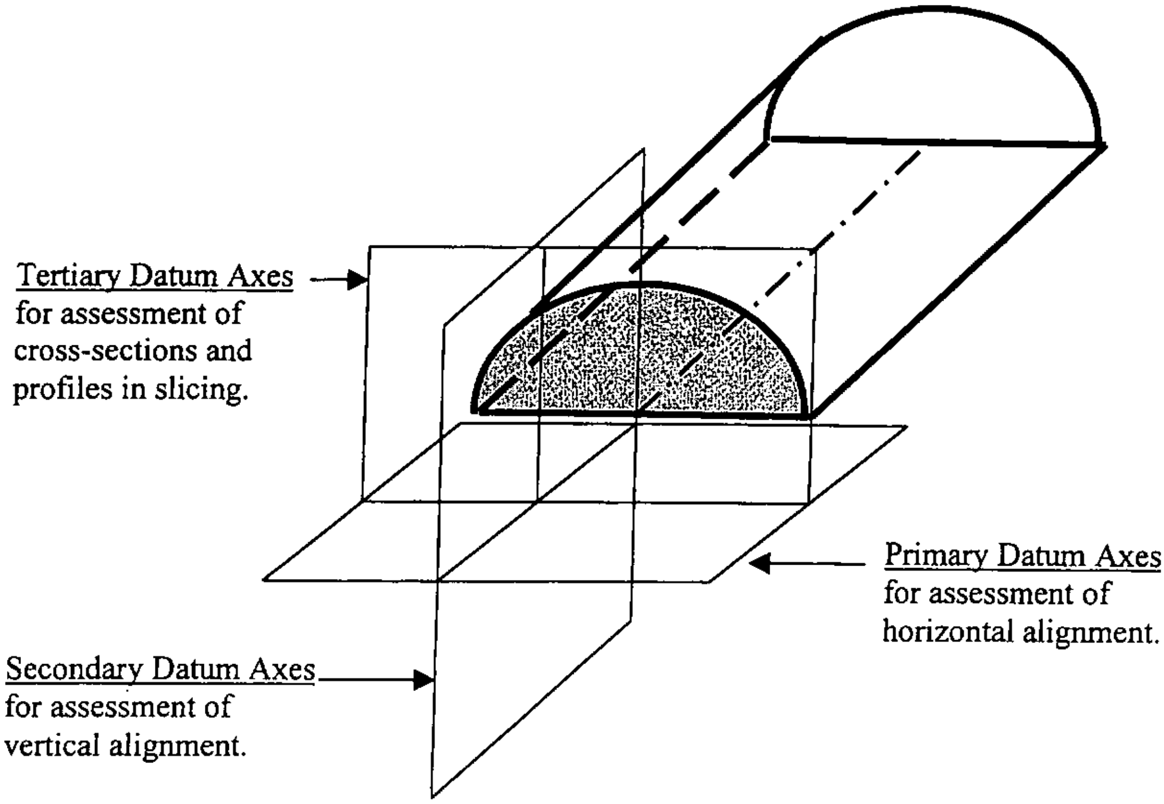


Figure 9.4 Establishment of primary, secondary and tertiary datum axes for assessment of geometric tolerances of tunnels

