

Decision support system for tunneling construction: Abu Dhabi case study

Muna Al kaabi¹, Ana Costa², Rita L Sousa³ and Herbert Einstein⁴

Masdar Institute of Science and Technology

PO Box 54224, Masdar City, Abu Dhabi, United Arab Emirates

¹mralkaabi@masdar.ac.ae

²acosta@masdar.ac.ae

³rsousa@masdar.ac.ae

⁴einstein@mit.edu

Abstract:

An extensive network of urban and transportation systems is planned within the Abu Dhabi 2030 master plan. This includes planning, implementing and operating underground infrastructure for which it is extremely important to consider the uncertainties, and the inherent risks, affecting them. The research presented here intends to account for natural geological uncertainties affecting underground infrastructure within the Abu Dhabi context through an integrated approach. The study of subsurface information, in areas for which future underground transportation is planned, identified the presence of gypsum within the tertiary bedrock that may be problematic due to its susceptibility to volume change by dissolution or swelling.

The paper discusses how an existing a decision support system (Decision Aids for Tunneling, see eg. Einstein, 2004) considers geology- and construction related uncertainties, and then produce cost-, time- and resource distributions. This in turn will serve as a basis for risk analysis and decision making regarding a variety of hazards including gypsum dissolution in Abu Dhabi. Very importantly and as shown, such a comprehensive tool will be integrated with existing optimization tools for transport infrastructure planning (Costa et al., 2013) that relate the planning decisions and the infrastructure layout with the infrastructure performance.

1. Introduction

Abu Dhabi is predicting a significant growth in population over the next 20 years [1]; further, it seeks to become an international destination for tourists, businesses, and investment while protecting its cultural heritage. A crucial aspect of achieving this goal is the development of an integrated transportation system to ensure Abu Dhabi becomes a sustainable city on a global scale. These plans are outlined in the Vision 2030 recently published by the Government of Abu Dhabi, a comprehensive master plan for the development of the Emirate. The Abu Dhabi Transport Master Plan 2030 will enable the

development of a world-leading transport system to support the government's broader strategies in the Abu Dhabi Vision 2030. Until recently the main means of transportation have been private cars or taxis with a recent opening of several bus lines within the city and extending outside the city. The ambitious vision of the Master Plan includes a multi-billion dollars integrated network of highways, high speed regional rail, a metro system and a light rail tram system with a complementary system of buses, taxis and park & ride facilities [2].

A well-conceived transportation system starts at the planning stage, and includes a complete study of the planning, construction, and operation phases. To optimize the transportation system, it must be studied as an entire system.

This paper presents preliminary results of the cooperative research program between Masdar Institute and MIT. The work focuses on studying the effect of geological and environmental uncertainties on transportation systems and on the ongoing development of an integrated decision support system for transport infrastructure, with the ultimate goal of contributing to the development and establishment of the sustainable and efficient integrated world leading transport system for Abu-Dhabi.

2. Abu Dhabi Geology

The Emirate of Abu Dhabi is located on the eastern part of the Arabian Peninsula between latitudes of 22°40' to 25°00' N and longitudes from 51°00' to 56°00' E. Among the seven United Arab Emirates, the Abu Dhabi emirate is the largest occupying more than 85% of total land area, consisting of 67340 km² of land, 700 km of coastline, 200 islands [3, 4]. The Arabian Peninsula consists mainly of a sedimentary deposits known as Arabian Shelf, overlying Precambrian metamorphic and igneous basement rocks. In the Abu Dhabi region the sedimentary sequence consists of an accumulation of Paleozoic through Cenozoic carbonates and evaporites with interbedded clastic horizons reaching a thickness of nearly 8,000 m. On top of this sequence one can find extensive Holocene Aeolian deposits that form the Rub' al Khali sand dunes and localized Sabkha sequences [5, 6]. Table 1, shows the generalized stratigraphic units in the coastal islands (e.g. Abu Dhabi Island) over the different geological ages. Table 2 shows the generalized stratigraphic units in the coastal Sabkha region (for Shakhbout City, Mohammad Bin Zayed).

