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Modeling and visualizing borehole information on virtual globes using KML

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ABSTRACT

Advances in virtual globes and Keyhole Markup Language (KML) are providing the Earth scientists with the universal platforms to manage, visualize, integrate and disseminate geospatial information. In order to use KML to represent and disseminate subsurface geological information on virtual globes, we present an automatic method for modeling and visualizing a large volume of borehole information. Based on a standard form of borehole database, the method first creates a variety of borehole models with different levels of detail (LODs), including point placemarks representing drilling locations, scatter dots representing contacts and tube models representing strata. Subsequently, the level-of-detail based (LOD-based) multi-scale representation is constructed to enhance the efficiency of visualizing large numbers of boreholes. Finally, the modeling result can be loaded into a virtual globe application for 3D visualization. An implementation program, termed Borehole2KML, is developed to automatically convert borehole data into KML documents. A case study of using Borehole2KML to create borehole models in Shanghai shows that the modeling method is applicable to visualize, integrate and disseminate borehole information on the Internet. The method we have developed has potential use in societal service of geological information.

1. Introduction

For engineering geological studies in urban areas, geological drilling is a common but important way to acquire subsurface information. Borehole data not only provide useful information around drilling locations, but also can be used to build 3D solid models of geological objects (Lemon and Jones, 2003). Over the past 2 decades, the management and visualization of borehole information has been one of the important research fields in engineering geology, geotechnical engineering and GIS (Chang and Park, 2004; Turner, 2006). The related research involves two essential aspects: the management of borehole data, as well as the modeling and visualization of borehole information. In the realm of the management of borehole data, the past research has focused on the design of data standards, coding systems and GIS-based management systems for boreholes. For example, Chang and Park (2004) implemented a typical standard form of borehole data in a Web-based GIS system for the management of borehole data. Several GIS-based borehole management and processing systems, such as Geotouch (Lees, 2000) and BoreIS (McCarthy and Graniero, 2006), were developed as tools to aid in the storage, manipulation and querying of borehole data. In the realm of the modeling and visualization of borehole information, the past research has focused on the drawing of borehole histograms and 3D models from different types of borehole logs. Several sophisticated boring logging or geological modeling software toolkits, such as WellCAD (Advanced Logic Technology, 2013), WinLoG (GAEA Technologies Ltd., 2013), RockWorks (RockWare Inc, 2013), MVS/EVS (C Tech Development Corporation, 2013) and 3D Borehole tools in ArcScene (DeMeritt, 2012), have been developed to visualize borehole information.

After careful studies, we have detected some serious shortcomings when using the existing systems to manage and visualize boreholes. A critical problem is that the existing systems rely heavily on GIS platforms. In current GIS systems, boreholes can be displayed as a set of 2D points representing drilling locations, lines on a 2D diagram (borehole histograms), as well as 3D "forest" of vertical cylinders or tubes (DeMeritt, 2012). However, these representations have limitations to a greater or lesser extent. For example, 2D points cannot reflect vertical distributions of strata. If detailed information about boreholes is required, corresponding data sets, borehole histograms or 3D models need to be extracted from the GIS database according to the drilling locations. Digitized histograms of boreholes, which generally emphasize the

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drawing of vertical information, fall short of the ability to represent geographic locations of boreholes. Therefore, it is hard to manage, publish and share huge amounts of borehole information only using borehole histograms. Commercial modeling toolkits can be used to create 3D borehole models, but their application domain is confined to the PC (personal computer) environment. Therefore, they are inappropriate in cases where network or mobile computing environment is needed. In addition, due to the absence of the suitable mechanism for free sharing, current geological modeling software toolkits cannot offer existing or built-in functions to freely transmit, render and share 3D models over the Internet.

As a typical kind of geospatial information, borehole data present an obvious characteristic of spatiality. Each borehole is contained in the Earth space and occupies proper coordinates in 3D space. Therefore, it is a natural and direct requirement to manage, visualize and distribute borehole information within a unified geospatial framework. The emergence of virtual globes opens up further possibilities to keep up with such scientific demand. In recent 10 years, several sophisticated virtual globes, such as Google Earth, NASA's World Wind and other free geo-browsers, have been developed. Virtual globes possess the ability to enhance science by providing reliable platforms for exploring, sharing and exchanging geospatial information in scientific research (De Paor, 2008; De Paor and Whitmeyer, 2011; De Paor et al., 2012; Simpson et al., 2012). Nowadays, virtual globes are important tools used by scientists to conduct research, exchange ideas and share knowledge with a global perspective in a natural and intuitive way. Recently, several geologists have launched a series of exploratory researches on how best to model and visualize subsurface geological information on virtual globes. For example, De Paor and Whitmeyer (2011) have used Keyhole Markup Language (KML), COLLADA and Javascript to model geophysical data on virtual globes. To support rapid and intuitive visualization of structural geology on virtual globes, Blenkinsop (2012) presented a macro-enabled Excel workbook that converts structural data into KML documents. In addition, a number of research teams have invested considerable effort in modeling and visualizing borehole information, and several methods to display 2D drilling locations and associated borehole logs on virtual globes were proposed and applied (Cummings, 2009; IODP, 2012; NOAA's National Climatic Data Center, 2013). However, up to now there are still no perfect methods for the modeling and visualization of huge amounts of 3D boreholes on virtual globes. Therefore, it is an essential task to develop suitable methods for the efficient management, visualization and dissemination of borehole information on virtual globes. In this paper, we discuss the modeling techniques and associated implementation methods for a large volume of borehole information, and our overarching goal contains modeling boreholes on virtual globes, as well as visualizing and distributing borehole models over the Internet.

