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City-Scale Modeling of San Francisco Bay Area Underground for Community-Scale Application of Geothermal Energy

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ABSTRACT

Geothermal energy is being used as a sustainable alternative to conventional fossil fuels. An efficient utilization of geothermal sources requires a thorough understanding of subsurface conditions and their interaction with above-surface activities. Determination of uneven variation of temperature in the underground will help to efficiently utilize the non-homogenous heat distribution, which can be considered as having the same consequences of an urban underground heat island. In addition to providing benefits in the efficient usage of geothermal energy, determining the distribution of underground temperature will also help with sustainable development efforts for future subsurface spaces regarding efficient heating and cooling performance. In this study, an underground 3D model of a specific region to determine possible vertical integration schemes of different geothermal energy systems is established. The development of underground maps of San Francisco Bay Area's Treasure Island neighborhood will be carried out based on the 3D model. In order to create a first-of-its-kind 3D subsurface model, subsurface geology, air temperature and groundwater maps combined with data regarding subsurface built-in environment was collected through published reports, governmental agencies and private companies. A coupled hydrothermal model will be developed using COMSOL finite element software to analyze the phenomena of simultaneous heat extraction and heat injection. The finite element model will involve the hydrothermal properties of the underground as well as information related to geological units and ground elevation. This work will lead to the development of a high-performance computing scheme for city-scale modeling in order to understand the impact of excess subsurface heat at the community scale.

1. INTRODUCTION

The vision of community-scale geothermal energy technologies is for communities to make optimal use of their subsurface in order to provide the community multiple sustainable energy and community resilience benefits. Development of a city-scale model of Treasure Island located in the San Francisco Bay Area is expected to be the starting point of understanding how above-ground activities impact the shallow temperature distribution underneath a developed community and how this shallow system can be utilized with Ground Source Heat Pump technologies. The modeling work includes combining the cross-sectional views of Treasure Island subsurface through a detailed analysis of geotechnical engineering reports that have been prepared for real estate development projects. Modeling the San Francisco Bay Area in a city-scale size will also aid in the assessment of the impact of the built environment on the shallow subsurface by evaluating how subsurface conditions couple to above-ground natural and human activities, and looking at how excess subsurface heat at the community scale could impact the development of a fully vertically integrated subsurface utilization strategy that includes geothermal district heating and cooling systems.

Uneven spatial distribution of excess heat in the subsurface can be viewed analogous to that of the urban heat island effect. The combined effect of the urban heat island and underground heat island has enhanced the subsurface temperature in many areas by several degrees (e. g., Bidarmaghz et al., 2020). With correct planning, this excess and unevenly distributed heat energy can be harnessed beneficially through the application of shallow geothermal energy systems with ground source heat pumps (e.g., Zhang et al., 2014; see Figure 1). If the current spatial-temporal variability of ground temperatures is known and future changes can be predicted, it would enable sustainable and resilient planning of underground activities in developed communities for both short and long-term.

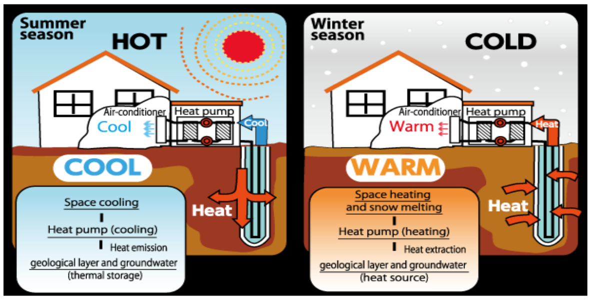


Figure 1: Concept of shallow geothermal energy application

In this study, an underground 3D model of Treasure Island is created to evaluate possible heat exchange schemes of different geothermal energy systems. The finite-element based software COMSOL is used for generating the 3D model by combining the two-dimensional cross-sectional views of the project site. The cross-section profiles are obtained from the Treasure Island Stages 2 and 3 Infrastructure Improvements held by ENGEO Inc. The hydrothermal properties of soils in the three-dimensional model are from a literature review, which includes the thermal conductivity, heat capacity and hydraulic conductivity. The modeled three-dimensional model will form the basis for the high-performance computing (HPC)-based city-scale simulation of the San Francisco Bay Area.