Table1: Generalized stratigraphic units of in the coastal islands [3]:

Geological Age	Approximate Elevation Range (m) (NADD)	Average Thickness Range (m)	Stratigraphic Unit	Common Lithologies
Holocene	+10 to -5	0 to 10	Made Ground	Silty sand with gravel and bioclasts
	0 to -5	2 to 5	Rub' al Khali Formation	Aeolian sand and silty sand
	+5 to -10	3 to 10	Abu Dhabi Formation	Calcareous silty sand with some gravel and bioclasts, clay and silt layers, and lenses
Pleistocene	-3 to -13	5 to 10	Saadiyat Formation	Marine limestone and calcarenite
	0 to -15	5 to 10 m	Ghayathi Formation	Calcareous silty sand or sandstone/calcarenite
Miocene	-10 to > -100	>100	Gachsaran Formation	Interbedded mudstone, siltstone, and gypsum

Table 2: Generalized stratigraphic units of costal Sabkha [3]:

Geological Age	Approximate Elevation Range (m) (NADD)	Average Thickness Range (m)	Stratigraphic Unit	Common Lithologies
Holocene	+5 to 0	< 1 to 4	Made Ground	Silty sand with gravel and bioclasts
	+3 to -8	3 to 10	Abu Dhabi Formation	Calcareous silty sand with some gravel and bioclasts, clay and silt layers, and lenses
Pleistocene	-5 to -10	0 to 3	Ghayathi Formation	Calcareous silty sand or sandstone/calcarenite
Miocene	-10 to > -100	>100	Gachsaran Formation	Interbedded mudstone, siltstone, and gypsum

3. Zayed City Study Area

Zayed city is located in the western region of Abu Dhabi with an area of 45 km² as shown in Figure1. The city will hold the Capital District project, a major development of the Abu Dhabi plan 2030. Additionally, this strategic location is bound by two major highways, the E20 and the E22. Subsurface conditions, however, are prone to gypsum dissolution hazards [7].



Fig. 1: Zayed City location

3.1 Geology

The west side of Zayed city consists of outcrops of white, silty and shelly limestone [3]. Limited descriptions of the geology underlying Zayed city are available in the literature. Analysis of data provided by the Municipality of Abu Dhabi City, which will be detailed in the next section, shows a sequence of sand, silt-clay, siltstone, gypsum, calcarenite, claystone, clay, sandstone, mudstone and limestone. The city shows approximately the same stratigraphic units as its neighbor cities, Mohammed bin Zayed city and Shakhbout City, as shown in Table 2. These are the coastal sediments of the Abu Dhabi Formation that lie directly over the Gachsaran Formation (Interbedded mudstone, siltstone, and gypsum). In addition, thin layers of the Ghayathi Formation (Calcareous

silty sand or sandstone/calcarenite) between the Abu Dhabi and Gachsaran formations are also present. A variable thickness (1-5m) of manmade fill has been placed over the costal sediments [3].

3.2 Borehole Data

For the purpose of the current study, 453 borehole logs data provided by the Spatial Data Division of the Municipality of Abu Dhabi City were used. The data cover Zayed City, as shown in figure 2. The depth of the boreholes ranges between 10 to around 20 m. The geological layers are sequences of sand, silt-clay, siltstone, gypsum, calcarenite, claystone, clay, sandstone, mudstone and limestone. Gypsum layers are found at different depths, near the surface or deeper at 20m, and they are mostly associated with the occurrence of mudstone. The gypsum layers range in thickness from a few meters up to about 7 m. According to the collected data, the gypsum layers are found to be located always below the water table level which increases their susceptibility to karst related problems.

