Study on the Method of Constructing Engineering Geological Three-dimensional Model of Hydrate Area in South China Sea Based on ArcGIS

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Abstract. The trial production of marine natural gas hydrates (NGH) in China is gradually increasing, attracting concerns on related environmental issues. The entire regional conditions of engineering geological environment must be investigated thoroughly before NGH production. These conditions should be defined, among others, in terms of seabed topography, stratigraphic structure, soil types, physical and mechanical characteristics, hazardous geological factors and distributions, and hydrodynamic characteristics, which provide a variety of geological spatial information and can be obtained from different sources. Due to the high cost and low efficiency of deep-sea engineering geological drilling, only few stations can be deployed. Hence, not enough data are available for the construction three-dimensional (3D) geological models. This study considered the data of only a few drilling stations and compared them with well logging and 3D seismic data. First, the engineering geological standard strata were established. Second, we interpreted and exported the stratigraphic (based on virtual boreholes) and spatial information (in terms of X, Y, and Z) of existent geological structures in GeoFrame. Finally, using several technical modules of ArcGIS (i.e., ArcMap, ArcScene, ArcCatalog), we constructed a spatial database and a comprehensively intuitive 3D visualization data management platform for engineering geological environmental surveys and evaluations in the hydrate area. By clicking any element included in the platform, the correspondent data or results can be looked over: this efficient and continuous systematic database can be used to support the future production of NGH in the area.

1. Introduction
Geographical information system (GIS) technology is very powerful in managing and analyzing spatial information and associated data. So far, it has been successfully applied to resource management, automatic mapping, facility management, city and regional planning, population and business management, transportation, oil and gas, education, and even to the military sector (with > 100 fields in nine categories and leading to considerable economic and social benefits) [1]. In the age of big data, ArcGIS is one of the most important desktop GISs: not only it is powerful in managing geographical data, but it is also helpful for conducting geographical spatial analyses, evaluations, predictions, and auxiliary decision-makings. The spatial analysis modules with extraction, transmission, calculation, and analysis functions, as well as those with 3D expansion modules, are often directly applied and further developed for the construction of databases, the editing of the resulting maps, and the 3D visualization of the spatial information and associated data [2].
In the last years, China has successfully implemented two production tests of natural gas hydrate (NGH) in the Shenhua hydrate area (northern South China Sea).

To ensure the stability of the seabed during the entire production process, it is necessary to first check the seabed soil types, as well as its physical and mechanical characteristics, stratigraphic structure, potential hazardous geological factors, hydrodynamic environment and other geological environment conditions near the test well area. Furthermore, it is particularly important to evaluate the interaction between these conditions and the production process by means of experimental simulations and indoor calculations. Simultaneously, real-time environment monitoring during the production and long-term environment monitoring after the production are indispensable for a green and sustainable development of NGH. So far, there is an abundance of relevant engineering geological data. The numerous planned production tests of NGH and its large-scale commercial production will require an increasing amount and a continuity of engineering geological investigations and evaluations; therefore, the collection of engineering geological environmental information and data will gradually increase. With the development of the digital ocean, there will be an increasing demand for the digitization and continuous update of engineering geological information and data regarding marine hydrate areas. Such information and data will play an important role in the production of NGHs. In early surveys and the associated studies, engineering geological data and results regarding hydrate areas were mainly managed and displayed in two dimensions.

Currently, there is not a comprehensive and 3D visualization intuitive management system or platform for large amounts of engineering geological information and data concerning on specific hydrate areas; hence, the processing and analysis efficiencies are relatively low. This study mainly focused on the engineering geological environment, discussing a method for the construction of an engineering geological environmental spatial database and a 3D model of the hydrate areas in the northern South China Sea. Moreover, we proposed a comprehensive 3D visualization management system or platform, a long-term basic data support (for the future production of NGH, continuous engineering geological surveys, research, analysis, and evaluations in hydrate areas), and showed an effective method for 3D digitization during ocean surveys.

Experts from China and abroad have achieved considerable progress in the application of GIS technologies on land for engineering information management and environmental geotechnical engineering, among others [4-7]. Nevertheless, these advances were mainly based on 2D editing, storage, query, management, and viewing. Such methods of management have the advantages of macroscopicity and integrity; however, they are also relatively non-figurative, and lacking intuition and reality. Through the construction of a 3D visualization model, it is possible to compensate the shortcomings of a 2D GIS, showing the spatial data and the correspondent results in a more systematic and intuitive way.