2. Classification and standardization of borehole information

Borehole information derived from different types of sources has different formats with complex data structures. In order to develop a general modeling methodology for boreholes on virtual globes, borehole information should be classified and standardized before being digitized. Based on adequate exemplifications (Chang and Park, 2004; Turner, 2006; Zhu et al., 2012), borehole information can be classified into three types: general information about boreholes, stratum information of boreholes, or property information of strata, depending on their characteristics and purposes. General information about boreholes contains borehole description (name, code and type), drilling location (longitude, latitude and elevation), drilling depth, groundwater level and other detailed drilling information. Stratum information of boreholes includes name, sequence number, depth, formation age, genesis and description of each stratum detected by boreholes. Property information of strata contains various types of property features like physical, chemical, engineering and hydrogeological properties distributed within the stratigraphic units. General information about boreholes and stratum information of boreholes are critical for defining spatial locations and geometrical shapes of boreholes, while the property information of the strata can be regarded as some attribute items associated with corresponding strata. For the sake of simplicity, we ignore the property information of the strata in the process of modeling boreholes on virtual globes.

To meet the special concern on the general information about boreholes and the stratum information of boreholes, we design a general standard form of borehole database for structuring and archiving borehole information. This standard form includes four datasheets: borehole type, general information about boreholes, stratum information of boreholes, and details of overall strata (Tables 1–4).

- Borehole type. Boreholes can be classified into different types, depending on their purpose and drilling methods. Each type of borehole has a string name and is assigned a code to distinguish it from others.
- General information about boreholes. The general information about individual borehole, such as the code, name, type, ground water level, date, driller, hole diameter, drilling location and drilling depth, is included in this datasheet. BoreholeCode, the key field of this datasheet, enables boreholes to be combined with corresponding stratum information.
- Stratum information of boreholes. A borehole usually detects more than one stratum. The sequence number, code, depth and detailed description for all detected strata are stored in this datasheet. There are two key fields in this datasheet: one is “BoreholeCode” and the other is “LayerNo”. BoreholeCode enables strata to be associated with corresponding borehole information, while LayerNo enables strata to be combined with details of overall strata.

Table 1
Borehole type.

Field	Details	Data type	Key field
BoreholeType	Code of borehole type	short	√
BoreholeTypeName	String name of borehole type	string	

Table 2
General information about boreholes.

Field	Details	Data type	Key field
BoreholeCode	Serial number to manage boreholes	long	√
BoreholeName	String name of borehole	string	
BoreholeType	Code referred to corresponding borehole type	short	
GroundwaterLevel	Depth to the groundwater level	float	
DrillingStartDate	Start date of the drilling	date	
DrillingEndDate	End date of the drilling	date	
Driller	Driller, engineer and/or inspector	string	
HoleDiameter	Diameter of borehole	float	
Elevation	Elevation of drilling location	float	
DrillingDepth	Total drilling depth	float	
Longitude	Longitude of drilling location	double	
Latitude	Latitude of drilling location	double	
Remarks	Remarks	string	

Table 3
Stratum information of boreholes.

Field	Details	Data type	Key field
BoreholeCode	Serial number referred to corresponding borehole	long	√
BoreholeName	String name referred to corresponding borehole	string	
LayerNo	Sequence number of stratum detected by borehole	short	√
StratumCode	Code referred to corresponding stratum	string	
From	Depth to the top of stratum	float	
To	Depth to the bottom of stratum	float	
Description	Detailed description of stratum	string	

Table 4
Details of overall strata.

Field	Details	Data type	Key field
StratumNo	Sequence number for overall strata	short	
StratumCode	Code of stratum	string	√
StratumName	String name of stratum	string	
FormationAge	Formation age of stratum	string	
Genesis	Genesis of stratum	string	
Color	Fill color for rendering stratum	long	
OverallDescription	Overall description of stratum	string	

- Details of overall strata. In sedimentary geological environment, the most important structural characteristic of strata is stratified (Zhu et al., 2012). Within a given stratum, depositional age and the mechanical properties are assumed to be approximately uniform. Therefore, each stratum can be regarded as being composed of the same soil or rock mass. In a given study area, each stratum is assigned a sequence number in terms of the top-to-bottom sequence, and an ordered strata list that contained overall strata can be arranged (Zhu et al., 2012). The common information of the overall strata, such as the sequence number, code, name, formation age, genesis, fill color and description, is included in this datasheet to reduce the redundancy in stratum information of boreholes.

3. Modeling steps

Current virtual globes provide flexible 3D-rendering environments for visualizing geospatial objects by supporting OpenGIS KML Encoding Standard (OGC KML). Without having to develop more sophisticated visualization environments from the low level, users of virtual globes only need to describe their geospatial information according to the KML Encoding Standard, and the existing virtual globes can load and visualize that information over the Internet. Based on the methods of representing scientific data sets in KML (Ballagh et al., 2011), we present an automatic method for modeling and visualizing boreholes on virtual globes. As Fig. 1 shows, the proposed method involves seven steps.

3.1. Standardize borehole information for building borehole database

For a given study area, maybe there are large numbers of boreholes with different data structures. Borehole information can be compiled and merged into a spreadsheet, used for subsequent digital model creation and visualization. The first step is to standardize borehole information according to a suitable data standard. We create an Excel workbook via Microsoft Excel. The workbook is arranged in the standard form of borehole database and contains four worksheets: borehole type, borehole information, stratum information, and overall stratum, corresponding to Tables 1–4. Borehole information can be inputted and/or imported into these worksheets to build a unified borehole database.

