Development of 3D geological model of Singapore

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ABSTRACT

In land scarce Singapore, the need for underground space development and usage has increased significantly in recent years due to more infrastructures built underground to accommodate the growing urbanisation. This leads to more competing usage and conflicts in the underground spaces. Failures that occurred in the past underground construction are associated with the lack of understanding of the underlying ground conditions and associated risks. Therefore, it is important to understand the subsurface conditions before carrying out underground space development works. In view of this, geological survey and investigation works were carried out in several parts of Singapore to study and investigate its geology, and also to identify suitable sites for underground space development. The geological survey works carried out include drilling of 170 deep boreholes and 155 km of seismic survey. These data were used to develop the Singapore-wide 3D geological model, which is able to provide a 3D visualisation of the geology of Singapore. The geological model is developed using the 3D earth modelling software GOCAD Mining Suite. In order to explore feasible area for developments of rock cavern, a 3D geotechnical hazard map has also been prepared based on lithology, rock mass quality, and distances from faults and folds. The current work proved that 3D geological model, in spite of its limitations, is very useful for interpreting and establishing the general lithostratigraphy and structure of Singapore’s geology.

Keywords: 3D geological model, geotechnical hazard, underground development

1 INTRODUCTION

To accommodate the growing urbanisation in Singapore, the need for underground space development and usage has increased significantly in recent years, e.g. common services tunnels, ammunition facility, and rock caverns for hydrocarbon storage. As more infrastructures will be built underground, the more competing usage and conflicts will arise in the underground spaces. The bedrock of Singapore is composed mainly of the Bukit Timah Granite (BT) and the Jurong Formation (JF), the former belongs to the Triassic granite, the latter comprises the Triassic to Jurassic sedimentary rocks. The Jurong Formation is folded and faulted under northeast-southwest horizontal compressive stresses in general. Failures that occurred in the past underground construction are associated with the lack of understanding of the underlying ground conditions and associated risks. Therefore, understanding of the complex subsurface conditions is important for planning underground developments.

In view of this, the Singapore Building and Construction Authority (BCA) has commissioned Kiso-Jiban Consultants (KJC) to carry out geological survey and investigation works in various parts of Singapore from 2012 to 2016, to study and investigate its geology, and also to identify suitable sites for underground space development. In addition, three-dimensional (3D) geological models were developed to provide a 3D visualisation of the geology of Singapore.

The present 3D geological models cover about 40% of Singapore Island and the total area of modelling is approximately 300 km². The several 3D models such as geological model, geotechnical engineering model and geotechnical hazard map have been developed and visualised based on available information, observations, analyses and
interpretations.

The 3D geological model can be a very useful tool for interpreting and establishing the general lithostratigraphy and structure of Singapore’s geology. The 3D geotechnical hazard map depicts the general and relative trend of geotechnical hazards for assessment of suitable area for rock cavern developments. The quality of 3D models is enhanced by quality document control, croscheck and third party review from data preparation to the final model. However, low densities of data available in certain area will jeopardise reliability and certainty of the 3D model created. This issue can be overcome by having more and deeper borehole data.

2 ORGANISATION AND RESOURCES

In 2012, BCA has commissioned KJC to carry out geological survey and investigation works, and one of the deliverables is to develop 3D geological models for the study areas, which were surveyed. These models were then reviewed by the British Geological Survey (BGS), who is the consultant engaged by BCA. In addition, BGS is tasked with delivering the nationwide 3D geological bedrock model of Singapore based on their geological observations and interpretations arising from the review of geo-survey works as part of the consultancy service. The organisation chart is presented in Fig. 1.

The geo-survey works were completed in 2017 and all the 3D geological modelling works were completed in mid-2018. The modelling team is comprised of engineering geologists and modellers. Both the geologists and modellers were trained to operate the 3D earth modelling software ‘GOCAD Mining Suite (GOCAD)’ by its developer, Mira Geoscience.