Interestingly, the research on the 3D stratum model technology has greatly progressed in China, mainly through the use of some large-scale analysis software (e.g., MapInfo, ArcInfo, GeoSTAR, MapGIS, IMAGIS, Gocad, Itascad, Surpac, DININE, GeoView, Geoengine, Micomine, Petrel, RMS, and Fastracker). Also, there are many modeling software with unique advantages depending on the industry of reference [8]. ArcGIS is commonly used for China’s geological surveys as a mapping and analysis software. This software has a very wide range of applications, especially for the construction of spatial databases, since its spatial analysis functions are complete and powerful. In this study, ArcGIS was used because of its common application, very powerful post-analysis function, good open secondary development, good compatibility, various possible mapping outputs, and the possibility of evaluating the results under multiple aspects. In a previous study focusing on technical methods relevant for 3D modeling, Zhu L F et al. [9] proposed to construct a stratum 3D model based on virtual borehole data; additionally, Guo Y J (2003) constructed a stratum 3D model based on both borehole data and cross-fold profile constraints. Different modeling methods can be classified based on the data source (e.g., borehole, profile, 3D seismic, and multi-source data) [12]. This study aimed at constructing the 3D model of a deep-water hydrate area. Due to the relative lack of borehole data, the model was mainly based on 3D seismic data, which were accurately compared with the borehole and
logging data. Finally, we investigated a set of methods for constructing a 3D model of the engineering geological environment in the hydrate areas of the northern South China Sea. Such model is projected to greatly improve the processing and analysis efficiency of large amounts of survey information and data for environmental assessments and the future production of NGH.

2. Study area and technical methods

In order to highlight the importance of production tests for marine NGH in China and provide practical services, this study focused on the key hydrate area of Shenhu in the northern South China Sea. As a matter of fact, the NGH in this area is very likely to be commercially produced in the future (Figure 1). The study area is located ~ 300 km away from the southern Guangdong Province (China), at a water depth of 1000–1500 m, and precisely on the continental slope of the South China Sea. The local geological deposition environment is relatively complex. At present, China has successfully implemented two production tests of NGH and conducted numerous geological environmental surveys and evaluations on the stability in the area. The collected engineering geological information and data collected must be detailed in order to allow a green (i.e., avoiding the destruction of the natural environment) and continuous production of marine NGH. In this study, we discussed the construction of a 3D model of the engineering geological environment in the study area: a procedure was developed for constructing a scientific, efficient, intuitive, and 3D visualization system or platform that would allow the management and analysis of engineering geological information and data, as well as support the production of NGH. In deep-water areas such as that considered in this study, engineering geological drilling is relatively expensive and not very efficient. In such context it is not possible to deploy as many high-scale boreholes as on land to ascertain the characteristics (e.g., seabed soil layers and types, the physical and mechanical characteristics, and the hazardous geological factors) of the hydrate area.

Figure 1 Location map of the study area.

Considering the few possible engineering geological drilling boreholes in the study area, this study will used geophysical data (e.g., logging and 3D seismic data and related results). First, we organized the processing, analysis, and classification of the engineering geological environment information and data collected in the hydrate area, according to different engineering geological conditions (e.g., the marine hydrodynamic environment, seabed topographic features, stratigraphic structures, soil types, physical and mechanical characteristics, hazardous geological factors and distribution, other basic data, and related achievements) (Figure 2). The key information for constructing the 3D geological model was represented by the stratigraphic divisions. These were defined based on the borehole, geophysical, logging data for a comprehensive comparison and interpretation; moreover, they were considered parallel to the evolution of the regional geological
deposition environment. Additionally, the standard strata in the study area and important data information (e.g., x, y, and z) were considered for constructing the 3D model. 

Second, we used the ArcGIS software platform (commonly used to design data management systems, as well as to classify, and vectorize engineering geological information and data) to construct an engineering geological spatial database based on a database technical module. 

Third, the ArcGIS platform was used also to develop a 3D model of the engineering geological environment for an intuitive 3D visualization of the key hydrate area in the Shenhu area. In this way, we obtained an intuitive and macroscopic 3D engineering geological information and data management system or platform. This system or platform provides long-term effective basic data that can be used to support the production of NGH. 

Notably, we developed two minor research paths: an analysis of the stability of the soil layer bearing hydrate by physical experiment simulations, and an evaluation of the seabed stability during the production of NGH by numerical simulations. The engineering geological spatial database assembled in this study and the 3D model were used to obtain basic and accurate parameters. The relevant evaluation and stability analysis results were returned to the corresponding storage module of the spatial database and to the 3D visualization management system. This system is able to continuously provide basic parameters applicable to the design and construction of hydrate drilling projects.