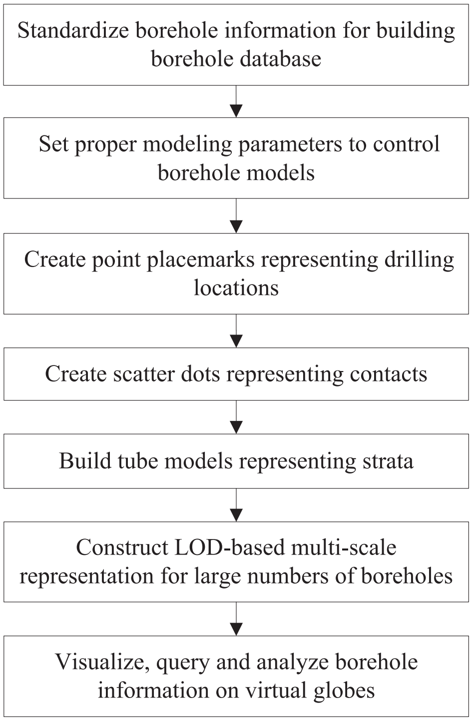


Fig. 1. Flow chart of modeling and visualizing borehole information on virtual globes.

3.2. Set proper modeling parameters to control borehole models

In the second step, we define three modeling parameters: the horizontal scale factor (S_H), the vertical scale factor (S_V) and the uplifted height (U) to adjust the geometrical size and the spatial location of borehole models.

In general conditions, the horizontal size of a borehole is relatively small (generally less than 500 mm), while the vertical size maybe up to dozens, hundreds or even more meters. If borehole models are drawn according to the actual size, we will create dozens of long thin cylinders displayed as lines in 3D space. Within 3D-rendering environments of virtual globes, these long thin cylinder models are neither attractive nor easy to perform such interactive operations as selection, query and analysis using graphical interactive devices. To solve this problem, we define two parameters to adjust the size of borehole models: one is the horizontal scale factor that adjusts the size of boreholes models in horizontal direction, and the other is the vertical scale factor that controls the size of borehole models in vertical direction.

In the real world, boreholes are located below the Earth's surface. However, current virtual globes have limitations when it comes to modeling subsurface features. Due to the current lack of support for negative values of altitudes (De Paor and Pinan-Llamas, 2006; Postpischl et al., 2011), it is hard to visualize subsurface features in the correct location beneath the Earth's surface (De Paor and Whitmeyer, 2011; Navin and de Hoog, 2011). In this paper, we bypass this problem by using a modeling parameter, the uplifted height (U), to elevate the vertical position of boreholes. Boreholes are positioned at the latitude and longitude of their drilling locations, but their altitudes are uplifted by U in order to make them visible above the Earth's terrain surface.

3.3. *Create point placemarks representing drilling locations*

There are several ways of looking at borehole data, such as drilling points, scatter dots and tubes. The simplest form in which boreholes can be viewed is as “drilling points”. Dozens of points, which are placed at correct geographical locations according to the latitude and longitude of boreholes, can be draped over the terrain surface of the virtual globe to represent the spatial distribution of boreholes. In this paper, we employ the KML ⟨Placemark⟩ element to create a series of point placemarks which mark drilling locations on the Earth's surface. The most basic point placemark includes a geographic location, an icon and a descriptive balloon (Wernecke, 2009). In the third step, we first extract the latitude and longitude of drilling locations from the borehole information worksheet, then use the ⟨Style⟩ element to customize the appearance of the drilling point placemark, and finally employ the ⟨Placemark⟩ element to define the geographic location and descriptive information for each drilling point.

To customize the appearance of the drilling point placemark, we define a special style for all drilling points by using the ⟨Style⟩ tag. There are two different types of substyles that need to be defined: one is the ⟨IconStyle⟩ element that specifies how icons for drilling point placemarks are drawn, and the other is the ⟨BalloonStyle⟩ element that contains the descriptive information of the borehole. The KML snippet for customizing the style of drilling points looks like this:

```
⟨Style id=“PlacemarkStyle”⟩
  ⟨IconStyle⟩⟨!--Icon style--⟩
    ⟨color⟩ff0000ff⟨/color⟩
    ⟨Icon⟩
      ⟨href⟩http://maps.google.com/mapfiles/kml/shapes/
   placemark_circle.png⟨/href⟩
    ⟨/Icon⟩
  ⟨/IconStyle⟩
  ⟨BalloonStyle⟩ ⟨!-- Balloon style --⟩
    ⟨bgColor⟩ffE6D8AD⟨/bgColor⟩
    ⟨textColor⟩ff000000⟨/textColor⟩
    ⟨text > ⟨![CDATA[$[description]]]⟩⟨/text > ⟨!--Text to be
 displayed--⟩
  ⟨/BalloonStyle⟩
⟨/Style⟩
```

Using the KML ⟨Point⟩ element, the geographic location of the drilling point can be defined. The descriptive information for the drilling point can be extracted from the borehole information worksheet, and displayed in the descriptive balloon of the drilling point placemark. In order to add the descriptive information to the balloon, we put the standard HTML code inside the CDATA and ⟨description⟩ tags. Here is an example of a KML snippet containing a placemark that represents a drilling point:

```
⟨Placemark⟩
  ⟨name⟩CQC30⟨/name⟩⟨!--String name of the borehole--⟩
  ⟨description⟩
    ⟨![CDATA[⟨!DOCTYPE HTML⟩
      ⟨html⟩
        ⟨meta charset=“utf-8”⟩
        ⟨body⟩
          ⟨!--Detailed descriptive information, omitted--⟩
        ⟨/body⟩
      ⟨/html⟩
    ]]⟩
    ⟨/description⟩
    ⟨styleUrl⟩#PlacemarkStyle⟨/styleUrl⟩⟨!--Applying the
 predefined style--⟩
    ⟨Point⟩⟨!--Geographic location of the drilling point--⟩
      ⟨altitudeMode⟩clampToGround⟨/altitudeMode⟩
      ⟨coordinates⟩121.44256381,31.599372008⟨/coordinates⟩
    ⟨/Point⟩
⟨/Placemark⟩
```