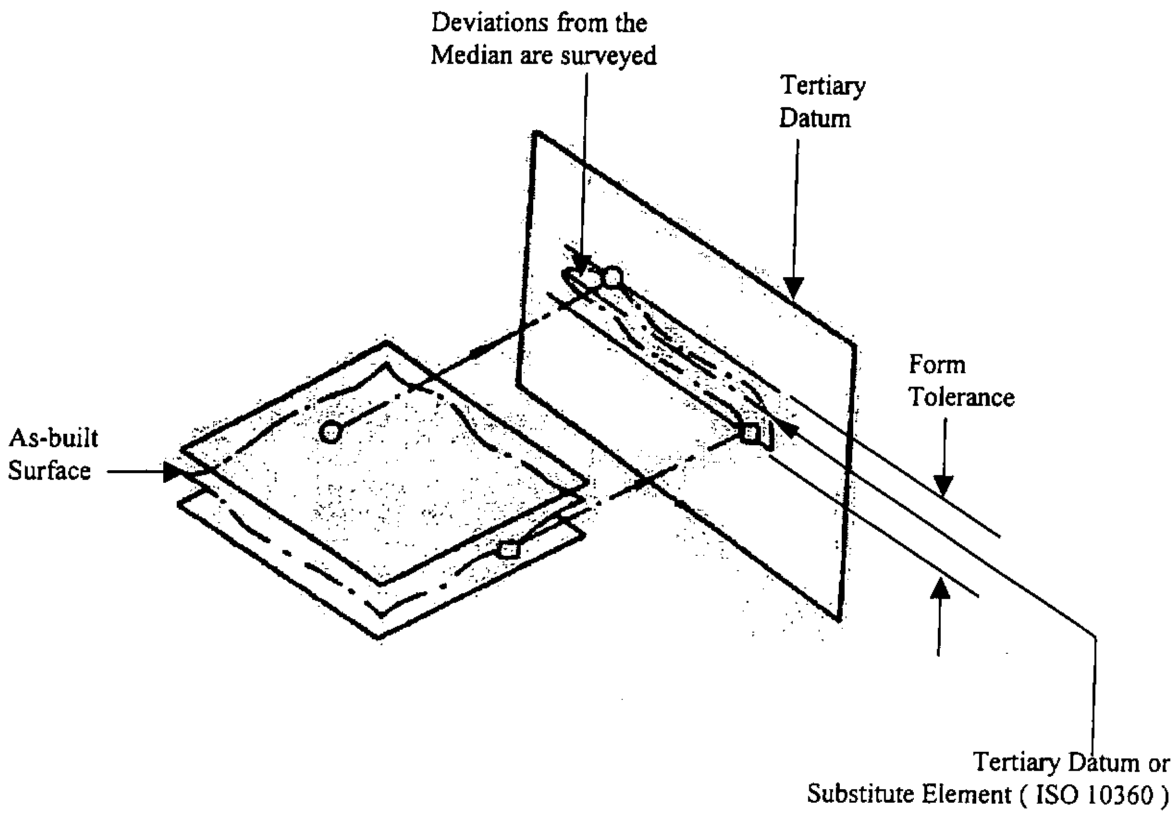


Figure 9.5 Establishment of tertiary datums for assessment of form tolerance of an as-built surface.