![Diagram](image)

**Figure 2** Methods used for the construction of the 3D model of the engineering geological environment in the Shenhu hydrate area.

### 3. Acquisition of the engineering geological data and stratigraphic divisions in the hydrate area

#### 3.1 Acquisition of the engineering geological data in the deep hydrate area

Field surveys are the main source of engineering geological information and data regarding deep-water hydrate areas. Such data are collected by means of multiple beams (AUV), shallow profiles, 2D or 3D seismic analyses, logging, ROV, submarine gravity sampling, engineering geological drilling, and CPT field testing, among others. Nevertheless, additional data can be obtained through indoor
geotechnical experiments, physical laboratory simulation experiments, numerical simulation calculation and analysis, and other thematic research analyses. The final aim is to obtain basic engineering geological data and related results data of the study area.

1) Multi-beam survey. This technique is commonly used for oceanic topographic surveys. The final results are obtained after post-processing by including the measured point coordinates and the water depth. The storage and display of these results is generally done in TIF bitmap, JPG, and other image formats. The raw data are usually saved in Excel or TXT files. Various softwares can be used for data vectorization, including Global Mapper, Surfer, ArcGIS. Notably, AUV and the deep-tow technology are continuously applied during high-precision topographic surveys in deep water.

2) Geophysical survey including shallow profiling and 2D or 3D seismic. This method allows to directly obtain an acoustic reflection section after data processing. If the results of this processing are combined with the available information on the regional sedimentary environment evolution, they allow the analysis and identification of seafloor stratigraphic units (their boundary and thickness), the interpretation of the horizontal expansive condition, and the identification of geological structures existing in the strata (e.g., faults, mud splits, and buried ancient channels). The collection of all these data often requires a large storage capacity; moreover, they need to be processed and interpreted through a geophysical professional software (e.g., GeoFrame and GeoSuite). The corresponding results are often displayed in the form of reports (text) and section pictures in common formats.

3) Logging survey: The logging-while-drilling parameters include natural gamma, lateral resistivity, neutron, density, and acoustic wave data (among others), which can be used to analyze in detail the vertical variation of the stratigraphic physical properties. These data can be further compared with drilling results, obtaining mathematical formulas that explain the relationship between different parameters. These are normally applied to infer the partial engineering geological parameters of the submarine soil layer in non-drilling areas (but where the logging survey was carried out). The final processed logging results are usually visualized in longitudinal variation charts and stored in an Excel document.

4) ROV survey: This type of survey is conducted through a real-time monitoring of the submarine site environment and directly observations of seabed cold springs, gas chimneys, and micro-landforms (e.g., pocket pits, drilling wells, and mud splits) in the hydrate area. The raw data and results (including coordinates and other information) are then stored and displayed in a video format.

5) Geological sampling survey: A gravity sampler is used to collect shallow seabed sediment soil on the ship and conduct indoor geotechnical tests, with the aim of determining the soil types, as well as the physical and mechanical characteristics of every soil layer. Chinese experts are struggling to develop in situ measuring instruments to be used for this scope. Notably, this type of survey is always used to quickly measure the geological environmental parameters of submarine shallow soil in deep areas. The correspondent results are usually stored in Excel and Word files.

6) Engineering geological drilling and CPTU (pore pressure static penetration) survey: Drilling sampling is conducted to obtain deep and relatively continuous engineering geological data of the soil layers below the seabed. Afterward, the samples (including soil layers bearing hydrate and the overlying soil layers) undergo field and indoor geotechnical tests that make use of a pressure-preserving corer. The CPTU technique can directly and continuously obtain in situ the partial physical and mechanical properties of the soil layers below the seabed. This information can then be used to identify the soil types and the stratigraphic structures; moreover, they are fundamental for engineering calculations and designs. The raw data and the final results are mainly displayed in a drilling comprehensive histogram and stored in Excel and Word files, moreover, eventual pictures can be stored in multiple formats.

7) Marine hydrodynamic characteristics and information related to earthquakes: The information is mainly obtained from the literature and previous thematic surveys conducted in hydrodynamic environments. These provide regional wind, wave, current, and other relevant environmental data, including information about the intensity and frequency of earthquakes in the study area.
8) Indoor geotechnical tests and thematic research: Geotechnical tests are done to directly obtain the physical and mechanical parameters of the soil layer and determining its engineering geological characteristics. A typical process includes physical and numerical simulation experiments aimed at determining the stability of the soil layer in view of hydrate production. The simulation experiments provide a large number of data, pictures, and text reports.