3.4. *Create scatter dots representing contacts*

A more complex way to look at borehole data is in the form of “3D scatter dots” (Horsman and Bethel, 1995). Each scatter dot has a location, an identifier for the borehole, an identifier for the stratum above the contact, and an identifier for the stratum below the contact. A small sphere placemark can be placed at each point in space where the scatter point occurs and is colored according to the color of the overlying or underlying stratum. In the fourth step, we first calculate the 3D coordinate of each scatter dot for each borehole, then use the ⟨Style⟩ element to customize the appearance of the scatter dot placemark, and finally employ the ⟨Placemark⟩ element to define the 3D location and descriptive information for each scatter dot.

For a given borehole, the latitude and longitude of each scatter dot are identical with the latitude and longitude of the drilling location. Therefore, we only need to calculate the altitude of the scatter dot. For a given stratum with a sequence number i, we first extract two depths (Z_{i_From} and Z_{i_To}) from the stratum information worksheet, and then calculate altitudes of scatter dots as follows:

$$Z_i = Z_0 - Z_{i\_From} \times S_V;$$
$$Z_{i+1} = Z_0 - Z_{i\_To} \times S_V;$$

where Z_i is the altitude of the ith scatter dot in the borehole, Z_{i+1} is the altitude of the $(i+1)$th scatter dot in the borehole, Z_0 is the uplifted elevation of the drilling location, Z_{i_From} is the depth to the top of the ith stratum, Z_{i_To} is the depth to the bottom of the ith stratum and S_V is the vertical scale factor.

3.5. *Build tube models representing strata*

The most complex representation of borehole data is in the form of tubes. A borehole can be decomposed into a set of segments. Each segment occurs between two contacts and is associated with a stratum (Lemon and Jones, 2003). A segment can be displayed as a tube placemark colored according to the fill color of the corresponding stratum. In the fifth step, we first calculate the 3D coordinate of the control vertices for the tube segment, then use the KML ⟨MultiGeometry⟩ element to define the spatial location of each tube segment, next employ the ⟨Style⟩ element to customize the appearance of the tube placemark, after that use the standard HTML code to define the descriptive information of the tube placemark and finally put above-mentioned KML elements inside the ⟨Placemark⟩ element to build a tube model representing a stratum.

In this paper, we represent the tube segment as a regular 12-sided prism. As illustrated in Fig. 2, the 3D coordinate of the control vertices in the top surface of a given tube segment can be calculated as follows:

$$X_j = X_{From} + Diameter/2\ \mathrm{Sin}\,(30^\circ \times j);$$
$$Y_j = Y_{From} + Diameter/2\ \mathrm{Cos}\,(30^\circ \times j);$$
$$Z_j = Z_{From};$$

where $j\,(j=1,\ldots,12)$ is the sequence number for a vertex, X_j, Y_j, and Z_j are 3D coordinates (longitude, latitude and altitude) of the vertex P_j, X_{From}, Y_{From}, Z_{From} are 3D coordinates of the top contact P_{From}, and *Diameter* is the resized diameter.

Similarly, we also can calculate the 3D coordinate of the control vertices in the bottom surface. At this point, we just need to use coordinates of the bottom contact (P_{To}) to replace the coordinates of the top contact (P_{From}).

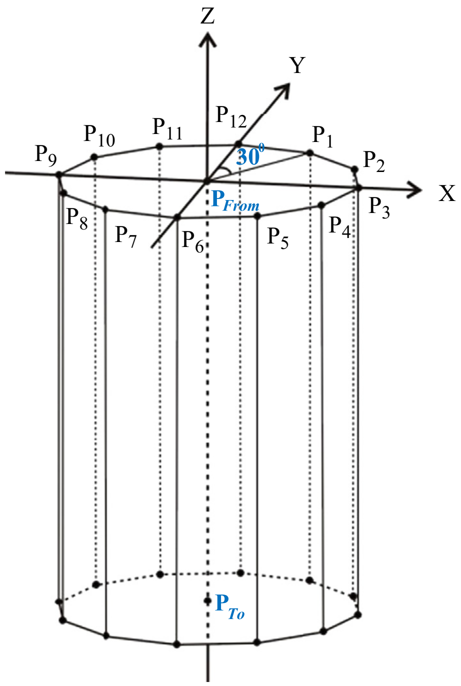


Fig. 2. A regular 12-sided prism representing a tube segment.