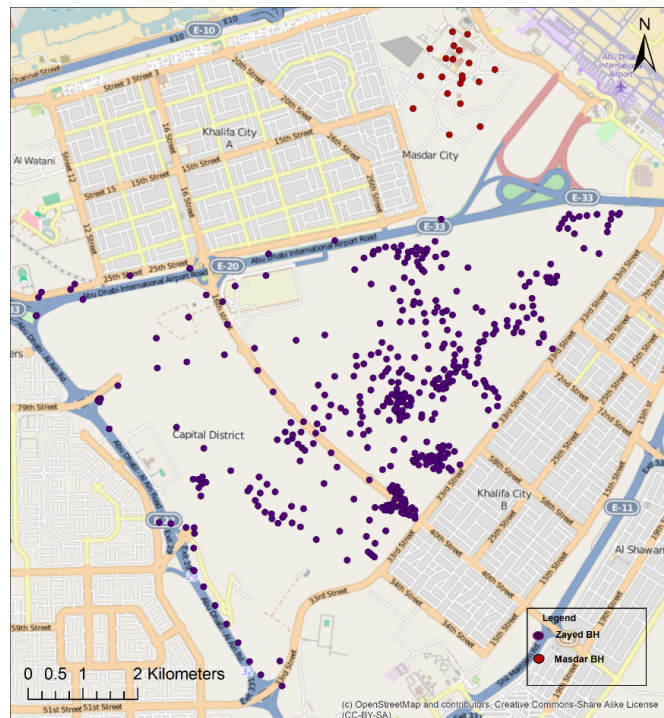


Fig. 2: All borehole logs data from Zayed city

3.2.1 Data pre-processing

A 3D geological model was developed using the ArcGIS software in combination with the GMS software from Aquaveo. GMS is a software platform

used to create groundwater and subsurface simulations in a 3D environment, based on the research by [8]. In this method the different geological layers are defined and assigned a specific number. A Horizon ID will be assigned to the contact points between geologies in boreholes. Horizons, which correspond to the top surface of each stratigraphic unit, are obtained by interpolation of the Horizon IDs [8].

Once the data are pre-processed GMS and ArcGIS are used to build and visualize a 3D geological model and geological structures. ArcGIS has extensive capabilities in assisting field data collection, creating high-quality maps, providing 3D visualization of geological features such as karst caves, efficient storage and data management [9].

3.3 Preliminary 3D Geological Model

A preliminary 3D geological model was conducted based on 27 boreholes logs in Zayed city, chosen along the planned metro line as shown in Figure 3. This was done to assess the capabilities of the software and decision support for future planning. The data set was pre-processed as mentioned in the section 3.2.1 and the resulting 3D model is presented in Figure 4.

