# GTP-based Integral Real-3D Spatial Model for Engineering Excavation GIS ($E^2$GIS)*

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**Abstract:** Engineering excavation GIS ($E^2$GIS) is a real-3D GIS serving for geosciences related to geo-engineering, civil engineering and mining engineering based on generalized tri-prism (GTP) model. As two instances of GTP model, G-GTP is used for the real-3D modeling of subsurface geological bodies, and E-GTP is used for the real-3D modeling of subsurface engineering excavations. Based on the discussions on the features and functions of $E^2$GIS, the modeling principles of G-GTP and E-GTP are introduced. The two models couple together seamlessly to form an integral model for subsurface spatial objects including both geological bodies and excavations. An object-oriented integral real-3D data model and integral spatial topological relations are discussed.

**Keywords:** real-3D spatial modeling, geosciences, engineering, GTP model, $E^2$GIS

## 1 Introduction

There are lots of researches on 3D GIS and 3D GMS (geosciences modeling system) recently (Dollner and Hinrichs, 2000; Wu et al., 2003a, Shi et al., 2003), such as researches on topological relations in 3D GIS. However, most of the 3D modeling methods in 3D GIS mainly deals with location information and elevation information of surface objects, few even none deals with subsurface objects. The 3DCM (3D city model) is a typical example of it. Although, in geology and engineering, researches on 3D GMS for subsurface geological objects have achieved a lot (Breunig et al., 1999; Wu et al., 2003a ). There are more than twenty 3D (includes pseudo-3D) models presented for GIS and GMS in geosciences during the past decade. The models presented include serial sections (Tipper, 1977), TIN (triangular irregular network) (Barry, 1991; Sapidis and Renato, 1991; Tsai and Alan, 1993), NURBS (Fisher and Wales, 1991), TEN (Tsai, 1993; Morackot et al., 1994), block (Simon, 1994), hybird (Shi, 1996, 2000; Li et al., 1997;), octree (Chen and Huang, 1998), 3D Voronoi (Gabriel et al., 2001), tri-prism (Zhang and Bai, 2001; Dai and Zou, 2001; Cheng and Gong, 2001; Gong et al., 2002), ATP (Wu et al., 2002; Qi et al., 2002) and so on (Jean-Laurent, 1997; Guo et al., 1999; Wang, 1999; Zhao, 1999; Bian et al., 2000; Sun and Chen, 2000), as in table 1. These models are classified as facial models, volumetric models and mixed models (Wu et al., 2003a).

With the fast development of information technology in geo-engineering, civil engineering and modern mining industry, an integral modeling of the subsurface geological bodies, subsurface engineering excavations and surface buildings is of great importance (Wu et al., 2002, 2003b, 2003c). Meanwhile, the spatial topology description on subsurface objects as well as on the spatial relations between subsurface engineering and surface spatial objects is meaningful. This paper aims to introduce the concept of engineering excavation GIS ($E^2$GIS), and to present an integral real-3D spatial model for subsurface objects, both geology and engineering.

**Table 1 Classification of 3D models for geosciences modeling (Wu et al., 2003a)**

| Facial Model | Volumetric model | | Mixed model |
|---|---|---|---|
| | Regular volume | Irregular volume | |
| Irregular Triangular Network (TIN) | CSG-tree | Tetrahedral Network (TEN) | TIN-CSG mixed |
| Grid | Voxel | Pyramid | TIN-Octree mixed or Hybrid |
| Boundary Representation (B-Rep) | Octree | Tri-Prism (TP) | Wire framework-Block mixed |
| Non-Uniform Rational B-splines (NURBS) | Needle | Geocellular | Octree-TEN mixed |
| Wire framework or Linked slices | Regular block | Irregular block | |
| Serial sections | | Solid | |
| Sections-TIN mixed | | 3D Voronoi volume | |
| Multi-DEMs | | ATP, GTP | |

# 2. What's $E^2$GIS

## 2.1 Definition of $E^2$GIS

Engineering excavation GIS ($E^2$GIS) is a real-3D GIS serving for geosciences related to geo-engineering, civil engineering and mining engineering. The geosciences mentioned here refers to the broad range of geology, geophysics, geochemistry, geo-engineering, subsurface engineering (such as tunnel, subway and mine etc.), geography and surface construction. Its modeling objects include subsurface geological bodies, subsurface engineering excavations and some surface buildings. Data base, geomathematics, computational geometry, topology and geo-information science are its scientific and technical foundations.