After calculating the 3D coordinate of each control vertex, we use the ⟨MultiGeometry⟩ element to define the spatial location of a tube segment. As Fig. 2 shows, each tube segment is bounded by 14 polygons: a top surface (the regular dodecagon), a bottom surface (the regular dodecagon) and 12-side surfaces (the rectangle). Each polygon can be defined by the ⟨Polygon⟩ element. Here is an example of using the ⟨Polygon⟩ and ⟨MultiGeometry⟩ tags to specify the spatial location of a tube segment in a borehole:

```
⟨MultiGeometry⟩
      ⟨Polygon⟩⟨!--The top surface--⟩
        ⟨extrude > 0⟨/extrude⟩
        ⟨tessellate⟩1⟨/tessellate⟩
        ⟨altitudeMode⟩absolute⟨/altitudeMode⟩
        ⟨outerBoundaryIs⟩
        ⟨LinearRing⟩
          ⟨coordinates⟩⟨!--3D coordinate, omitted--⟩
            …
          ⟨/coordinates⟩
        ⟨/LinearRing⟩
      ⟨/outerBoundaryIs⟩
      ⟨/Polygon⟩
      ⟨Polygon > ⟨!--The bottom surface-- >
        ⟨extrude⟩0⟨/extrude⟩
        ⟨tessellate⟩1⟨/tessellate⟩
        ⟨altitudeMode⟩absolute⟨/altitudeMode⟩
        ⟨outerBoundaryIs⟩
        ⟨LinearRing⟩
          ⟨coordinates⟩⟨!--3D coordinate, omitted--⟩
            …
          ⟨/coordinates⟩
        ⟨/LinearRing⟩
      ⟨/outerBoundaryIs⟩
      ⟨/Polygon⟩
      ⟨Polygon⟩⟨!-- The first side surface--⟩
        ⟨extrude > 0⟨/extrude⟩
        ⟨tessellate⟩1⟨/tessellate⟩
        ⟨altitudeMode⟩absolute⟨/altitudeMode⟩
        ⟨outerBoundaryIs⟩
        ⟨LinearRing⟩
          ⟨coordinates⟩⟨!--3D coordinate, omitted--⟩
            …
          ⟨/coordinates⟩
        ⟨/LinearRing⟩
      ⟨/outerBoundaryIs⟩
      ⟨/Polygon⟩
      ⟨Polygon⟩⟨!--The k-th side surface, k=2, …, 12--⟩
        ⟨extrude⟩0⟨/extrude⟩
        ⟨tessellate⟩1⟨/tessellate⟩
        ⟨altitudeMode⟩ absolute ⟨/altitudeMode⟩
        ⟨outerBoundaryIs⟩
        ⟨LinearRing⟩
          ⟨coordinates⟩⟨!-- 3D coordinate, omitted--⟩
            …
          ⟨/coordinates⟩
        ⟨/LinearRing⟩
      ⟨/outerBoundaryIs⟩
    ⟨/Polygon⟩
            …
  ⟨/MultiGeometry⟩
```

Similar to the drilling point placemarks, we employ the ⟨Style⟩ tag to customize the appearance of the tube placemark. The descriptive information associated with the tube segment includes the current stratum information and the general information about the corresponding borehole. We use the standard HTML code to organize this type of descriptive information, and put the HTML code inside the CDATA, ⟨description⟩ and ⟨Placemark⟩ tags to create a tube model for representing a segment. Here is the KML code:

```
⟨Placemark⟩
      ⟨name > CQC30: 1_1⟨/name⟩⟨!--Borehole name and
  stratum code--⟩
      ⟨description⟩
          ⟨![CDATA[⟨!DOCTYPE HTML⟩
          ⟨html⟩
          …⟨!--Detailed descriptive information, omitted--⟩
          ⟨/html⟩
          ]]⟩
          ⟨/description⟩
          ⟨styleUrl⟩#FFC1B6FF⟨/styleUrl⟩
          ⟨MultiGeometry⟩
            …⟨!--Spatial location of the tube segment, omitted--
  ⟩
          ⟨/MultiGeometry⟩
  ⟨/Placemark⟩
```

3.6. *Construct level-of-detail based (LOD-based) multi-scale representation for large numbers of boreholes*

In a larger study area like a big city, usually there are thousands of boreholes that need to be modeled on the virtual globe. Due to the vast amount and complicated geometry of borehole models, it is either hard or impossible to load and display all boreholes at one time. Several technical problems, such as slow access speed and server overloading, may occur in virtual globe applications when the volume of borehole information is huge. In order to enhance the efficiency of visualizing large volume of borehole information on virtual globes, we need to apply the multi-scale representation method as well as the LOD (level of detail) rendering strategy. The sixth step is to define the control parameters for loading and displaying borehole models by using KML ⟨Region⟩, ⟨LOD⟩ and ⟨NetworkLink⟩ elements.

In this paper, borehole models constructed from the previous steps can be classified into two different levels: the simple level and the detailed level, depending on their generating methods and application fields. Point placemarks representing drilling locations belong to the simple level model. Due to its simple data structure and less data volume, the simple level model is suitable for occasions when the overview of large numbers of boreholes needs to be displayed with lower resolutions. The detailed level model includes scatter dots and tube models that represent internal structures and details of boreholes. Because of the sheer volume of the data, the detailed level model can only be used for revealing detailed information about boreholes within a very limited range. Here is an example of using KML elements to control the loading and displaying of borehole models with different levels of detail:

```
⟨NetworkLink⟩ ⟨!--Controlling the simple level model--⟩
  ⟨name⟩140130030(CQC30)⟨/name⟩⟨!-- Code and name of a
  borehole--⟩
  ⟨Region⟩⟨!--Geographical area for activating the simple level
  model--⟩
    ⟨LatLonAltBox⟩⟨!-- Bounding box for the drilling
  location--⟩
      ⟨north⟩31.6084⟨/north⟩
      ⟨south⟩31.5904⟨/south⟩
      ⟨east⟩121.452⟨/east⟩
      ⟨west⟩121.434⟨/west⟩
    ⟨/LatLonAltBox⟩
    ⟨Lod⟩
      ⟨minLodPixels⟩32⟨/minLodPixels⟩
      ⟨maxLodPixels⟩-1⟨/maxLodPixels⟩
    ⟨/Lod⟩
    ⟨/Region⟩
    ⟨Link⟩
      ⟨!--A KML file referring to the point placemark
  representing the drilling location--⟩
      ⟨href⟩140130030_Point.kml⟨/href⟩
      ⟨viewRefreshMode⟩onRegion⟨/viewRefreshMode⟩
    ⟨/Link⟩
⟨/NetworkLink⟩
⟨NetworkLink⟩⟨!--Controlling the detailed level model--⟩
  ⟨name⟩strata at CQC30⟨/name⟩⟨!--Borehole name--⟩
  ⟨Region⟩
    ⟨LatLonAltBox⟩
      ⟨north⟩31.6084⟨/north⟩
      ⟨south⟩31.5904⟨/south⟩
      ⟨east⟩121.452⟨/east⟩
      ⟨west⟩121.434⟨/west⟩
    ⟨/LatLonAltBox⟩
    ⟨Lod⟩
      ⟨minLodPixels⟩512⟨/minLodPixels⟩
      ⟨maxLodPixels⟩-1⟨/maxLodPixels⟩
    ⟨/Lod⟩
    ⟨/Region⟩
    ⟨Link⟩
      ⟨!--A KML file referring to scatter dots and tube
  models--⟩
      ⟨href⟩140130030_Cylinder.kml⟨/href⟩
      ⟨viewRefreshMode⟩onRegion⟨viewRefreshMode⟩
    ⟨/Link⟩
⟨/NetworkLink⟩
```