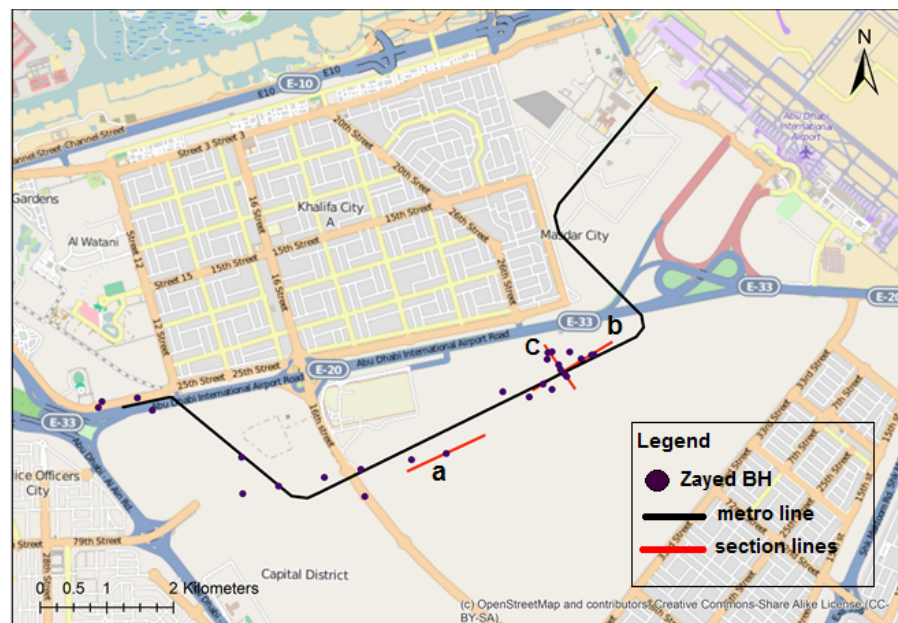


Fig. 3: 27 boreholes logs were chosen in around Zayed city

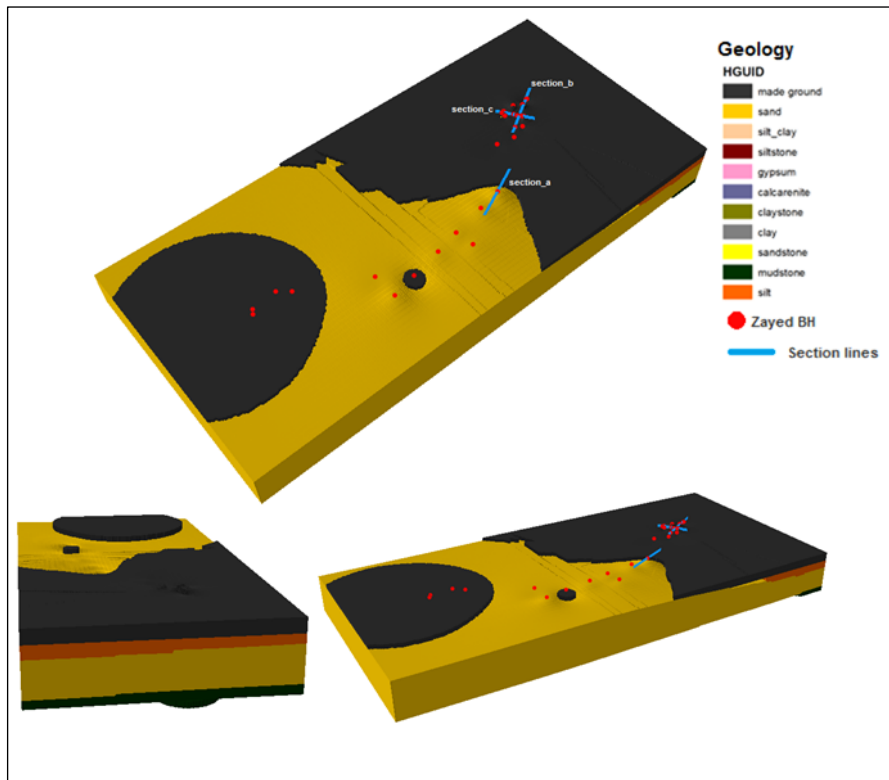


Fig. 4: Preliminary 3D model for the chosen area including 27 borehole logs and 3 cross sections (a, b and c).

Cross sections were obtained along the planned Metro line to obtain a better idea of the geological sequence along the line. Cross section (b), in Figure 5, shows that gypsum layers are interbedded with mudstone layers, which compares well with existing geological studies in the neighboring areas as shown in table 1 and 2.

The remaining boreholes are right now in a pre-processing stage and more comprehensive studies will be developed in the future.

4 Decision Support Systems

4.1 Decision Aids for Tunneling

The Decision Aids for Tunneling (DAT) are an interactive tool that allow one to simulate tunnel construction and determine cost and times of construction including uncertainties associated with geology and construction. The DAT has been developed over the years at MIT, in collaboration with the Ecole

Polytechnique Federale de Lausanne, and they have been applied to a large number of cases [11].