3 DATA COLLECTION

Geological survey and investigation works were carried out in several parts of Singapore as shown in Fig. 2.

The data set used for the modelling includes 170 deep boreholes, about 13,200 shallow borehole data and 155 km of seismic survey data. The depths of deep boreholes mainly range from 100 to 200 m. In addition to these deep borehole data, the existing shallow borehole data (generally 30 m to 70 m deep) from past projects conducted by both public and private sectors were used in developing the models. The seismic survey penetrated up to depths of 300 to 500 m depending on the energy source used.

4 MODELLING PRINCIPLE

The 3D geological model is developed based on all available information including the following:

a) desk study which includes existing borehole and geophysical survey data, laboratory test results, geology map of Singapore, soil profiles, regional geological records, aerial photographs
b) geological outcrop mapping data
c) discontinuity log of rock cores
d) field monitoring data, e.g. groundwater data
e) geophysical survey and borehole geophysics works
f) laboratory test results, e.g. petrographic analysis
g) 2D seismic profiles
h) digital elevation data

The Digital Elevation Model, surface geology line-work, borehole data and geological cross sections along seismic survey lines are used in modelling as constraints in the form of point and curve.

The geological model and geotechnical engineering models are prepared based on the stratigraphy classification, and geotechnical classification and Rock Mass Rating (RMR) classification respectively.

5 MODELLING WORKFLOW

Fig. 3 shows a flowchart of 3D geological modelling process. The modelling workflow is composed of 4 main steps, namely data import, preparation of modelling, surface creation and 3D model creation.
The details of each step are described below.

5.1 Data import
After conducting the desk study, the following entry data are obtained, prepared and imported into the GOCAD.

a) Digital Elevation Model (30 m mesh) and high resolution (2 m in elevation) Digital Terrain Model
b) surface geological map including geological boundaries, faults, folds, strike and dip of bedding, and shoreline
c) borehole data including SPT N-value, RQD, weathering grade, strength, joint parameters, dip data, classification, in situ test results and laboratory test results
d) geological cross sections created mainly from the interpretation of 2D seismic lines

5.2 Preparation of modelling
The model extent is defined to incorporate all the entry data and to cover 500 m in depth. The top or bottom of each geological/geotechnical unit is extracted as points from the borehole data. The curves of geological/geotechnical contact are digitised by correlating the borehole data and the surface geological map as shown in Fig. 4.

5.3 Surface creation
The fault network is established from the surface geological map and the geological cross sections to generate surfaces of fault planes. The surfaces of geological/geotechnical contact are interpolated from the points and curves created during the preparation of modelling. The GOCAD employs the Discrete Smooth Interpolation (DSI) algorithm (Lévy and Mallet, 1999) for surface creation. Where the created surfaces are mutually intersected, unwanted parts are cropped from the surfaces. Fig. 5 shows created surfaces in the 3D model.

5.4 3D model creation
Two types of 3D geological model, namely shell and solid models are created from the geological/geotechnical contact surfaces, fault plane surfaces and the area boundary surface. The cell size of solid model is defined as 15 mW x 15 mD x 10 mH. The 3D models developed based on different geological/geotechnical classifications are checked in terms of model consistency. Properties such as RQD and RMR values are assigned to the corresponding cells of solid models.

A GOCAD module of ‘Geotech’ is used to create 3D geotechnical hazard maps. The 3D geotechnical hazard map shows the distribution of Hazard Index on fence diagram surfaces.
6 CREATED 3D MODEL

Three categories of 3D models were developed, namely geological model, geotechnical engineering model, and geotechnical hazard map.

6.1 Geological model

The 3D geological model was created for each study area based on the stratigraphy classification used in the Geology of Singapore published by DSTA (2009). Fig. 7 shows the integrated 3D geological model, which provides a 3D visualisation of the distribution of lithostratigraphic units and faults. It depicts folded structures under northeast-southwest horizontal compressive stresses.

