

THE DIGITAL ROCK ENGINEERING SYSTEM BASED ON 3D GIS TECHNOLOGY

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Commission IV, WG IV/8

KEY WORDS: 3D GIS, 3D Model, Rock Engineering, Subsurface, Geological Model, Underground

ABSTRACT:

This paper proposes a framework of Digital Rock Engineering (DRE) System which is based on 3D GIS technology adapted for underground development. The objective of such DRE system is to facilitate collaborative participation in underground engineering planning, feasibility study and construction management. The concept of DRE is first introduced to be followed by the design of the DRE system based on 3D GIS technology including: a) the framework of the DRE system; and b) the key technique in DRE system. Finally, this paper developed a prototype of DRE system according to the framework following these steps: a) Build an integrated relation database and file database; b) Develop a DRE system server side program named *DataManger* to manage the integrated database; c) Develop a true 3D DRE system client side program named *3DRock* to visualize, query and analyze the integrated spatial data so that it could help the users to make an informed decision during the planning phase and construction phase; and d) Developed a WebGIS application for users to view, query and analysis the borehole information using internet.

1. INTRODUCTION TO DIGITAL ROCK ENGINEERING (DRE) SYSTEM

With the fast-pace development of urban area, the demand for city space also extends from surface to subsurface rapidly. There are increasing underground projects such as underground roads and subway tunnels, sewage tunnels, civil defence shelters, underground caverns for storages and military facilities and etc. All these engineering projects require consideration on the design, the cost and site selection with respect to existing topography and its surrounding which includes aboveground and underground structures and services as well as statutory regulations and requirements. Other special considerations would include geological and hydrological conditions to prevent flooding and other environmental hazards. Developments in geographical information systems (GIS) have revolutionized the way geoscientists manage geo-data. However, most GIS in use are still in the 2D domain which is inadequate to display and analyze subsurface geological structures and hence inadequate for underground space development. To move forward, there is a need to research into 3D modelling and 3D visualization techniques for better harnessing of geological information. This paper discusses the development of a 3D GIS-based Digital Rock Engineering (DRE) System to facilitate collaborative participation in the site selection, master planning, feasibility studies and construction management for underground rock cavern construction.

2. DESIGN DIGITAL ROCK ENGINEERING SYSTEM BASED ON 3D GIS

2.1 The Framework of Digital Rock Engineering System

According to the requirements of underground development, we propose the framework of DRE System in Singapore as illustrated in Figure 1.

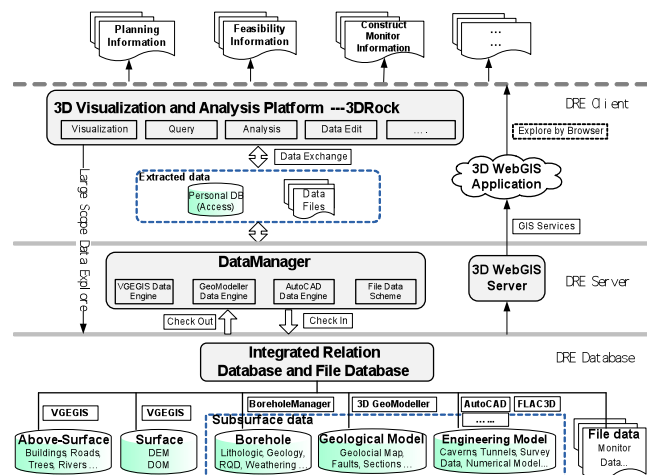


Figure 1. The Framework of Digital Rock Engineering System

In this Framework, the Digital Rock Engineering System is divided into DRE System Database, DRE System Server and DRE System Client.

1) DRE System Database

Data is the key of a system. The spatial data that 3D GIS manages include not only the surface data, but also the above-surface and subsurface features. So, the resulting DRE system is required to integrate all the above-surface, surface and subsurface data. Peng and Tor (2009) had described the integration details of the general multi-source spatial data. Based on the research, an Integrated Relation Database and File Database for DRE system in Singapore is proposed. We organize the buildings, roads, trees, rivers etc as above-surface data and use the *VEGIS* developed by the State Key Laboratory of Information Engineering in Surveying & Mapping and Remote Sensing of Wuhan University in China to build the cybercity model database. We organize the digital

elevation model (DEM) and digital orthophoto map (DOM) etc for the surface data and also use *VGEGIS* to store subsurface data. For subsurface data, it contains borehole data, geological maps, faults, sections, caverns, tunnels, survey data and numerical model etc. A software named *BoreholeManager* was developed using C# for borehole data entry and editing. *3DGeoModeller* is used to build the geological model and use *AutoCAD* to build the cavern and tunnel model and *FLAC3D* to build numerical models such as hydrological and displacement model. Monitoring data and information from other software are organized as file data.