## 2.2 Features of $E^2$GIS

For the specialties of its application domains, an $E^2$GIS will possess the following basic features: 1) the spatial objects, surface and subsurface, are described and modeled in real-3D as an integrity; 2) the topological relations between the spatial objects, surface and subsurface, are described and stored in spatial data base; 3) the real-3D model is scale-related so as to support the LOD (level of details) model for visualization, spatial inquiry and analysis; 4) the engineering excavations can be synchronously and seamlessly manipulated inside the subsurface geological bodies; 5) it supports not only the virtual reality for subsurface engineering alone, but also the virtual reality for subsurface geological bodies, subsurface engineering excavations and surface buildings as a whole; 6) it provides the mechanism for numerical FEM (finite element method) analysis on the influence of engineering excavations to its geological surroundings and related surface environment.

## 2.3 Functions of $E^2$GIS

In consideration of the basic features of $E^2$GIS and its application demands, an $E^2$GIS should have basic functions as: 1) real-3D spatial data organization: a powerful spatial data base should be designed to manage the complicated dynamic spatial data about subsurface geology bodies, engineering excavations and surface buildings, which has different source, precisions, scale, format and temporal label; 2) integral real-3D modeling and visualization: a integral real-3D modeling mechanism should be provided to model and to visualize the subsurface geological bodies, engineering excavations and surface buildings as a whole; 3) interactive visualized inquiry and geo-statistical analysis: a interactive 3D visualization interface should be provided to facilitate the location-based, range-based, attribute-based and object-based inquiries as well as geo-statistical analysis, such as ore grade analysis, mineral storage statistics etc.; 4) powerful support for engineering: a digital environment and a group of powerful modular should be provide to support the engineering design, engineering modification, safety evaluation, influence analysis and economical analysis.

## 3 Integral real-3D spatial model

### 3.1 G-GTP model for subsurface geological bodies

As drill holes for its data source, and considering the divergent of drill holes as well as the complexity of geological structure, a GTP (generalized tri-prism) model (Wu et al., 2003a；Wu et al., 2003c；Wu 2003d), modified and developed from ATP (analogous tri-prism) model (Wu et al., 2002; Qi et al., 2002), was presented for 3D GMS. Especially, the GTP for modeling geological bodies is called as G-GTP model, being a special case of GTP model, in this paper.

A component of GTP model, as shown in figure 1, is comprised of six geometrical primitives: node (P1), TIN-edge (P2), side-edge (P3), TIN-face (P4), side-face (P5) and GTP (P6), and three diagonals (P7) as intermediary elements for spatial operation. There are three upper nodes, three lower nodes, three upper TIN-edges, three lower TIN-edges, three side-edges, one upper TIN-face, one lower TIN-face, three side-faces and three diagonals in a single general GTP component.

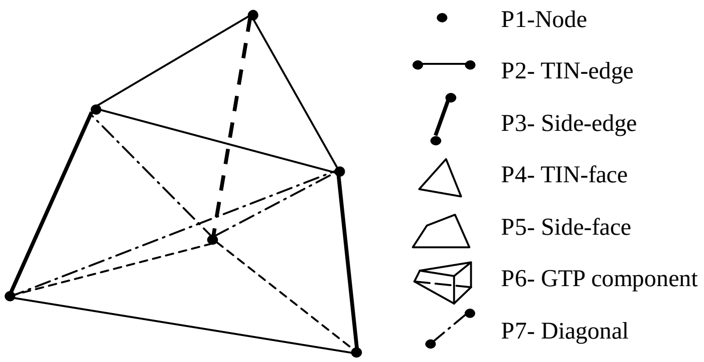



**Fig. 1 The geometrical primitives of G-GTP model based on divergent drill holes (Wu et al., 2003d)**

The side-face will not always be a plane for the deviation of drill holes, i.e. the four nodes of each side-face would not always be in a plane. Three diagonals, as shown in figure 1, which split up each side-face into two triangles and cut a GTP component into three tetrahedrons are introduced to deal with the non-coplanar side-face, so as to assistant the spatial operation and spatial analysis including volume calculation, spatial chipping, inclusion inquiry, geo-statistics and so on (Wang et al., 2003). For the minimizing of data redundancy, the diagonals will not be stored in databases but automatically generated during the process of spatial operations and spatial analysis. Obviously, the GTP model will get TP model in condition that the drill holes are vertical, so the TP model could be looked as a special case of GTP model.