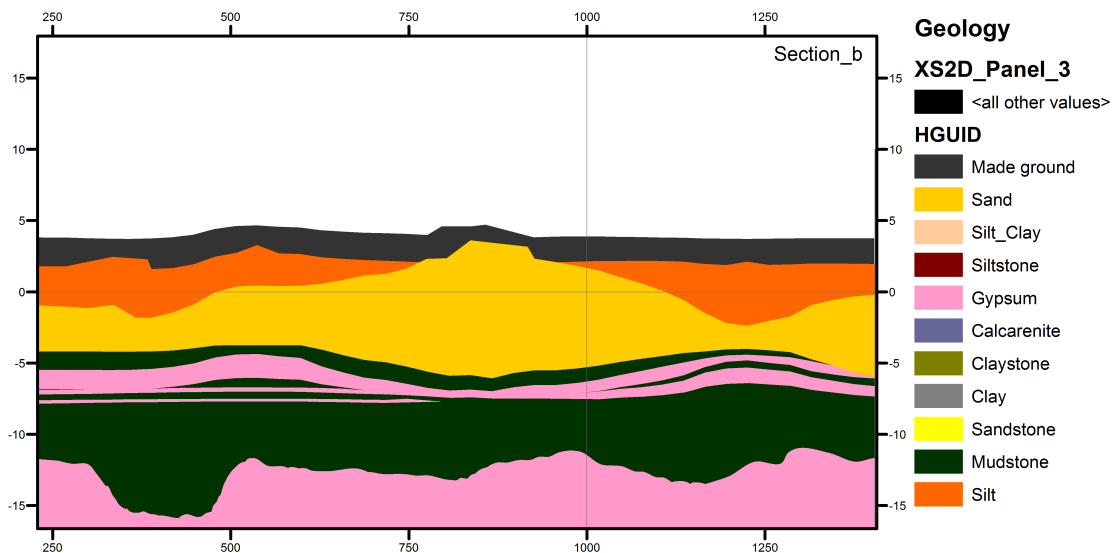
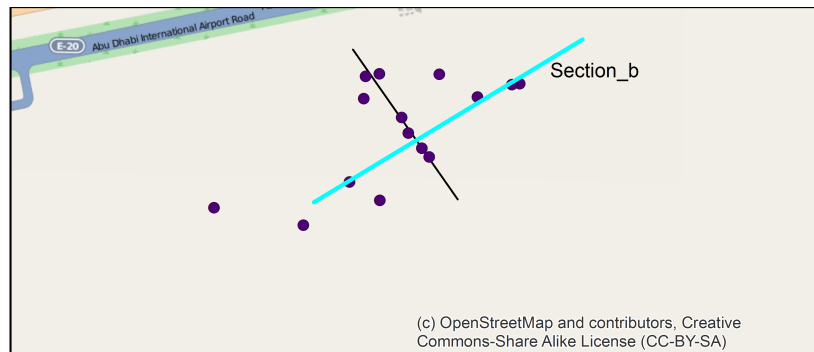


Fig. 5: Cross Section_b

The DAT consist of three major components:

1. Geology Description
2. Construction Simulation and Construction (Resource) Management
3. Updating

The Geology description module produces geological and geotechnical profiles along the tunnel, in which the input is based on geotechnical survey data and information given by geologists. The generated profiles reflect the probability of

particular geological conditions occurring in certain locations of the tunnel. These probabilities are obtained through a combination of objective information and subjective estimates by experts.

The construction Module simulates the construction process through the generated geological profiles, which involves relating the geological conditions along the tunnel profile to tunneling methods. The construction process can be described as detailed as a user desires, ranging from simply producing advance rates and linear costs for each construction method to describing all activities (drilling, loading, blasting, etc.). Costs and time uncertainties can be considered for each construction method.

The Monte Carlo Method is used to simulate the construction process. First the probabilistic geological profiles are generated, then for each generated profile the construction is simulated cycle by cycle. Figure 6 shows a typical output from the DAT. Resource modelling, considering uncertainties, is also available.

Once tunnel construction starts, new information regarding the geological conditions and construction cost and time is obtained. Predictions for the remainder of the “unexcavated” tunnel can and should be refined based on those observations. A formal procure to do such updating has been incorporated in the DAT [12].

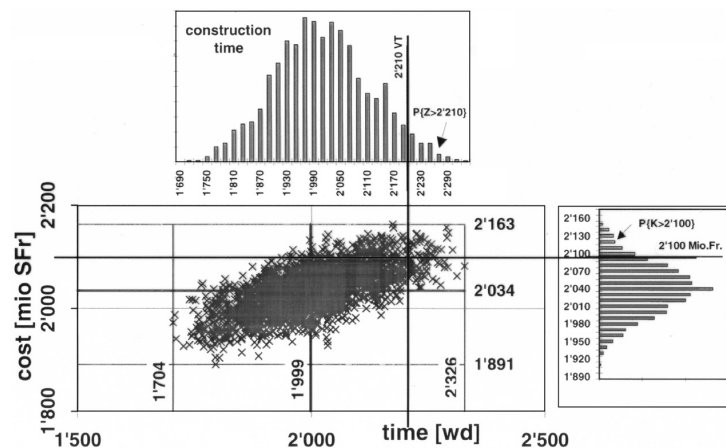


Fig. 6: An Example of Time-Cost Scattergram produced by the DAT [13]