2) DRE System Server

The DRE System Database is designed to store all underground spatial data for the whole of Singapore. Its scope is large. Considering the database security and software efficiency, we propose to develop a software named *DataManager* for the DRE System Server. The *DataManager* will be developed based on the *VGEGIS* data engine and *3DGeoModeller* data engine. In the DRE System Server, two basic data management operations called “Check Out” and “Check In” shall be implemented. The operation called “Check Out” is used to extract sub dataset from DRE System database according to the user requirement. The “Check In” operation is used in the reverse way. Some further operations, such as semantically called “Clip”, “Merge” and “Replace”, are required to complement the “Check Out” or “Check In” operations.

With the rapidly development of Web and GIS technology, what could be done in 2D WebGIS would be able to be done in 3D WebGIS platform in the future. In our DRE System, we also consider the 3D WebGIS as a part of the framework. In the DRE System, there will be a 3D WebGIS Server which could publish various GIS services such as the 3D map services, WMS, WFS, WCS and 3D analysis services. The 3D WebGIS Server could be a product of commercial company or an open source product.

3) DRE System Client

The DRE system Client provides a program called *3DRock* to fulfill various functions to aid in the planning, management, construction and monitoring construction. In this study, all the 3D visualization, query, analysis and data edit functions are outside the existing 3D tools. All of these functions are implemented in *3DRock*. It provides a series of functions on 3D visualization and application, including virtual navigation, visualization effect setting, voxel modelling and attributes assignment, animated walk through, visualization query and 3D analysis. So, through overlay and analysis of the above-surface data, surface data and subsurface data, *3DRock* could satisfy the need for the planning, feasibility study and construction management in the whole procedure of rock engineering project.

In the 3D WebGIS application, it would keep all GIS function such as the 3D navigation, overlap analysis, viewshed analysis, volumetric calculation, search by attribute, 3D vector algorithm, buffer analysis and so on. It will also create a new impression that 3D WebGIS platform is not only a viewing and flying tool but also an extremely versatile and flexibility query and 3D analysis tool.

2.2 The Key Technique in Digital Rock Engineering System

In this framework of DRE system, it refers to many key techniques. So we need to solve these technological problems.

In this paper, we paid attention to 3 problems: 1) Integrating engineering data in DRE system; 2) 3D model conversion; and 3) 3D WebGIS in DRE system.

2.2.1 Integrated Engineering data in DRE System

In this DRE System, there are many engineering data from other software and numerical analysis. Such as the cavern or tunnel displacements model generated by pressures, the hydrological model generated based on the water pressure distribution. Measured displacements of the roof and the side wall along the longitudinal axis of the caverns and tunnels ahead and behind the excavation face are very important. We obtain these deformation data through direct survey and monitoring instrument and fiber-optic (Figure 2). To integrate these deformation data into 3D GIS, we use GIS functions such as volumetric calculation to determine the various change in dimension between the compared 3D objects. If the max value of the displacement exceeds the design value, it will be dangerous for the cavern or tunnel. Volumetric calculation will also provide a good means to measure excavation rate and total volume of shotcrete or rock excavated. We also obtain the hydrological model through seepage analysis.

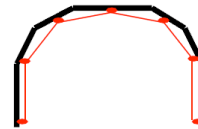


Figure 2, Cable layouts for testing on the cavern

To present these hydrological model and displacements model in DRE System, we had considered these models as volumes (CSG simple shape, cubes, cylinders, cones). A voxel (volumetric pixel) is a volume element, representing a value on a regular grid in three dimensional space. Figure 3 shows a series of voxels in a stack and a single voxel is highlighted.