In this example, a point placemark representing the drilling location of borehole CQC30 (numbered 140130030) is stored in a KML file (*140130030_Point.kml*), while the scatter dots and tube models representing details of borehole CQC30 are merged into another KML file (*140130030_Cylinder.kml*). We define a geographical region (a KML Region) that encompasses the drilling location of borehole CQC30 by using the KML ⟨LatLonAltBox⟩ tag. This Region affects the display of borehole models. The minimum limit of the visibility range for activating the drilling point placemark is 32, which means that the drilling point placemark comes into view when the Region defined by the ⟨LatLonAltBox⟩ tag occupies 32 square pixels on the screen. However, the minimum limit of the visibility range for activating scatter dots and tube models of borehole CQC30 is 512 square pixels. That is, only when the Region occupies 512 square pixels, the detailed level model, including scatter dots and tubes, is drawn on the screen. By utilizing this region-based network link technique, we can dramatically simplify the amount of borehole data fetched and displayed to the viewer, and greatly improve the responsiveness and interactivity for the visualization and analysis of borehole information on virtual globe applications.

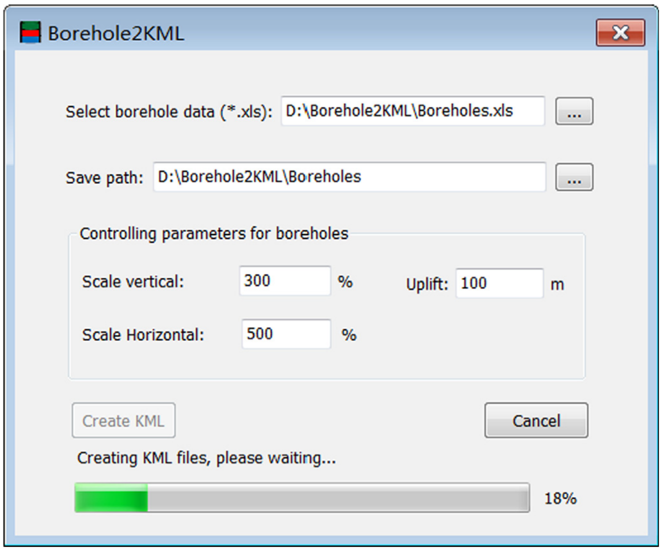
3.7. *Visualize, query and analyze borehole information on virtual globes*

Finally, the modeling result is added to the digital globe for 3D visualization and spatial analysis. With the help of the advanced visualization tools provided by virtual globes, we can examine and analyze the internal structures and details of boreholes. Using graphical interactive devices like the mouse and the keyboard, we can select boreholes on digital globes and search the detailed information about drilling points, scatter dots or tubes. In this way, it is possible to view the spatial distribution and internal characteristic of large numbers of boreholes on virtual globes.

4. Implementation program: Borehole2KML

To implement the proposed modeling method, a program, termed Borehole2KML (Boreholes to KML), is developed with Microsoft Visual C++ 2010 on the Windows platform. Borehole information stored in an Excel workbook can be automatically converted into KML documents via Borehole2KML, and the KML documents can be loaded into virtual globes to represent the spatial distribution and internal characteristic of boreholes.

As shown in Fig. 3, Borehole2KML provides a simple user interface to create KML documents. When the program is executed, we first select an Excel file (like *D:|Borehole2KML|Boreholes.*



Select borehole data (*.xls): D:\Borehole2KML\Boreholes.xls

Save path: D:\Borehole2KML\Boreholes

Controlling parameters for boreholes

Scale vertical: 300 %

Uplift: 100 m

Scale Horizontal: 500 %

Creating KML files, please waiting...

18%

Fig. 3. User interface of Borehole2KML.