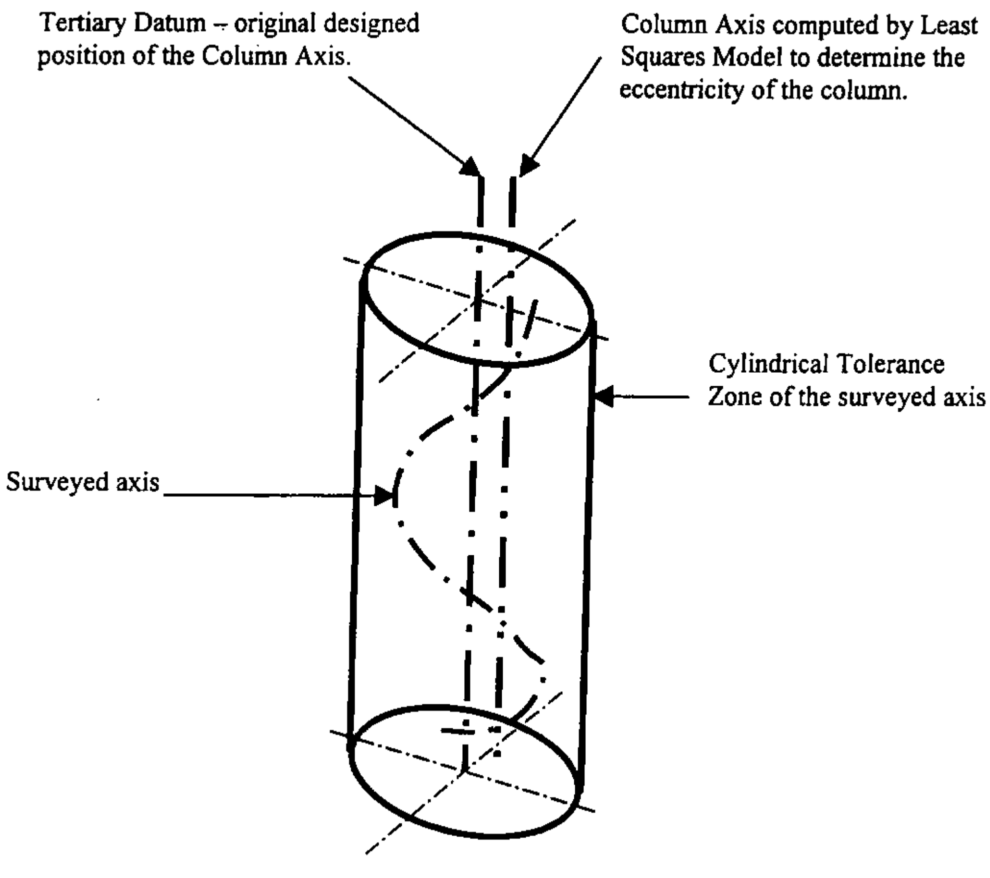


Figure 9.6 Assessment of straightness tolerance of a column axis.

Mathematical rules for establishing datum systems and constructing tolerance zones depend on the types of tolerances (dimensional or geometrical) and the types of feature representation method, but are independent of the specific geometry of the features (Requicha, 1986). The type of feature geometry is important for determining the number of sampling points required of tolerance assessment. According to the recommendations of BS 7172, the minimum number of sampling points to assess a geometric feature in a coordinate system is given in Table 9.2.

Table 9.2 Minimum number of sampling points to assess tolerance of geometric features (BS 7172; Henzold, 1995, Table 18.12).

Geometric Feature	Number of Points		Remarks
	Unique Solution	Recommended	
Straight Line	2	5	
Plane	3	9	Distributed on three lines.
Circle	3	7	For assessment of three-lobed forms.
Sphere	4	9	Distributed on three parallel sections.
Cylinder	5	12	For assessment of straightness distributed on four radial sections.
		15	For assessment of roundness distributed on three radial sections.
Cone	6	12	For assessment of straightness distributed on four radial sections.
		15	For assessment of roundness distributed on three radial sections.

In general practice, the minimum number of sampling points should be equal to the number of definition points. For example, a circle requires three inspection points to check its radius or diameter. For curved features, points should be surveyed at changes of geometry and the spacing of points should be closer for regions of small radii of curvature than for regions of larger radii of curvature. There is also a recommendation that at least 8n points should be surveyed on the geometric feature, where n is the mathematical minimum number of points (Henzold, 1995).

As described in Chapter 4, the use of slicing planes perpendicular to the principal tunnel alignment is the general procedure for as-built surveying and tolerance evaluation of the finished structures. These slicing planes yield a set of cross-sections when intersecting with substitute (or designed) geometric models of the tunnel. During slicing, coordinate points on a set of slicing planes are surveyed by total stations. At each surveyed point, the geometric error of the tunnel is computed. This geometric error is expressed as an orthogonal deviation distance or the shortest distance from the measurement point to the ideal cross-section. Inspection procedures are implemented so that a statistical probability or confidence level of 95% should be achieved.

By experience, the efficiency of this slicing method using total stations depends very much on (1) the selection of measurement locations, (2) the density of points to be surveyed, and (3) the technique for evaluating the orthogonal deviation distance. The slicing strategy is not only intuitive but also cost-effective, and it is easier to program the precise geometric models of tunnels for use with microcomputer systems. These advantages have been illustrated by the TAS computer system in the previous chapters.

CHAPTER 10

CONCLUSIONS AND FUTURE DEVELOPMENTS

From both a conceptual and practical viewpoint, this thesis has focussed on the geometrical and topological aspects of precise digital models for construction surveying of highway tunnels. Three significant contributions of this thesis are the surveying techniques and standards, the description of various geometric modeling systems, and the various methods to formulate and assess tolerances in construction surveying of highway tunnels.