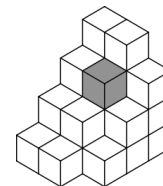


Figure 3, Voxels in a stack (<http://en.wikipedia.org/wiki/Voxel>)

Voxel could represent the concave features such as the overhangs, caves, arches, and other 3D terrain features. Polygons are able to efficiently represent simple 3D structures with lots of empty or homogeneously-filled space, while voxels are good at representing regularly-sampled spaces that are non-homogeneously filled. And voxel could be assigned properties to each volume element one by one. So we use voxel to present the engineering models.

A Geo-object in voxel representation is split into many voxels (Figure 4) and its properties are distributed through voxels. To produce a voxel representation, the 3D space is split by equal intervals along the main orthogonal coordinate axes to obtain $n_x \times n_y \times n_z$ voxels.

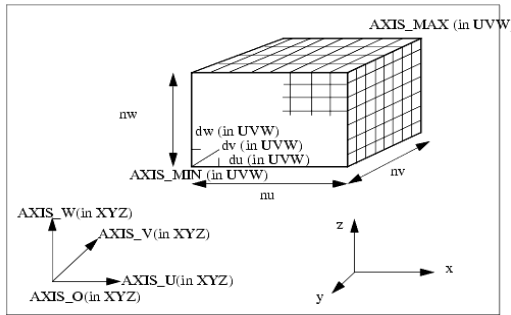


Figure 4, Voxel File geometry specifications

In this study, we have the cavern hydrological model from the seepage analysis. According to the requirements of the clients, we should represent the cavern hydrological model in DRE system. So we adopted the algorithm of *OpenCascade* (<http://www.opencascade.org>) to “voxelized” the cavern hydrological model, the different colour presents the different hydraulic conductivity (Figure 5).

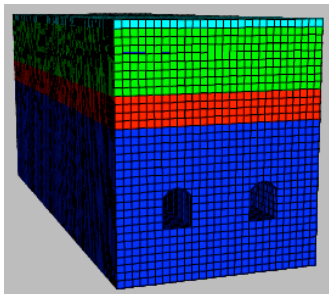


Figure 5, “Voxelized” the cavern hydrological model

2.2.2 3D Model Conversion in DRE system

In this study, we use the *3DGeoModeller* developed by Intrepid Geophysics to construct the 3D geological models from geological maps, sections, faults, boreholes, etc. The 3D geological model generated by *3DGeoModeller* takes into account not only the geology 'boundary' data (geology contacts or interfaces or limits) but also incorporates the dip of the geology formations. However, *3DGeoModeller* does not have enough capabilities to query, analysis the 3D spatial information, and it could not help human to make a decision. So we need to develop some GIS functions in the DRE system. The first step is to visualize the 3D geological models that created by *3DGeoModeller*. So we developed a function to convert the 3D geological models format to our defined format so that we could visualize them in 3D scene. Figure 6 shows the data flow that from original data to *3DGeoModeller* model then converted and visualized in *3DRock*.

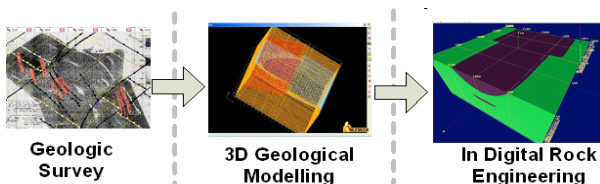


Figure 6, Data flow of 3D geological model

How to convert the *3DGeoModeller* format to our format? *3DGeoModeller* provides the function to export model in several kinds of format, and the default is to export 3D models in BRep format (Boundary Representation) and storage them in *.shp files. The BRep format is presented as ASCII file, it is a proprietary format of MATRA Datavision. This format, particularly effective for the storage of geometrical objects designed by CSG methods (Constructive Solid Geometry), and is available across the entire range of Quantum products developed by MATRA Datavision (EUCLID, etc.). In this study, we defined our data formats relative to the object classes of *3DGeoModeller*, such as *.prj file to respond to Project metadata of *3DGeoModeller*. In DRE System Client - *3DRock*, we represent the geological models as TIN models, each model was visualized as TIN. All the TIN models files are referenced in an ASCII file with extend file name “gsm”.