In summary, a large amount of survey data related to engineering geology in the hydrate area are typically produced. These are usually showed and stored in the form of Office documents (Excel, Word, TXT files), pictures in different formats (e.g., vectorized graphs), tables, and videos.

3.2 Stratigraphic divisions in the Shenhu hydrate area

The main aim of constructing an accurate 3D model of the engineering geological environment was to get information on the strata, so to describe and sub-divide the stratigraphic structure of the study area. Due to the high cost of deep-sea engineering geological drilling and the low survey efficiency, relatively few stations have been deployed in this area. Hence, we established the regional standard strata through a comprehensive analysis and interpretation of the geophysical data (e.g., shallow profiles, 2D or 3D seismic, and borehole data) and by considering them in the context of the regional sedimentary environment evolution.

First, the soil layers were divided according to the characteristics of the regional sedimentary environment. Afterward, the engineering geological layers were subdivided mainly based on: 1) their geological environment, age of deposition, and sedimentary characteristics; 2) their lithological and soil characteristics; 3) their engineering geological properties and the soil strength characteristics; 4) the obviously reflective surfaces in the geophysical profile. Notably, the bottom-simulating reflector of the soil layer bearing hydrate was dependent only on the temperature and pressure conditions below the seabed. Hence, it generally showed a cross-strata phenomenon: the soil layer bearing hydrate was described and expressed as a separate structure from the regular strata. The key hydrate area of Shenhu was identified at 400 m below the seabed and finally divided into 5 layers and 8 sub-layers, with comprehensive comparison and explanation (Figure 3, Table 1):

Layer 1 (H1) was mainly represented by Quaternary slump deposits, had an overall thickness of ~ 0–60 m, a high silt content, and a low natural gamma value. The typical feature of the correspondent seismic facies was a set of stratified weak amplitude reflections. This layer could be further divided into two sub-layers (H1-1 and H1-2), which presented obviously different engineering geological properties. The H1-1 layer was made of very soft calcareous clay, while the H1-2 layer was made of soft to hard calcareous clay.

Layer 2 (H2) was represented by muddy natural embankment deposits with an overall thickness of 0–40 m. The silt content was lower than that of the H1 layer, while, its natural gamma value was relatively high. The typical feature of the correspondent seismic facies was a set of weak amplitude reflections indicating a poor stratification. The soil was mainly of firm to hard clay.

Layer 3 (H3) was represented by muddy channel deposits with an overall thickness of 0–76 m and a widely varying stratum thickness. The silt content was relatively low compared to that of the H1 and H2 layers, while the natural gamma value was relatively high. The typical feature of the correspondent seismic facies was a set of medium-amplitude reflections indicating a good stratification. This layer was divided into two sub-layers (H3-1 and H3-2) presenting largely different engineering geological properties. The H3-1 and H3-2 layers were composed of hard and very hard calcareous clay and silt, respectively.

Layer 4 (H4) was mainly represented by slump deposits with silt. Its overall thickness was 0–53 m; moreover, its silt content was relatively high, while its natural gamma value was relatively low. At the bottom of this layer, hydrate gradually appeared as the resistivity value suddenly increased and the seismic reflections increased in amplitude. The typical feature of the correspondent seismic facies was a set of weak amplitude reflections indicating poor stratification. The thickness of the stratum, which was mainly composed of dense and hard silt, varied greatly.
Layer 5 (H5) was mainly represented by hydrate and channel turbidity deposits; moreover, its overall thickness was 0–175 m. This layer was further divided into two sub-layers (H5-1 and H5-2), which were clearly differentiated from the soil bearing hydrate. The amount of NGH was lower in the H5-1 layer, and the typical feature of the correspondent seismic facies was a set of weak amplitude reflections with good stratification; meanwhile, the H5-2 layer contained a relatively high amount of NGH, and the typical feature of the correspondent seismic facies was a set of strong amplitude reflections indicating poor stratification. The soil of layer H5 was represented by very dense silt and very hard calcareous clay.

In general, the lateral continuity of the sub-layers was poor, and it is often distributed in partial area. Due to the limited longitudinal accuracy of the geophysical profile, only the stratigraphic division results for the area near the drilling borehole can be considered accurate, while in other areas it is mainly speculated.

Figure 3 Comprehensive comparative analysis of engineering geological drilling, 3D seismic, and logging data.