Fig. 7. Geological shell model at Areas B, E and F (red indicates BT, greenish and bluish colours indicate JF).

6.2 Geotechnical engineering model

The 3D geotechnical engineering model was created for each area according to the geotechnical classification specified by Land Transport Authority of Singapore (2010), primarily based on the weathering grade as shown in Fig. 8. The engineering rockhead is considered to correspond to the top of moderately weathered rock or better in the geotechnical engineering model.

Fig. 8. Geotechnical engineering shell model based on geotechnical classification at Area B (vertical exaggeration factor = 3x, reddish and greenish colours indicate igneous and sedimentary rocks respectively, darker colour indicates fresher rocks).

Another 3D geotechnical engineering model was created based on RMR class evaluated from RQD, strength and weathering grade of intact rocks, etc. according to Bieniawski (1989) as shown in Fig. 9.

6.3 Geotechnical hazard map

To assess the geotechnical risk to rock cavern development, the Hazard Index was computed from hazard scores based on properties of stratigraphy classification and RMR class, and distances from fault and fold of the 3D geological models as presented in Fig. 10.

A hazard score was assigned to each stratum by considering the type of rock comprising the stratum, e.g. limestone. The RMR classes were also scored in order of class. For faults and folds, they were scored depending on distances from their locations.

The distribution of the Hazard Index was visualised on fence diagram surfaces as shown in Fig. 11 to understand and explore the feasible area for developments of rock cavern. Fig. 11 illustrates that the north-eastern part has a relatively low geotechnical risk, whilst the south-western part has a higher geotechnical risk due to concentrations of faults and folds at Area B. Therefore, the north-eastern part was identified more suitable for rock cavern development.

Fig. 9. Geotechnical engineering solid model based on RMR class at Area B (vertical exaggeration factor = 3x, up to a depth of 200 m, darker colour indicates better RMR class).

Fig. 10. Geotechnical hazard index for rock cavern.

Fig. 11. Geotechnical hazard map at Area B (vertical exaggeration factor = 3x, up to 200 m depth, warmer colour indicates higher Hazard Index).
6.4 Quality control of modelling
A total of about 13,400 deep and shallow boreholes are available for the modelling. Since the quality of the borehole data is variable, the borehole data were classified into three categories based on reliability evaluated from the description in the borehole logs. The present boreholes undertaken by KJC were classified in Certainty Category of A. The existing borehole data were classified as either Certainty Category of B: reasonably reliable data or Certainty Category of C: unreliable data. Only boreholes classified in Categories A and B, about 13,300 boreholes, were incorporated in the model.

Furthermore, strength and weathering grade of rock have been determined based on British Standards in the borehole data of the past projects. To unify different classifications in the model, the strength and weathering grade were reinterpreted based on ISO 14689-1 used in the present borehole logs during the data preparation.

After visualising all available data in 3D space, position and consistency of those data were checked and optimised before correlating lithostratigraphic units.

A metadata was prepared along with the 3D model to provide information on the created model, e.g. purpose, version, date, spatial domain, coordinate system and description of objects comprising the model.

The BGS was involved in reviewing the workflow, the data set collected and KJC’s interpretation on those data including the 3D models based on BGS’s practice and anticipated geology. The third party review by BGS has provided comments on consistency and limitation in some form of QC check on the created 3D model.

7 DISCUSSION

7.1 Application of 3D geological model
Since all available information is integrated into the 3D geological model, the model can be used as a geological database of Singapore. The 3D spatial and attribute data sets enable users to find the desired information easily. The 3D geological model could be updated when new findings are gathered from additional investigation works.

The 3D visualisation of the distribution of lithostratigraphic units, fault and fold networks allows better understanding on the geology, even the geological evolution of Singapore. According to Leslie et al. (2017), the Jurong Formation has been deformed and that culminated in the development of a large scale northeast-vergent thrust system, most likely in the late Triassic to earliest Jurassic Indosinian Orogeny. The fold and thrust structures are observed in the bedrock of Singapore. The 3D geological model can help geologists with spatial thinking on the complex geology.