Generally, the GTP model has the following features: 1) based directly on sampling data and without data interpolation to model the basic pattern of strata interfaces in the form of TIN, the reliability and the quality of the 3D geosciences model so constructed could be maximatily ensured; 2) opening modeling technique that the initial GTP model can be locally modified, updated and extended without influence to the entire structure; 3) 2.5D GMS be its subset: Since the upper and lower interface of a group of G-GTP components of a stratum are represented in TIN structure, which is the basic modeling technique of 2D GMS, so the 2.5D GMS based on TIN is a subset of 3D GMS based on G-GTP model; 4) Pyramid and TEN are the degradation of GTP: As shown in figure 2, a GTP component is to degrade to a pyramid if a side-edge shrink to a node, or degrade to a tetrahedron if a TIN-face shrink to a node. The pyramid and tetrahedron will actually occur and will be powerful in the location of strata bifurcation, thinning-out and some fault region. Hence, the GTP model is the common 3D model of tetrahedron model, pyramid model and TP model.

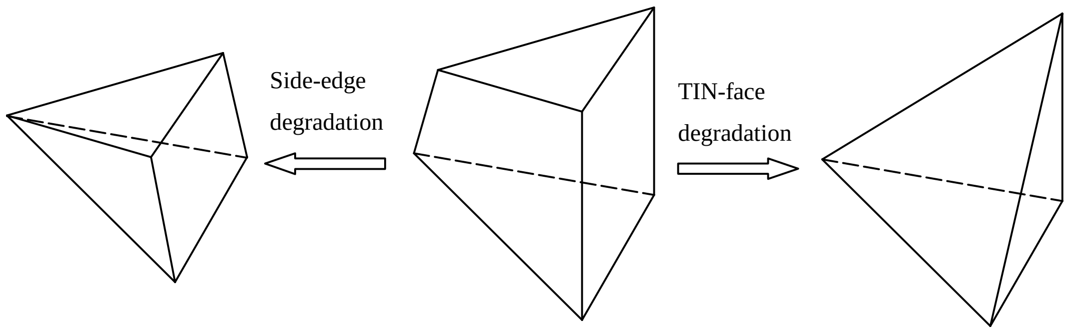



**Fig. 2 The degradation of a GTP component to pyramid and tetrahedron (Wu et al., 2003a)**

### 3.2 E-GTP model for subsurface engineering excavations

Subsurface excavations are special spatial objects of defined shape, size, direction and location inside subsurface geological surroundings. Usually, a subsurface excavation is of special attributes such as functions and support pattern, which are correlated to the features of surrounding geological bodies. Hence, the modeling of subsurface excavations should: 1) be able to visualize the location and shape of a excavation integrated with its surroundings in real-3D at high precision; 2) be able to conduct virtual wander through the surroundings along the excavations to watch exactly the actual geological conditions around the excavations, which demands that the modeled excavation body cut seamlessly the surrounding geological body in real-3D; 3) be able to conduct engineering calculations and analysis such as excavation volume and support consume, which demand that the modeled excavation body is real-3D and with attributes embodied; 4) be able to support topological inquiry and analysis such as what is 10m under the excavation and how far is the excavating head away from the aqueous body, which demands that the excavation body and the surrounding geological bodies are topologically coupled together.

Based on the concept of GTP, an E-GTP model is suggested here to meet the demands of real-3D modeling for subsurface excavations. The E-GTP model is another special case of GTP model for modeling subsurface engineering excavations. E-GTP model takes also node, TIN-edge, side-edge, TIN-face, side-face, GTP component and diagonal as its seven primitives. The difference between E-GTP and G-GTP lies in: 1) different data source: E-GTP take engineering survey and design information as its data source; 2) different data precision: the data for E-GTP is of higher precision than G-GTP, usually cm-grade location precision is demanded for E-GTP; 3) different spatial scale: usually, the scale of excavation body is much small than that of surrounding geological bodies; 4) different spatial distribution: the side-edges of a G-GTP component must be along the drill holes and must not be parallel to stratum surface, while the side-edges of an E-GTP component can be at any direction.