The 3D model conversion from *3DGeoModeller* to *3DRock* is made up by several steps as below (Figure 7):

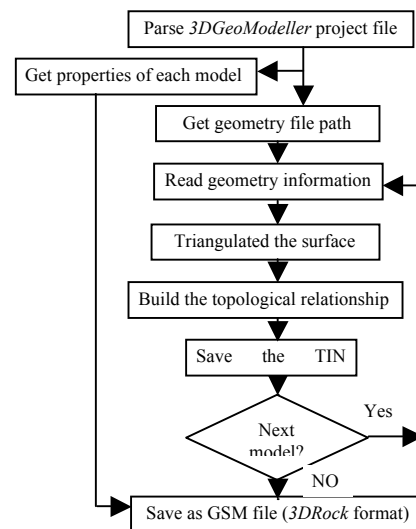


Figure 7, The flow chart of 3D model conversion

- 1) Parse the 3D GeoModeller project metadata file, for example project.xml file;
- 2) Find XML Node named “Formation”, which described the properties of each model , such as model’s name, shading color, text size, and so on;
- 3) Find the XML Node named “OutputShape3DOfFormations”. Its sub-nodes had referenced the relevant path of data files that geometry information of each model saved;
- 4) Open the data files found at step 3, read geometry information of each model, triangulated the boundary surface of geometry for TIN model;
- 5) For each model after triangulation , built the topological relationship between point ID and triangle ID;
- 6) Save the topological relationship, point ID and point’s coordinates separately;
- 7) Repeat steps 4,5 and 6 to each 3D model;
- 8) Record the file location of data file created at step 6, saved them into a “gsm” file with properties obtained at step 2 .

Through this way, now we had converted all the geological models to the DRE system. The follow pictures show the conversion result between the *3DGeoModeller* and *3DRock*:

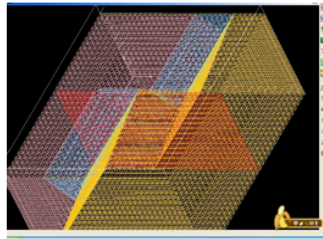


Figure 8(a), 3D models in *3DGeoModeller*

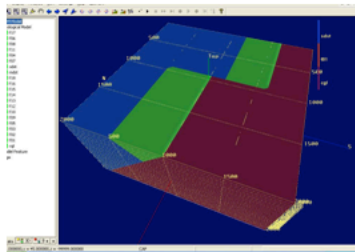


Figure 8(b), 3D models in DRE system (*3DRock*)

2.2.3 3D WebGIS in DRE System

A powerful WebGIS platform makes it easy for organizations to share mapping services and applications across the Web. With WebGIS platform, you can

- ✓ Connect more people with the information they need to make better decisions;
- ✓ Publish fast, intuitive Web mapping applications and 2D/3D/Analysis services tailored to your audience;
- ✓ Simplify access to your services, data, and imagery.

2D WebGIS is very popular and mature but not for 3D WebGIS. How to solve the challenge of large scope 3D viewing and 3D analysis in the web is currently the hot topic. OGC has published the draft specification about Web 3D Service (W3DS). W3DS is a portrayal service for three-dimensional geodata such as landscape models, city models, textured building models, vegetation objects, and street furniture. Geodata is delivered as scenes that are comprised of display elements, optimized for efficient real time rendering at high frame rates. Since the 3D WebGIS is the hot topic in GIS field, so research on this field is ongoing. In the digital rock engineering system, we will need to: a) develop a powerful 3D WebGIS server to publish the 2D/3D map services and spatial analysis services; and b) develop a powerful 3D WebGIS application so that the users could view the 3D scene and execute the GIS query and analysis functions across Web.

In this study, we had developed a 2D WebGIS application according to the users' requirements under DRE System as first step. We choose the *GeoServer* which is an open source product as WebGIS server. We use ESRI *ArcGIS Flex API* to develop our WebGIS application. The *ArcGIS Flex API* allows the creation of Rich Internet applications on top of *ArcGIS Server*.