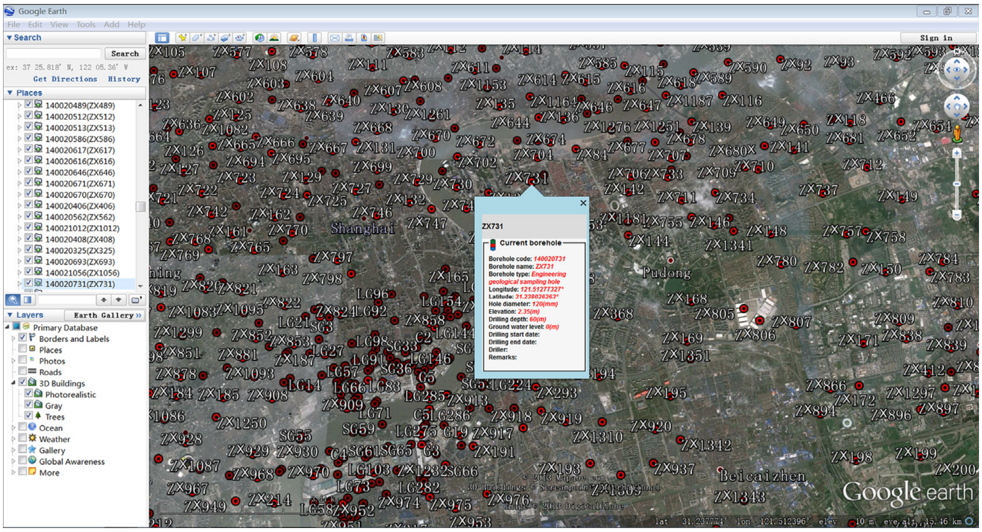
xls) that stores borehole data, then set a save path for target KML files and three modeling parameters to control borehole models, and finally click the “Create KML” button to convert borehole data into KML documents. Borehole2KML automatically creates drilling point models, scatter dot models and tube models for all boreholes, and saves these models into corresponding KML files. In addition, Borehole2KML also creates a KML file (like *Boreholes.kml*) to construct LOD-based multi-scale representation for large numbers of boreholes. The base name of this KML file is the same as the input Excel file. When we open this KML file in a virtual globe application, borehole models are automatically loaded and displayed in the 3D environment of the virtual globe.

5. Example: boreholes in Shanghai, China

Shanghai, the largest city in China, is located in the alluvial plain of the Yangtze River Delta. In the central district of Shanghai, there are a large number of boreholes derived from different types of construction projects. We collect 2747 typical boreholes and archive them into an Excel workbook (named *Boreholes_Shanghai.xls*). Using Borehole2KML, we generate a series of models to represent boreholes with different levels of detail, and create a KML file (named *Boreholes_Shanghai.kml*) to archive them into a hierarchy of region-based network links.

We load *Boreholes_Shanghai.kml* into Google Earth, and experiment with different viewpoints. When we first pan to Shanghai from very far away, no boreholes are visible. As the view moves closer, a set of drilling point placemarks comes into view (Fig. 4). Choosing a drilling point placemark, the general information about this borehole pops up from the descriptive balloon. As the view moves even closer, detailed level models for boreholes appear and hover over corresponding drilling points (Fig. 5). We can freely explore these models in a variety of ways. When we choose a scatter dot in a borehole, the descriptive information associated with this dot is displayed in the descriptive balloon (Fig. 6). Choosing a tube segment, we can query the stratum information corresponded with the segment (Fig. 7).

In order to share these boreholes on the Internet, we store them into a web server and design a webpage (http://202.127.1.14/Borehole2KML/en/Boreholes_Shanghai.html) that embeds a Google Earth instance. Any browser, which already has the Google Earth Plugin installed, can freely access this webpage from anywhere and at any time through the Web.



ZX731

Current borehole

Borehole code: *140020731*
Borehole name: *ZX731*
Borehole type: *Engineering geological sampling hole*
Longitude: *121.51277327°*
Latitude: *31.238026263°*
Hole diameter: *120(mm)*
Elevation: *2.35(m)*
Drilling depth: *60(m)*
Ground water level: *0(m)*
Drilling start date:
Drilling end date:
Driller:
Remarks:

Fig. 4. A partially zoomed-in view of Shanghai, China, with a number of drilling point placemarks displayed and one descriptive balloon visible.

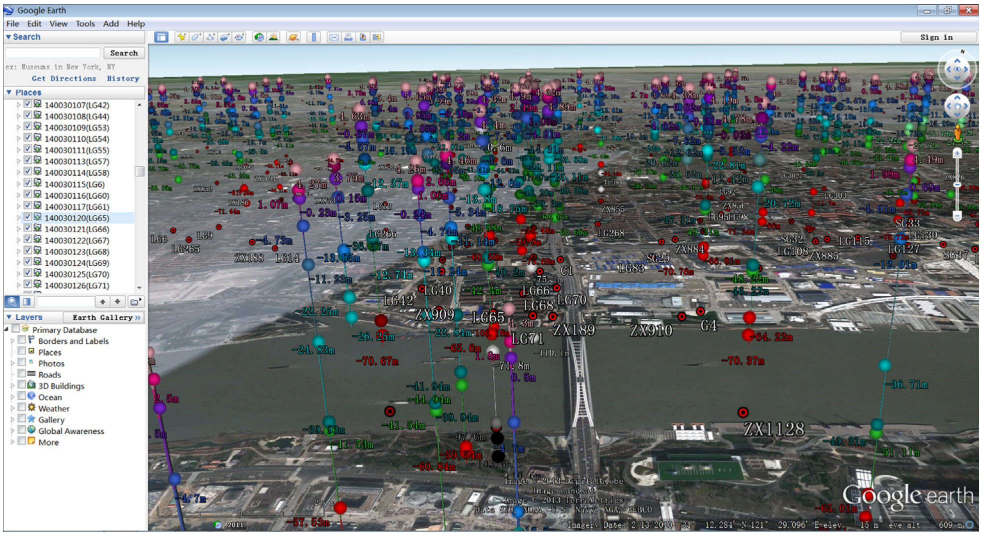
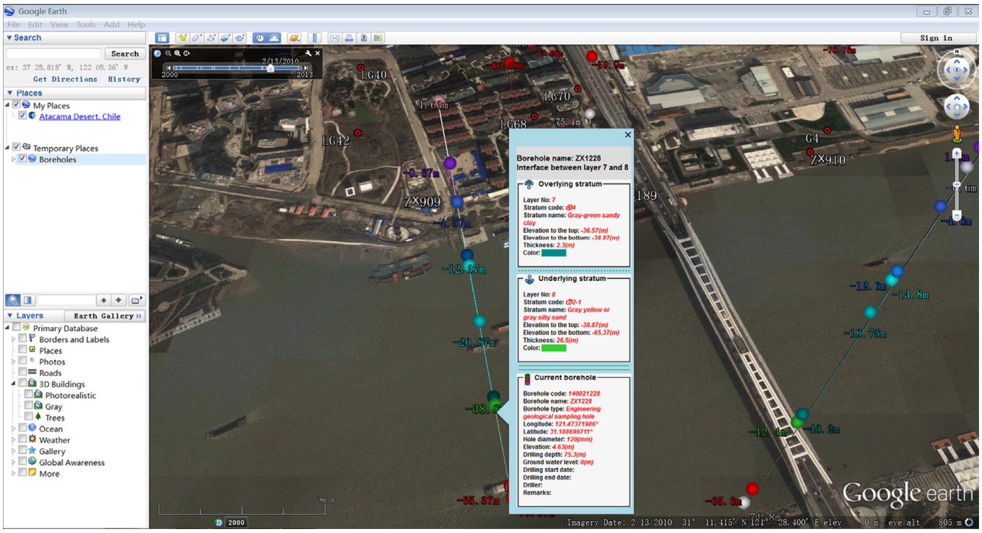