Figure 3 shows the principle for E-GTP modeling a portion of circle-shaped tunnel. Since the section of an excavation body will be different shaped, for example it may be circle, circle-arch, rectangle, trapezoidal etc., a controlling line along the main direction of it should be defined for the convenience of triangulation of each section and of conversion from surveyed data to the controlling line. The controlling line is the common side-edge of those E-GTP components of a portion of excavation body. As shown in figure 4a, the node of controlling line is defined at the center point of the upper circle; in figure 4b, the node of controlling line is defined at the intersection point of the two diagonals; and in figure 4c, the node of controlling line is defined at the intersection point of the half-height line and the bisector of upper and lower edges. The advantage of this schema lies in that the obtained controlling line could replace the long-shaped excavation in LOD model at small scale for visualization.

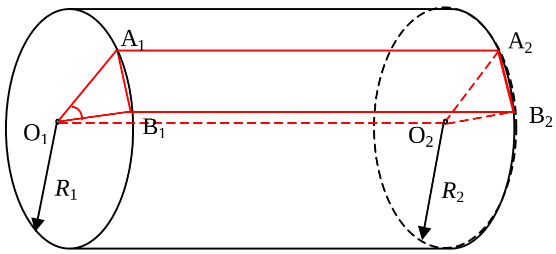
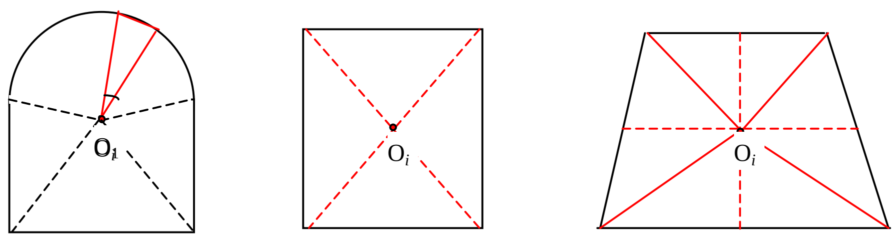



**Fig.3 The E-GTP modeling for a portion of circle-shaped tunnel**




(a) circle arch section (b) rectanle section (c) trapezoidal section

**Fig.4 The triangulation for different shaped section of excavations**

In many situations, the section shape of an excavation will change along its chief direction. For example, a circle section may change in to a circle-arch section gradually, a circle-arch section may also change into a trapezoidal gradually. The key to model the complex-shaped excavation is to model each section of changed shape reasonably and reliably. Three rules are to be obeyed: 1) the controlling points of two adjacent sections should be connected together; 2) the important shape-points (such as $A_1$, $B_1$, $C_1$, $E_1$, $G_1$ and $A_2$, $B_2$, $D_2$, $F_2$ in figure 5) and auxiliary shape-points (such as $D_1$, $F_1$ and $C_2$, $E_2$, $G_2$ in figure 5) of two adjacent sections should be connected one to one; 3) the number of shape-points of two adjacent sections depends upon the more complex section (a circle section is more complex than a rectangle section). Figure 5 shows the triangulation schema for a portion of irregular tunnel with semi-circle arch section and trapezoidal section at both ends.

### 3.3 The coupling of G-GTP and E-GTP model

Hence, the subsurface surroundings and engineering excavations can be integrally modeled respectively based on G-GTP and E-GTP components. The seamless coupling (or spatial matching) of G-GTP and E-GTP is the key issue. Local subdivision of G-GTP and/or E-GTP components around the boundary of engineering excavations is a potential solution, and the balance of node number and the fusion of edge and face will be the focus. In brief, an object oriented integral data model for 3D GMS based on GTP is shown in figure 6.