In the first contribution, the thesis has summarized the accuracy standards and codes of practice which govern the accuracy of 3D geodetic control networks, detail surveying, setting-out operations, as-built surveys and deformation monitoring in the design and construction of highway tunnels. The allowable tolerances and codes of practice given in these standards become the key factors or guidelines in the selection of the geometric modeling systems and the determination of precision required of such systems.

In the second contribution, the thesis has uniquely presented the precise geometric modeling systems together with their practical algorithms, data structures and precise digital models which are applied by the author in construction surveying of highway tunnels. These geometric modeling systems comprise Sweep models, Skinning models, computational geometry for irregular surfaces and tunnel intersections, Mesh models, and the combined CSG and B-Rep models. The Sweep models are currently adopted by tunnel surveying systems in construction projects. The other models are not yet adopted and their conceptual models are presented in the thesis by the author. All the geometric modeling systems given in this thesis comply with geometric design standards of both highway and tunnel alignments, and are adaptive to design processes from two-dimensional projection planes to three-dimensional geometry. Advantages and limitations of applying them in construction surveying are summarized in Table 10.1.

In the third contribution, the thesis has proposed the application of geometric tolerances together with their formulation and methods of assessment for the first time in the construction of tunnels. Currently, geometric tolerances are being applied in the design and construction of steel works. In order to minimize the costs of production, CAD/CAM researchers try to optimize the allocation of allowable tolerances of dimensions by tolerance analysis and synthesis of the functional relationships between model variables, tolerance variables and design variables. These optimization concepts should be migrated into tunnel construction, civil engineering and building construction for the betterment or advancement of the construction industry.

Table 10.1 Advantages and limitations of the tunnel geometric modeling systems.

Geometric Modeling Systems	Advantages	Limitations
1. Sweep	– The parametric model represents accurately constant cross-sections along tunnel alignments. – Its analytical framework assists subsequent skinning, TIN, mesh generation, CSG representation or B-Rep. – A small data set is needed to specify the shape from 2D cross-sections.	– It is unable to represent tunnel intersection and solid model alone. – It is unable to represent variable cross-sections along tunnel alignments.
2. Skinning	- Its linear faceted representation is easy to implement in solid modeling and construction. - It is adaptive to tunnel surveying techniques and construction machines.	– The faceted model must pass flatness criterion with respect to allowable tolerances to become valid. – It is unable to model tunnel intersection alone.
3. TIN	- It is most suitable for modeling irregular surfaces in drill and blast construction processes. – It facilitates the design of tunnel surfaces and intersections generated by 3D points on designed cross-sections.	– Large computer memory and high-speed computer systems are needed. - The facetted design surface must pass flatness criterion to become valid.
4. Mesh	– It has the solid volume capability for setting-out and analyzing the structural and mechanical properties of tunnel objects.	– Large computer memory and high-speed computer systems are needed to achieve the desired mesh density distribution and well-shaped elements.
5. CSG + B-Rep	– Simple CSG primitives are used to form complex solids. – Precise geometry is stored in B-Rep providing setting-out data effectively.	– Vast amount of tessellation lines is needed for an accurate B-Rep in order to comply with allowable tolerances. Thus, large computer memory and high-speed computer systems are needed.

Nearly all tunnel surveying software which are now available in the software market are still based on planar cross-sectional designs for setting-out and construction processes. Solid modeling has been found, from this research project, as the technological solution to automating and integrating design and construction functions for tunnel construction projects. This has been proved successful by CAD/CAM researchers in the manufacturing industry but hampered by the requirement of expensive computer systems and computer software in production. Further research is now needed to develop a solid modeling system or a combined modeling system so that it could be applied efficiently and cost-effectively with personal computers in construction surveying of highway tunnels. More advanced data structures are under investigation to suit various geometric models, construction methods and robotic machines.

In this thesis, new knowledge or new understanding of geometric modeling systems for tunnel surveying has been reported. Continual research is recommended to investigate the computational algorithms and precise digital models so that new automated systems and construction methods could be created to facilitate CAD, FEA, CAPP, CAM and construction surveying of different kinds of tunnels (e.g. railway and utility tunnels) and their associated structures. If readers have any valuable comments on all aspects of computer systems as applied in tunnel construction, it is hoped that they would be brought to the attention of the author.