4.2 Tools for the Optimization of a Linear Transport Infrastructure

Decision support systems for the planning of robust high-speed rail (HSR) systems considering the effects of natural hazards exist and have been applied to real transportation problems [14], specifically the planning of a HSR line. A complex relation exists between the constraints of the HSR design and the multiple HSR configurations, both in terms of 3D layout and the cross-

sections that may be used. Given that the quality of the HSR performance depends on the 3D layout, the deployment site and the cross-sections used. It is extremely complex to determine the HSR configuration yielding the most value.

Costa [15] developed an integrated approach that is capable of dealing with large datasets of real problems and systematically considers all factors influencing HSR decision-making. Mathematical optimization models have been developed that consider the construction costs, the alignment geometry, the connection of intermediate locations and land-use concerns and natural hazards. Heuristics are used to test different infrastructure configurations and solve optimization models, finding the optimal solution.

This decision support system has been applied to the present case considering the gypsum seam hazard and the impacts on built transport infrastructure. Specifically, once gypsum dissolution is modeled for the conditions present in the Abu Dhabi subsurface, and based on the identification of the location of gypsum seams, hazard maps can be produced that form the basis for the scenario definition. The decision support system then assess the impact on the transport infrastructure based on its vulnerability to the gypsum dissolution hazards. With the definition of scenarios and the characterization of the infrastructure specifics, multiple hazards can be combined to attain a robust infrastructure. Optimization methods are used to obtain the best infrastructure configuration.

4.3 Integrating the DAT with the optimization tools

As discussed, the DAT have extensive capabilities in considering geology- and construction related uncertainties. For a specific infrastructure configuration, they are then able to produce cost-, time- and resource distributions. These are fundamental for risk analyses and decision making regarding a variety of hazards including gypsum dissolution in Abu Dhabi. Extending the capabilities of the DAT, it is integrated with the existing optimization of linear transport infrastructure [15]. The optimization tool searches for possible layouts (Figure 7). These are analyzed with the DAT, and the results of the analyses are fed back to the optimization tool for evaluation of the solution's value. Such an integrated approach couples the capabilities of DAT with a tool that is able to search and find optimal configurations for real problems combining the infrastructure layout with the infrastructure performance.

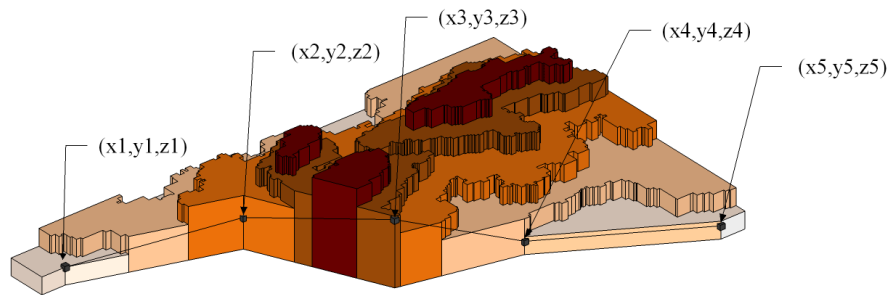


Fig. 7: Searching for optimal solutions

5. Concluding remarks

The preliminary studies discussed in this paper allowed us to assess and demonstrate the capabilities of two decisions support tools, as well getting an initial idea of the geology along the planned metro line. The preliminary geologic study is used as a base case for the development of a comprehensive integrated tool. In parallel a more a detailed geological model is being developed considering the remaining borehole data and other geological data. Once completed it will serve as input to one of the major DAT components (geological description). Along with information on the planned tunneling methods, cost and time distributions can be determined with the DAT. This in turn will be used to compare alignments, and constructions strategies in order to optimize the tunnel system configuration (layout, alignments, and construction strategies) through the integrated decision tool.

Acknowledgments

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