Table 1. Stratigraphic divisions in the Shenhu hydrate area.

| Layer number | Main characteristics considered for the stratigraphic division | Lithological characteristics |
|--------------|---------------------------------------------------------------|-------------------------------|
| H1           | Quaternary slump deposits, high silt content, low natural gamma value, correspondent seismic facies characterized by a set of weak amplitude reflections (good stratification). | Very soft calcareous clay Soft to hard calcareous clay |
| H1-1         |                                                               |                               |
| H1-2         | Natural embankment deposits, lower silt content and higher natural gamma value than H1, correspondent seismic facies characterized by a set of weak amplitude reflections (poor stratification). | Dominated by firm-hard clay |
| H2           |                                                               |                               |
| H3           | Mainly channel deposits, lower silt content and higher natural gamma value than H1 and H2, correspondent seismic facies characterized by a set of medium-amplitude reflections (good stratification). | Hard calcareous clay or silty clay Very hard calcareous clay |
| H3-1         |                                                               |                               |
| H3-2         |                                                               |                               |
or silty clay

H4

Slump deposits, low natural gamma value, resistivity in the bottom boundary that increases suddenly, strong Mainly dense and amplitude, correspondent seismic facies characterized by hard silt a set of weak amplitude reflections (poor stratification).

H5-1

Bearing hydrate layer, channel turbidity deposits, correspondent seismic facies characterized by a set of Less hydrate weak amplitude reflections (good stratification), but also by a set of strong amplitude reflections (poor stratification) in the lower part of the layer.

H5

More hydrate

4. Construction of the 3D model of the engineering geological environment in the Shenhu hydrate area

Although geological 3D modeling software such as RMS and Petrel have been widely used in the petroleum industry, the management and analysis of spatial information and data have not been as widely and powerfully applied using GIS software. At present, the application of ArcGIS in actual geological work is widespread. The possibility of quickly querying engineering geological information, data, and related evaluation results is of great significance and allows to efficiently output 2D and 3D geological maps. Hence, it is advisable to deepen the study on the use of GIS platforms for the construction of 3D geological models.

Based on the ArcGIS platform, the vectorization of various engineering geological information, data, and achievements is generally done in two ways. Data can be massively input using specific tools (e.g., drawing and table tools), in accordance with the prescribed format, and then imported or converted in the GIS framework. Afterward, by using the ArcGIS Catalog module and relevant technical methods, it is possible to manage the information and data related to all engineering geological conditions, create multiple geodatabase models, and establish spatial connections and indexes between related data or information. This can be done according to actual applications (through topological and hyperlink functions) (Figure 4), which form an engineering geological spatial database of the key hydrate area in Shenhu. Finally, the ArcScene module can be used to construct a 3D visualization model of the engineering geological environment in the study area. This would contain links to all the pictures, tables, data, and documents contained in the spatial database. Users would be able to click on the elements of the 3D model and quickly query the corresponding results.

4.1 Vectorization of various engineering geological information and data

As described above and shown in Table 2, engineering geological information, data, and achievements are mainly obtained through field surveys, monitoring, indoor experiments, and thematic research, but are also collected from historical literature and thematic reports. The form and format of these data and information can vary a lot: the usually include data tables, pictures, vector diagrams, document reports, and videos, among others, both analogic and electronic. The vectorization process can be described as follow: 1) document reports, non-vectorized pictures, and videos are directly input in the database; 2) field survey and monitoring stations, geophysical survey lines, and survey areas are directly converted into basic elements (i.e., points, lines, and areas) in ArcGIS; additional features (e.g., faults, shallow gas, buried ancient channels) are also converted into point, line, and area elements according to their spatial distribution characteristics; 3) the data are sorted and analyzed in the attribute table and the related information is added or modified based on the results of a spatial direct analysis, which allows the calculation of distances, areas, and volumes; then, the results of the field and grid calculations are combined in a suitable mathematical model.

Table 2. Engineering geological data sources and vectorization.

| Data source | Data content | Data format | Vectorization |
|-------------|--------------|-------------|---------------|

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### Historical literature
- Marine hydrodynamics, earthquakes, etc.