APPENDIX I

CSG TREE STRUCTURE FOR SOLID MODELING

A CSG tree structure in the C language is given in the following Figure I.1:

```
struct operator
{
        int   op_type;        /* union, intersection or difference operator   */
              L_type;         /* left node type: 0 = operator, 1 = primitive  */
              R_type;         /* right node type: 0 = operator ,1= primitive  */
       void   L_ptr;          /* left node                                    */
              R_ptr;          /* right node                                   */
              P_ptr;          /* parent node                                  */
};

struct primitive
}
        int   Prim_type;             /* type of primitive                     */
     double   Pos_x, pos_y, pos_z;   /* position of instance                  */
     double   ori_x, ori_y, ori_z;   /* orientation of instance               */
       void   Attribute;             / * value of dimensions of the attribute */
}
```

Figure I.1 A CSG tree structure in C language (Lee, 1999, Fig. 5.24).

APPENDIX II

THE HALF-EDGE DATA STRUCTURE FOR SOLID MODELING

Figure II.1 and Figure II.2 illustrate, respectively, the hierarchical components and data structure of the half-edge model used by Mantyla (1988) in solid modeling.

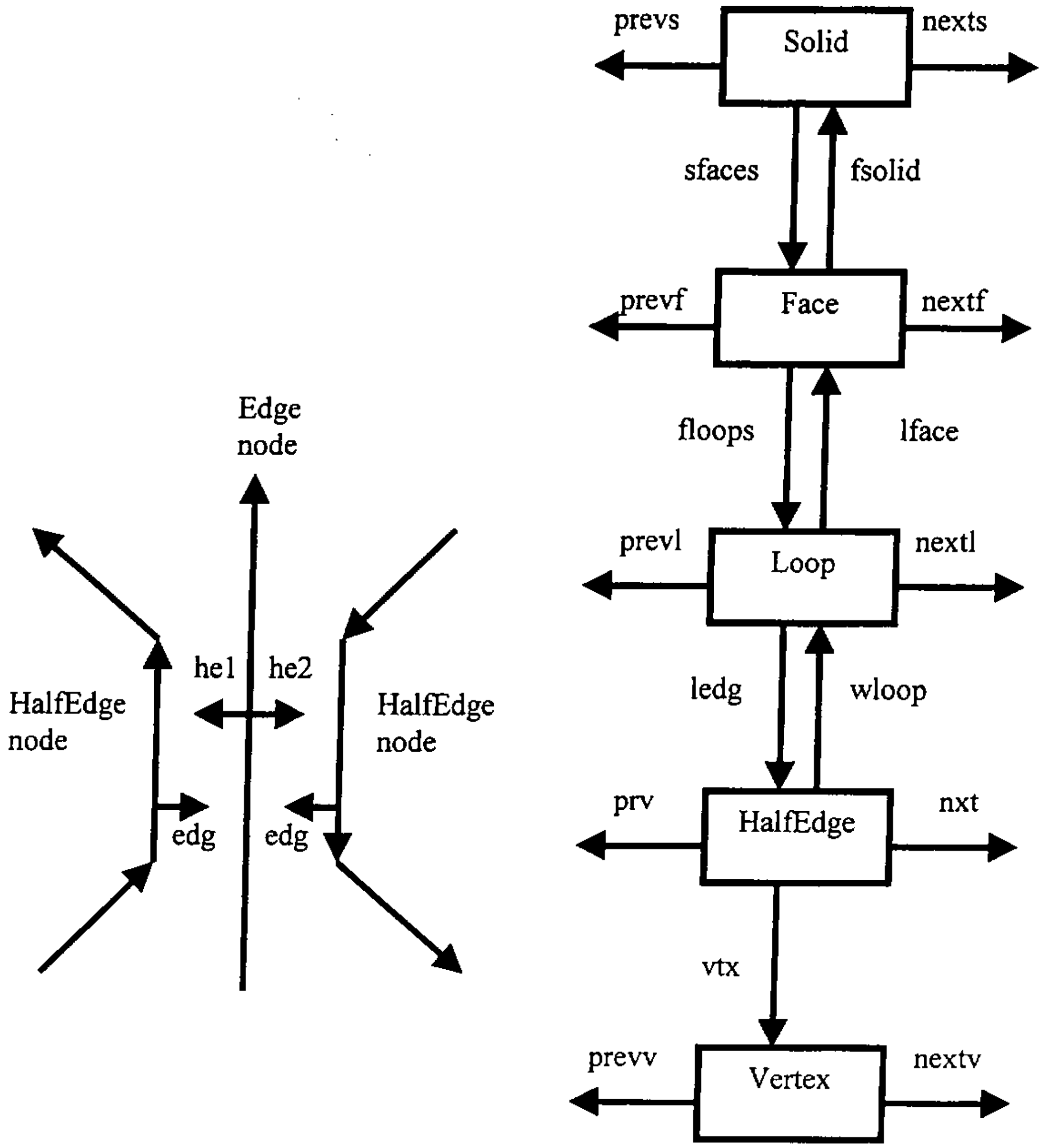


Figure II.1 Hierarchical components of the half-edge data structure (Mantyla, 1988, Figures 10.2 and 10.3).

```
typedef   float                       vector [4];
typedef   float                       matrix [4] [4];
typedef   short                       Id;
typedef   struct   tunnel_solid       Solid;
typedef   struct   tunnel_face        Face;
typedef   struct   tunnel_loop        Loop;
typedef   struct   tunnel_edge        Edge;
typedef   struct   tunnel_halfedge    HalfEdge;
typedef   struct   tunnel_vertex      Vertex;
typedef   union    nodes              Node;

Struct tunnel_solid
{
        Id      solidno;      /*solid identifier             */
        Face    *sfaces;      /* pointer to list of faces    */
        Edge    *sedges;      /* pointer to list of edges    */
        Vertex  *sverts;      /* pointer to list of vertices */