It is based on the free Adobe Flex framework. The Flex framework is a client-side technology that is rendered by *Flash Player 9* and above, or by Adobe *AIR*. All Flex 3.x SDK versions are now supported. We already extended the *ArcGIS Flex API* so that it could access the WMS published by *GeoServer*. The architecture of WebGIS as Figure 9:

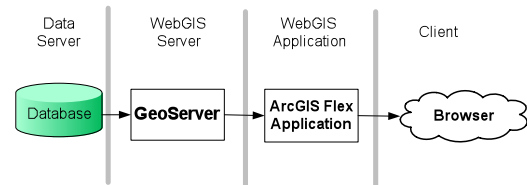


Figure 9, The architecture of WebGIS in DRE system

This web application is developed by using *GeoServer 2.0.1*, *ArcGIS Flex API 1.3*, *JDK 1.5.0.16*, *Tomcat 5.517*, *Eclipse 3.4*, *WMS specification is 1.1.1*. This web application also is integrated with Google map. In this web application, users could navigation the web map which integrated with image, borehole data, geological data. The WebGIS application provides a powerful 2D and 3D GIS functions, such as query borehole properties including pictures, create charts based on the borehole properties, viewshed analysis etc. The Figure 10 shows the query function:

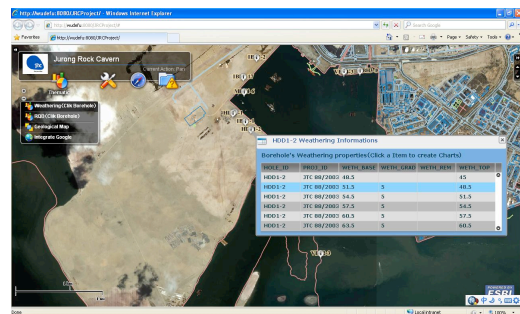


Figure 10: The query function of WebGIS in DRE system

3. APPLICATION OF DIGITAL ROCK ENGINEERING SYSTEM

According to the requirements of underground development in Singapore, we developed a prototype based on the framework of Digital Rock Engineering System. We could use the prototype of DRE System during our work according to the following workflow:

In planning stage, the planner could use the DRE System to help in the site selection work. He could first of all explore and query all the above-surface data such as land use, roads, rivers, buildings, surface data and subsurface data such as geological model, caverns, tunnels, subways etc. and execute the GIS analysis function to realize which region is the most suitable for underground construction. The sub-dataset including borehole data, tunnels, caverns, geological models of the suitable region from DRE system database could then be extracted for feasibility study. During the construction phase, the users could monitor the construction through instrumentation and real time monitoring; and also perform spatial and thematic analysis to help the users make informed decision. In advanced analysis, edited data or new data from analysis could be imported to the DRE system database. Figure 11 shows the workflow of DRE System in rock engineering project.

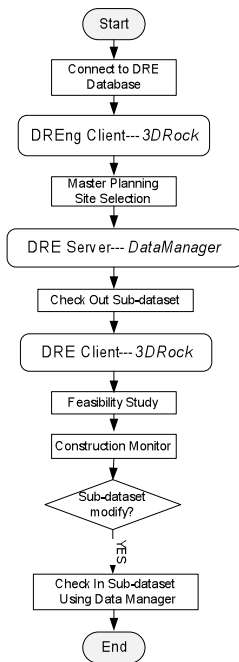


Figure 11, Workflow in DRE System

Of course, the users could use the WebGIS application in the DRE System to view and query borehole information. The WebGIS application will provide the 3D view and 3D analysis function in the future. Although the DRE system is still under developing, the prototype has been using by clients currently and will be keep on enhancing. The figures below show some functions of the prototype DRE system that totally developed by authors:

- 1) Integrated 3D geological model, engineering model and boreholes in 3DRock

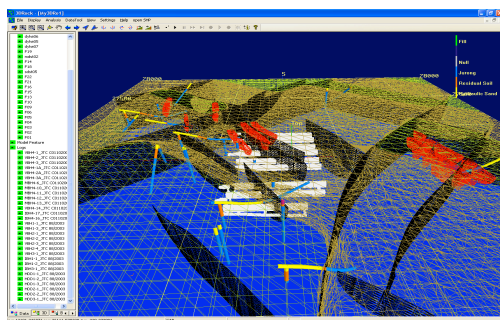


Figure 12, Visualize all the 3D models in 3DRock

- 2) Voxel model in 3DRock. Every element could be assigned attribute value.