### Monitoring data
- Waves, current
- Multi-wave velocity, water depth measurements, engineering geological drilling and subsea sampling, CPTU, logging, geophysical profile, ROV

### Survey data
- Geotechnical test data and processing analysis chart
- Relevant features (e.g., information on the sedimentary environment and stability evaluations)

### Test data
- Data tables, pictures, and reports
- Data tables, vector diagrams, pictures, and reports
- Data tables, vector graphics, pictures, reports, and videos
- Data tables and pictures

1) Non-vectorized results are directly input in the database;
2) the vectorization features of the data are converted into basic elements (i.e., points, lines, and areas) through ArcGIS;
3) the attribute table is modified, and further spatial calculations and analyses are conducted.

| Historical literature | Marine hydrodynamics, earthquakes, etc. | Data tables, pictures, and reports |
|-----------------------|------------------------------------------|-----------------------------------|
| Monitoring data       | Waves, current                           | Data tables, vector diagrams, pictures, and reports |
| Survey data           | Multi-wave velocity, water depth measurements, engineering geological drilling and subsea sampling, CPTU, logging, geophysical profile, ROV | Data tables, vector graphics, pictures, reports, and videos |
| Test data             | Geotechnical test data and processing analysis chart | Data tables and pictures |
| Related thematic research | Relevant features (e.g., information on the sedimentary environment and stability evaluations) | Data tables, vector diagrams, pictures, and reports |

# 4.2 Construction of an engineering geological spatial database

Based on the vectorization of all the available information and data, the ArcGIS’s ArcMap platform was used to load the 3D topography of the study area as the background base map. Notably, the vectorized information and data were classified according to the different engineering geological environmental conditions through the geodatabase module. Finally, 10 sub-file databases were obtained (Figure 4-1). Furthermore, we created several data models and attribute libraries in each sub-file database as needed for the production of NGH, and established the spatial connections between each element.

1) Using multi-beam data, we created topographic and geomorphic vector raster maps of the study area. In particular, the DEM map was created based on water depth data. Through the color classification function, we prepared the basic 3D map, whose clarity depended on the number and accuracy of the raw data;
2) All the vectorized data and information were classified according to the conditions of the engineering geological environment. Using the special tools of the ArcGIS’s Catalog, we then constructed several sub-file databases, data models, and attribute libraries in the sub-file database. Furthermore, topological relationships were established between related data;
3) According to the classification of the sub-file database, all the points, lines, and areas that could be directly displayed on the ArcGIS platform were loaded into ArcMap or ArcScene and spatially linked to the corresponding non-vectorized elements (e.g., data tables, pictures, document reports, and videos). It was fundamental to establish separately the single spatial connections according to the spatial relationships and through hyperlink functions (Figure 4-3 and 4-4). First, the field of the storage path was added in the corresponding attribute table of the element. Second, the function of the supporting hyperlinks was selected in the layer of the element and the document type was selected, successfully establishing the connections. For example, the processed pictures of the geophysical profiles were linked to the field survey lines through the procedure shown in Figure 4 (4-1). Finally,
the storage, management, query, and calling of all data were realized with the support of the GIS platform and database.

![Figure 4](image)

**Figure 4** Construction of the engineering geological spatial database of the Shenhu hydrate area through the establishment of sub-file databases and the creation of spatial connections.

**4.3 Construction of the 3D model of the engineering geological environment using ArcGIS**

First, based on the processed 3D spatial data regarding the strata, we created an attribute database of virtual boreholes, which was then exported by GeoFrame. Due to the availability of only few engineering geological drilling data in the study area, it was not possible to directly construct a 3D model based solely on the stratigraphic data of the borehole. A previous division of the stratigraphic structure was mainly based on geophysical data; hence, we obtained stratigraphic data mainly from the interpretation of geophysical profiles, processed, and finally stored them in GeoFrame. Three main steps were necessary to arrive from the interpretation to the export of the spatial data: 1) The strata were interpreted and divided in the interpretation module of GeoFrame by the abovementioned methods; 2) the results of the stratigraphic division were visualized in the base map, which was then adjusted; 3) according to a designed distance in the horizontal direction and the vertical interpreted strata interfaces, the coordinates of a certain point on the survey lines (X, Y) and the corresponding elevation of each layer (Z) were exported in the data management module. In addition, the spatial information and data of particular structures (e.g., faults, buried ancient channels, bearing hydrate layer) were exported separately. Among the spatial data, the Z value was often in seconds; it needed to be converted into meters through a formula. Finally, using ArcGIS, we vectorized and imported the 3D information and data into the spatial database. According to the distance or the number of acquisition points, countless virtual boreholes can be potentially acquired to establish a special attribute database of regional stratigraphic spatial information (Figure 5).
Figure 5 Virtual boreholes exported from the key hydrate area in Shenhua by GeoFrame and location of the geophysical survey lines and section lines.