        Solid   *nexts;       /* pointer to next solid       */
        Solid   *prevs;       /* pointer to previous solid   */
};

Struct tunnel_face
{
        Id      faceno;       /* face identifier             */
        Solid   *fsolid;      /* back pointer to solid       */
        Loop    *flout;       /* pointer to outer loop       */
        Loop    *floops;      /* pointer to list of loops    */
        vector  feq;          /* face equation               */
        Face    *nextf;       /* pointer to next face        */
        Face    *prevf;       /* pointer to previous face    */
};

struct tunnel_loop
{
        HalfEdge  *ledge;     /* pointer to ring of halfedge */
        Face      *lface;     /* back pointer to face        */
        Loop      *nextl;     /* pointer to next loop        */
        Loop      *prevl;     /* pointer to previous loop    */
};
```

Figure II.2 A half-edge data structure in C language (Mantyla, 1988, Program 10.1.).

```
struct tunnel_edge
{
        HalfEdge   *he1;        /* pointer to right halfedge */
        HalfEdge   *he2;        /* pointer to left halfedge  */
            Edge   *nexte;      /* pointer to next edge      */
            Edge   *preve;      /* pointer to previous edge  */
};

struct tunnel_halfedge
{
            Edge   *edg;        /* pointer to parent edge       */
          Vertex   *vtx;        /* pointer to starting vertex   */
            Loop   *wloop;      /* back pointer to loop         */
        HalfEdge   *nexthe;     /* pointer to next halfedge     */
        HalfEdge   *prevhe;     /* pointer to previous halfedge */
};

struct tunnel_vertex
{
              Id   vertexno;    /* vertex identifier         */
        HalfEdge   *vedge;      /* pointer to halfedge       */
          vector   vcoord;      /* vertex coordinates        */
          Vertex   *nextv;      /* pointer to next vertex    */
          Vertex   *prevv;      /* pointer to previous vertex */
};

Union nodes
{
           Solid   s;
            Face   f;
            Loop   l;
        HalfEdge   h;
          Vertex   v;
            Edge   e;
}
```

Figure II.2 (continued)

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