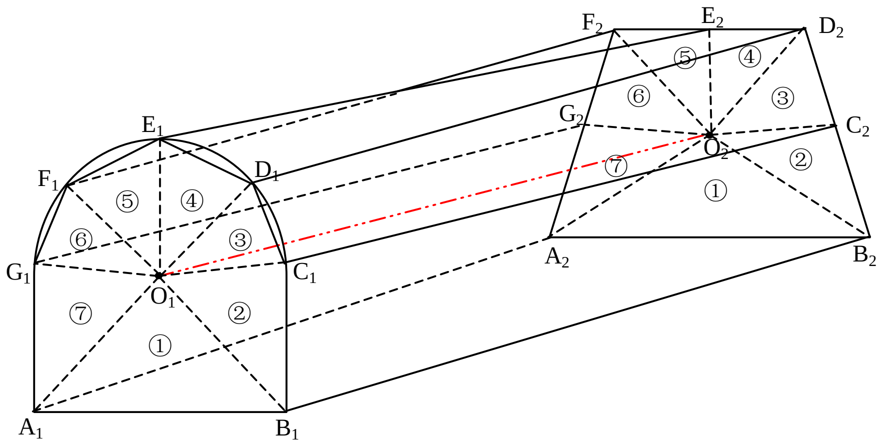



**Fig.5 E-GTP division schema for a portion of shape-changed tunnel**

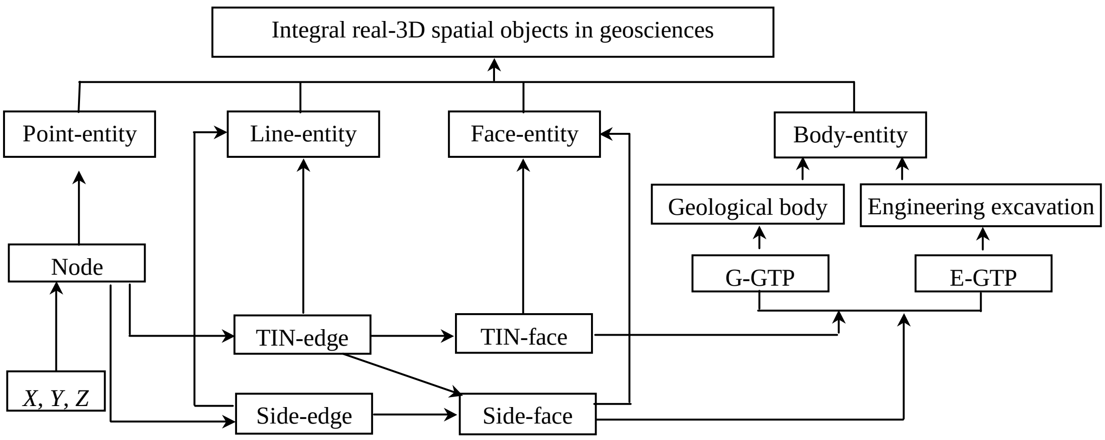



**Fig.6 The object-oriented integral real-3D spatial data model for $E^2$GIS**

## 4. Integral topological descriptions

There are massive achievements related to the researches on topological relations of spatial objects, and 3D topology has being a hot spot. For example, La Losa and Bernard (1999) suggested that the volumetric topological relations of 3D simple geometric primitives could be described based on 9-intersection model of Robert and Max (1992); Li (1997) studied the 3D topological relation and its dynamic construction for geological unit based on vector data structure; Breunig et al. (1999) pointed out that the complex geological body could be unified represented in 3D Euclidean space, which means the possibility to develop a 3D model for geological modeling with 3D topological relations embodied. Hou et al. (2003) had also suggested an object-oriented 3D topological model based on component for geology modeling. Nevertheless, no report shows that the above discussions have been programming realized in a practical 3D GMS.

Based on object-oriented technology, the data structure of the six basic primitives, node, TIN-edge, side-edge, TIN-face, side-face and GTP component, of GTP models are designed. The difference between the sampling node of G-GTP and E-GTP, and the difference between the attribute of G-GTP and E-GTP component are identified respectively in the data structure of node and GTP (Chen and Wu, 2003). Except for the six tables for topological description (Wu, 2003d), some basic topological relations between the six geometrical primitives are embodied in the data structures (Chen and Wu, 2003). Based on the topological relations distinctly or implicitly defined, the spatial relations between the geological objects and the engineering excavations could be integral described or deduced. For example, the adjacency relations, the disjoint relations and the inclusion relations, which all are meaningful for geo-engineering, could be definitely deduced from the integral real-3D data model based on attribute matching and topological checking for GTP components.

## 5. Conclusions

The GTP is a powerful spatial data model for real-3D modeling in geosciences. The G-GTP model and E-GTP model are respectively fit for the complexity and characteristics of geological bodies and engineering excavations, and the seamlessly coupling of them is the key. A software system, GeoMo$^{3D}$, has been developed based on G-GTP model and been applied for modeling the geological surrounding of coal mine and city (Wu, 2003d). The further work is the programming realization of E-GTP model in GeoMo$^{3D}$ system, and the topological handling of spatial objects, both geology and engineering. Besides, the interactive visualized manipulating for the integral model is challenging.

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