Secondly, based on the ArcGIS platform, the spatial data of the strata and relatively complex structures were used to construct a comprehensively 3D visualization model of the engineering geological environment. A mathematical interpolation algorithm was applied to perform the interpolation and spatial fitting for discrete boreholes. In this study, the Kriging interpolation method was selected to generate a regular grid and create a TIN model of each stratum interface.

For the 3D modeling of faults, buried ancient channels, the bearing hydrate layer, and other geological structures, this study only provides an example for faults and buried ancient channels because of similar method. First, we identified to what element (i.e., point, line, or area) the structural feature was close to, in order to properly display the spatial features of the structures in the 3D model. Each fault plane showed the spatial distribution of a fault, while the bottom of an ancient river showed the spatial distribution of a buried ancient channel. Second, according to the previous identification, we set the necessary parameters in GeoFrame and exported the spatial data based on the coordinates and elevation of the interfaces (or other features), which were mostly the same as those in the stratigraphic interface. Finally, based on the ArcGIS’s ArcScene module, the spatial distribution characteristics of the faults and buried ancient channels were displayed in a 3D model (Figure 6). Here are listed the specific methods and steps followed: 1) we analyzed the spatial distribution characteristics (i.e., point, line, area, and volume) of the structures and identified which ones could accurately and easily be displayed in the 3D model; then, we exported the spatial points (i.e., X, Y, and Z) with GeoFrame (all elements were composed of points); 2) we converted the discrete points into vectors (generating DEM and TIN files) by using the raster interpolation tool in the ArcGIS’s ArcToolbox with the Kriging mathematical geometry interpolation method. The interpolation range corresponded to the projection area of the structure on the seabed; 3) the ArcScene module-generated surface elements were projected on the seabed structures; then, we set the base elevation for these surface elements by loading the DEM file generated in the previous step, creating a comprehensive 3D visualization model of the geological structures on a geomorphological background map (Figure 6).
Finally, based on the strata interface model, we used the stretching tool in the ArcToolbox to stretch the stratigraphic interfaces in the vertical direction according to the thickness of the soil layer; through this process, we obtained several geological solid models. These models were then stacked together according to their spatial positions, generating a comprehensive 3D geological model. By combining the previously constructed engineering geological spatial database and structure 3D model, we finally constructed a 3D visualization model that included information and data related to the engineering geological environment in the study area. This final model was able to display geological columns, section planes, 3D geometric solids, and other engineering geological elements and data (Figure 7). The specific constructing steps were the following. 1) The TINs of the stratigraphic interfaces were
generated by vectorizing the virtual boreholes through Kriging interpolation. The TIN domain tool was used to get the coverage of the TIN, corresponding to the area of the DEM generated from the vectorization of the water depth. The TIN of each interface was located in its correct spatial position by importing the DEM file in ArcScene. 2) The extrude between function was used to stretch the space between adjacent TINs, in order to construct the geological solid model of each stratum. 3) According to their spatial positions, the solid models were superimposed and merged, creating the complete 3D stratum model of the study area.

Based on the 3D geometric model, the displayed elements, and the spatial database (e.g., soil types, physical and mechanical parameters, thickness of the strata, tendency, trend, distribution area, and volume of structures, hydrodynamic environmental characteristics), the models of the corresponding attribute data could also be constructed. Hence, the joint modeling of the geometries and internal attributes of the geological entities was done in a 3D space. Topological relationships and hyperlinks were further established to achieve spatial connections, creating a comprehensively intuitive and 3D visualization engineering geological information management system or platform.

In summary, using the ArcGIS platform, we were able to construct an engineering geological spatial database of the hydrate area in Shenhu and a 3D visualization model of the engineering geological environment. This not only provides a potential long-term service and supports the analysis and evaluation of the engineering geological environment in the hydrate area, but also provides a scientific and efficient management system or platform for an intuitive 3D visualization and for the spatial calculation and analysis of engineering geological information and data. This system or platform can be used to comprehensively and systematically get engineering environmental information and data (e.g., on the regional marine hydrodynamic environment, seabed topography, stratigraphy, soil types, structures’ distribution characteristics, results), providing a basis for engineering geological simulations, calculations, analyses, and evaluations of the reservoir and seabed stabilities for future hydrate production.