Fig. 5. Scatter dots and tube models hovering over drilling point placemarks.



Borehole name: ZX1228
Interface between layer 7 and 8

Overlying stratum

Layer No: 7
Stratum code: ⑥4
Stratum name: Gray-green sandy clay
Elevation to the top: -36.57(m)
Elevation to the bottom: -38.87(m)
Thickness: 2.3(m)
Color: ■

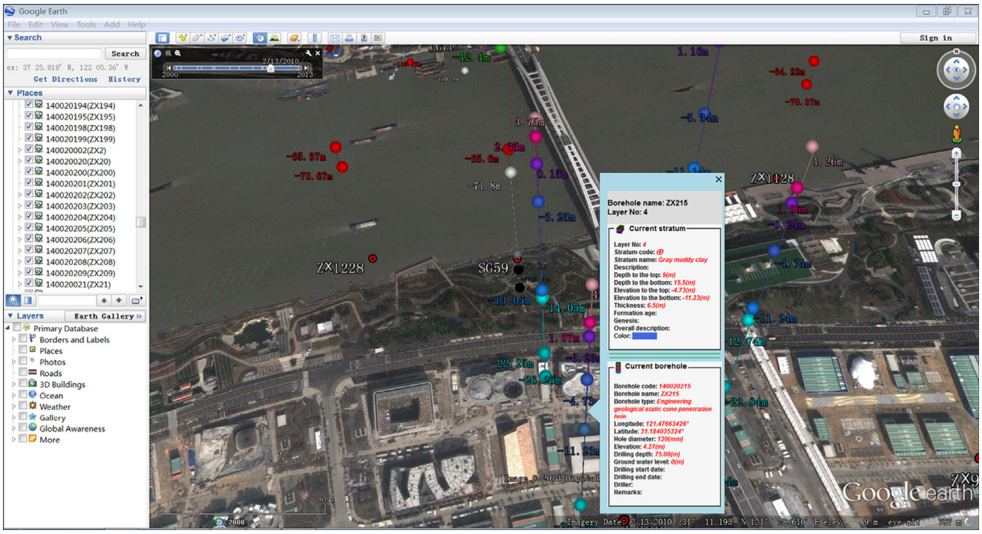
Underlying stratum

Layer No: 8
Stratum code: ⑦2-1
Stratum name: Gray yellow or gray silty sand
Elevation to the top: -38.87(m)
Elevation to the bottom: -65.37(m)
Thickness: 26.5(m)
Color: 🟩

Current borehole

Borehole code: 140021228
Borehole name: ZX1228
Borehole type: Engineering geological sampling hole
Longitude: 121.47371986°
Latitude: 31.188699711°
Hole diameter: 120(mm)
Elevation: 4.63(m)
Drilling depth: 75.3(m)
Ground water level: 0(m)
Drilling start date:
Drilling end date:
Driller:
Remarks:

Fig. 6. Displaying the descriptive information associated with a scatter dot.



Borehole name: ZX215
Layer No: 4

Current stratum

Layer No: 4
Stratum code: ④
Stratum name: Gray muddy clay
Description:
Depth to the top: 9(m)
Depth to the bottom: 15.5(m)
Elevation to the top: -4.73(m)
Elevation to the bottom: -11.23(m)
Thickness: 6.5(m)
Formation age:
Genesis:
Overall description:
Color: 🟦

Current borehole

Borehole code: 140020215
Borehole name: ZX215
Borehole type: Engineering geological static cone penetration hole
Longitude: 121.47663426°
Latitude: 31.184035324°
Hole diameter: 120(mm)
Elevation: 4.27(m)
Drilling depth: 75.08(m)
Ground water level: 0(m)
Drilling start date:
Drilling end date:
Driller:
Remarks:

Fig. 7. Displaying the descriptive information associated with a tube segment.

6. Conclusion

We have developed an automatic method for modeling and visualizing boreholes on virtual globes. A concrete example shows that the modeling process is simple, automatic and effective. In addition, borehole models generated from this method are well-suited to the dissemination, integration and visualization on the Internet. Therefore, the widespread future use of this method will help the Earth scientists share their borehole data more easily. This will make borehole information accessible to a broad user base, and may promote the development on the societal service of subsurface geological information.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.cageo.2013.09.016.

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