7.2 Application of 3D geotechnical hazard map
We attempted to present the geotechnical hazard using a semi-quantitative approach in the 3D model. Whilst the Hazard Index was computed from the hazard score of each hazard property, the scores have yet to be justified. Further studies should be undertaken to establish a quantitative approach to geotechnical hazards. After the establishment, the hazard map can be a powerful tool to identify risks to be encountered during underground construction.

Since the width of influence zone of fault and fold was estimated based on observations of borehole data and seismic interpretation, there were only a limited number of data available to be used for this estimation. Despite the limitations, the 3D geotechnical hazard map can help the user to better understand the general and relative trend of geotechnical hazards, to seek feasible area for siting rock cavern in the study area.

7.3 Limitations of 3D model
There are only about 170 deep boreholes distributed over a total area of approximately 300 km². In addition, restrictions on temporary occupation of land have reflected uneven distributions of boreholes. As a result, distances between deep boreholes vary from 0.5 to 3 km and the 3D model was created even at the region where deep borehole data are available at low densities. Although the seismic survey penetrated up to a maximum depth of 500 m, most of the deep boreholes were sunk up to 200 m in depth. Therefore, the 3D model below 200 m depth is considered having greater uncertainty. More and deeper borehole data can help to improve the reliability and certainty of the 3D model.

8 CONCLUSIONS
The 3D geological model, geotechnical engineering model and hazard map were developed for the study areas in Singapore. The aforementioned results and discussions are summarised as follows:

a) The 3D geological model can be utilised as a geological database of Singapore and it is a very useful tool for interpreting and establishing the general lithostratigraphy and structure of Singapore’s geology.

b) The 3D geotechnical hazard map depicts the general and relative trend of geotechnical hazards for an assessment of feasible area for developments of rock cavern. Further studies should be undertaken to establish a quantitative approach to geotechnical hazards.

c) The quality of 3D models is ascertained and enhanced by quality document control, crosscheck and the third party review from the data preparation to the final model.

d) Low densities of available data will affect reliability and certainty of the 3D model created. Having more and deeper borehole data can help to overcome this issue.
REFERENCES

1) Bieniawski, Z. T. (1989): Engineering rock mass classifications: a complete manual for engineers and geologists in mining, civil, and petroleum engineering, John Wiley & Sons, US.

2) Defence Science and Technology Agency (DSTA) (2009): Geology of Singapore (2nd Edition), DSTA, Singapore.

3) Hillier, M., de Kemp, E. and Schetselaar, E. (2013): 3D form line construction by structural field interpolation (SFI) of geologic strike and dip observations, *Journal of Structural Geology*, 51, 167-179.

4) International Organization for Standardization (ISO) (2003): International Standard ISO 14689-1 Geotechnical investigation and testing – Identification and classification of rock - Part 1: Identification and description (First Edition), ISO, Switzerland.

5) Land Transport Authority of Singapore (2010): Civil Design Criteria for Road and Rail Transit Systems, Singapore.

6) Leslie, A.G., Dodd, T.J.H., Gillespie, M.R., Kendall, R.S., Bide, T., Dobbs, M.R., Lee, K.W., Chaim, S.L. and Lat, K.K (2017): Mesozoic Arc Accretionary Tectonics and Dextral Strike-Slip Faulting in Singapore, *Newsletter of the Geological Society of Malaysia*, 43, 3, 229-230.

7) Lévy, B. and Mallet, J.-L. (1999): Discrete smooth interpolation: Constrained discrete fairing for arbitrary meshes, Available on www at https://www.researchgate.net/publication/228430000_Discr ete_smooth_interpolation_Constrained_discrete_fairing_for _arbitrary_meshes.