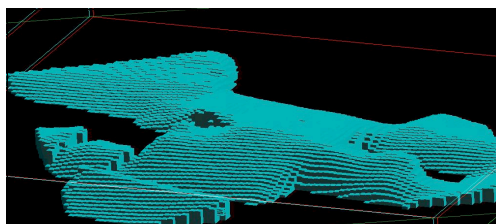


Figure 13, Voxel model in 3DRock

- 3) Analyze the borehole Hydraulic conductivity in 3DRock. Users could select any borehole in 3D scene and then get the analysis result by creating charts.

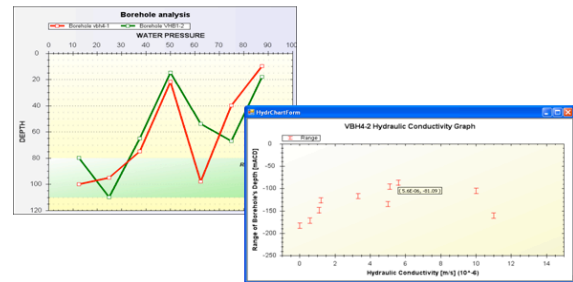


Figure 14, Analyze function in 3DRock

- 4) 3D Analysis Function on cross-sectioning in 3DRock. Users could draw a line on top of the geological model in the 3D scene to cut the geo-objects then get the cross-section result.

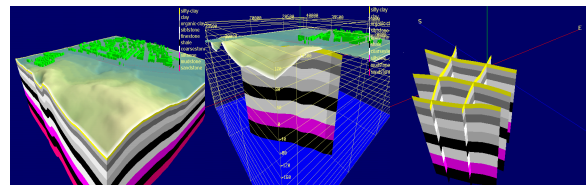


Figure 15, cross-section function in 3DRock

- 5) BoreholeManager manages the borehole database. Users could use it to keyin data and query, export data.

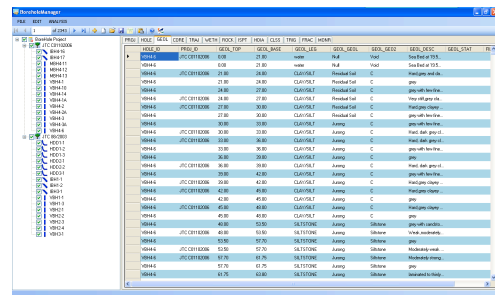


Figure 16, BoreholeManager manages borehole database

- 6) Viewshed analysis in WebGIS prototype

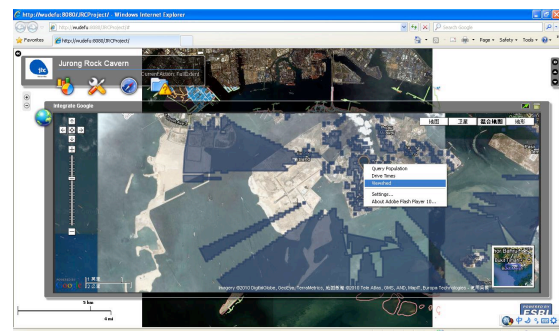


Figure 17, Viewshed analysis in WebGIS prototype

4. CONCLUSIONS AND RECOMMENDATIONS

Aimed at satisfying the requirements of the underground engineering planning, feasibility study and construction monitoring, this paper proposed a framework of Digital Rock Engineering (DRE) System based on 3D GIS technology for underground development. The authors discussed the key techniques in Digital Rock Engineering System which focus on: 1) How to integrated engineering data in DRE System; 2) How to convert 3D models in DRE System; and 3) 3D WebGIS in DRE System. Finally, the authors developed a prototype of the DRE System according to the proposed framework. In the prototype of DRE system, an integrated relational database and file database was developed; a DRE system server program called *DataManger* will help to manage the integrated database; a true 3D DRE system client program called *3DRock* was developed which could be used to visualize, query and analysis the integrated spatial data so that it could help the users to make informed decision during the planning and construction phases; a WebGIS application was developed for more users to view, query and analysis the borehole information across web.

One of the main challenges facing the development of the DRE system lies in adapting 3D GIS in underground engineering applications. For example, how to optimum the dynamic 3D visualisation of the voxel model in large scope and how to propagate optimally the assigned or predicted attributes to each voxel element. The 3D WebGIS is one of the trends in GIS field. How to solve the large scope 3D view and 3D analysis across web is the hot topic currently. All these requirements should be considered to enhance the prototype.

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