![Figure 7 3D model and spatial visualization of the engineering geological environment in the key hydrate area of Shenhu.](image)
5. Conclusion and outlook

Due to the high cost and low efficiency of drilling operations in deep waters, early engineering geological drilling boreholes in hydrate areas are mainly located near production test wells. Over the entire Shenhua hydrate area, the engineering geological drilling holes are particularly scarce; hence, they cannot provide enough information for the construction of a 3D engineering geological model of the hydrate area. In order to successfully construct such a model (practically meaningful for the future of hydrate production in the area), we used all the available engineering geological drilling data and compared them with the logging and 3D seismic data, simultaneously considering the relevant results of the sedimentary environment evolution. First, we established the engineering geological standard strata in the key hydrate area of Shenhua. Second, through the geophysical professional software GeoFrame, the 3D seismic data were systematically and finely interpreted according to the lateral extension of the seismic reflections. Afterward, we exported a large number of virtual boreholes and spatial information (i.e., X, Y, and Z coordinates) on the strata and particular geological structures (e.g., faults and buried ancient channels). This was a key step for an accurate description in the 3D space. Finally, based on multiple GIS technical modules in ArcGIS (e.g., ArcMap, ArcScene, ArcCatalog, ArcEngine) we were able to comprehensively construct the engineering geological spatial database and a 3D visualization model of the engineering geological environment in the hydrate area. Furthermore, by establishing the spatial topological relationships and connections between the elements included in the 3D model with specific data, tables, pictures, reports, and other relevant results, we eventually obtained a set of 3D visualization management platforms of the engineering geological comprehensive information and data aimed at supporting environmental surveys, evaluations, and a long-term green production of hydrate in deep waters.

The application of our research results is of great significance. In particular, the relevant technical methods and the 3D visualization management platform (which contains clickable elements linked to all related results), can be used to effectively manage, process, and analyze all the information and data of the engineering geological environment in the Shenhua hydrate area; moreover, they can be applied as basic data to support future hydrate production. Considering the lack of spatial calculations in the proposed method, in future research we will still aim at integrating the needs of hydrate production, but also embed additional mathematical models related to the calculation of the engineering geological stability and evaluation analysis in the 3D model; moreover, we will develop additional output modules containing automatic calculations and evaluation functions, so to obtain multiple outputs from a one-time input.

References

[1] Yan Shaobing, Feng Qimin, Wu Yuntao 2009. Research on spatial simulation information system of engineering geological evaluation based on GIS J. World Earthquake Engineering(4)
[2] Wei Shujing, Yuan Zhengyu 2018. exploring the application and development trend of GIS technology in the field of engineering geological evaluation J. Information recording materials19(11)
[3] TIM U S. 1995. The application of GIS in environmental health sciences: Opportunities and limitations J.Environmental Research 71(11) pp 75—88.
[4] Zheng Guoping, Yang Zhen, Zhu Hehua, Hu Zhanfei 2003. Design and Development of Geological Information System for Engineering Investigation J.Computer Application of Engineering Geology (3)
[5] Bao Shitai, Xia Bin, Jiang Peng, Fu Wensheng 2004. Design and implementation of GIS-based geological survey information system J.Geography and Geographic Information Science20(4)
[6] Li Shaojun 2005. Study on three-dimensional intelligent information system of slope safety evaluation D.Hubei: Wuhan Institute of Rock and Soil Mechanics, Chinese Academy of Sciences
[7] CARRARA A, GUZZETTI F, CARDINALI M 1999. Use of GIS technology in the prediction and monitoring of landslide hazard J. Natural Hazards (20) pp 117—135.
[8] Wang w,Wu J,Fang L, et al. 2015. Design and implementation of spatial database and geo-processing models for a road geo-hazard information management and risk assessment system. J. Environmental Earth Sciences 73(3) pp1103-17

[9] Zhu Liangfeng, Wu Xincai, Liu Xiuguo, Shang Jianga 2004. Construction of a three-dimensional stratum model based on borehole data. J. Geography and Geographic Information Science 20(3)

[10] Li Anlong, Xiao Peng, Yang Xiaodi, Luo Xiaoqiao, Lin Lin, Yang Yanxing 2016. Based on shallow profile data Construction of a three-dimensional submarine stratum model. J. Journal of Ocean University of China: Natural Science Edition 0(3)

[11] Guo Ming 2006. Application of GIS in the field of geotechnical engineering. J. West China Exploration Engineering 18(7)

[12] ZHANG Yangyang, ZHOU Wanpeng, WU Zhichun, GUO Fusheng, ZHENG Xiang 2013. The Development Status of 3D Geological Modeling Technology and Modeling Instances. J. Journal of East China Institute of Technology (3) pp403-09