2. DESCRIPTION OF TREASURE ISLAND

Treasure Island is a man-made artificial island which was constructed in 1936-1937 by hydraulic filling behind a perimeter dike. Being initially planned to host the 1939 Golden Gate International Exposition and then serve as an airport for Pan American Airline's Pacific Rim flying boat service, it became part of the Treasure Island Naval Base during WWII. In 1996, Treasure Island was decommissioned by the Navy and has been opened for public use and development. Today, it is a part of District 6 of the City and County of San Francisco.

Lee and Praszker (1969) describe that the Treasure Island fill was placed upon Yerba Buena Shoals with a shallow water area of in excess of 735 acres. In the direction of the northwest point of Yerba Buena Island, a small portion of the fill area was a sand spit. The above-water area of the fill is about 400 acres, with a width of 3410 feet and a length of 5520 feet. Fill used for construction of Treasure Island was composed of 65% (by volume) fine to coarse loose sand and 35% soft mud. Lee and Praszker (1969) state a noteworthy incident during the construction of the island as follows: Following the completion of the east sea wall, a section of 500 feet long suddenly settled 10 to 14 feet and disappeared from sight. As a precaution, construction plans were modified by flattening the side slopes of the wall and depositing a mattress of heavy sand on the bottom beyond the toe of the slope to act as a counterweight and prevent the underlying plastic mud from heaving and thus resulting in additional settlement in the fill.

Andrus et al. (1998) used spectral analysis of the surface waves method for profiling the south-eastern corner of the island, which is also called an Improved Soil Area. Recorded shear wave velocities are presented for the first 20 meters, which is shallow for community-scale geothermal project considerations. The authors observed that the first 12 meters of Treasure Island fill is sand, with samples above a depth of 6 m contain as much as 17 % fines. Beneath the sand fill, 3 meters of native silty clayey sand followed by 27 meters of soft to stiff clay with interbedded sand layers have been recorded. Sandstone and shale bedrock are reported to occur at a depth of 87 meters, while the water table was about 2 meters below the ground surface.

Baise et al. (2003) installed a deep instrumentation array through the soil to the bedrock for Treasure Island in order to collect information on site response. The soil profile presented in this study is consistent with the results from Andrus et al. (1998). One upside of this study is presentation of shear wave velocities up to 110 meters from the ground surface. According to this soil profile, the first 12 meters is composed of artificial fill, which overlies up to 40 meters Holocene Bay sediments. Between depths of 40 meters and 90 meters, Pleistocene Bay sediments were recorded. The same study concludes that Franciscan bedrock is reached at depth around 90 meters.

One of the most comprehensive soil profiling studies for Treasure Island is presented in Power et al. (1998). Soil profiles are provided for depths varying between 70 and 100 meters. Comprehensive soil profile cross sections are provided both for the transverse and longitudinal directions of Treasure Island. While the underground profile data is consistent with the other studies for Treasure Island, Power et al. (1998) also include the Standard Penetration Test (SPT) data up to depths of 60 feet.

3. MODEL GEOMETRY AND SOIL PROPERTIES

The three-dimensional model of the Treasure Island considers the southern part of the island as shown in Figure 2. The dimensions of the model are 300 m in length and 600 m in width.

Figure 2: Surface area of three-dimensional Treasure Island model

The finite element method-based software COMSOL is used for modeling the three-dimensional representation of Treasure Island. The modeling stage started with obtaining two-dimensional cross-sections of the study area from ENGEO Inc. In Figure 3, locations of all of the available cross-section views are presented. From all of the available options, sections T6-1 and T6-2 (see Figure 4) are selected because they are considered as adequate for representing the desired part of the island where the future real estate developments are expected to occur.

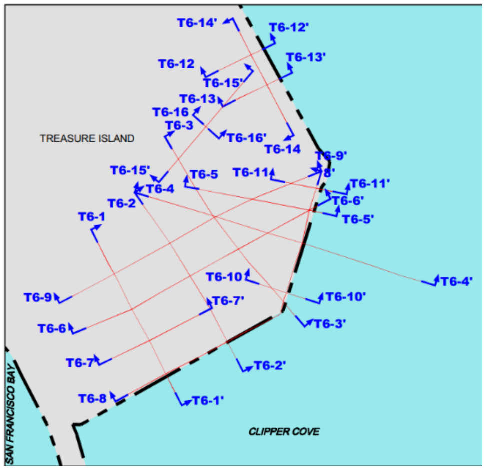
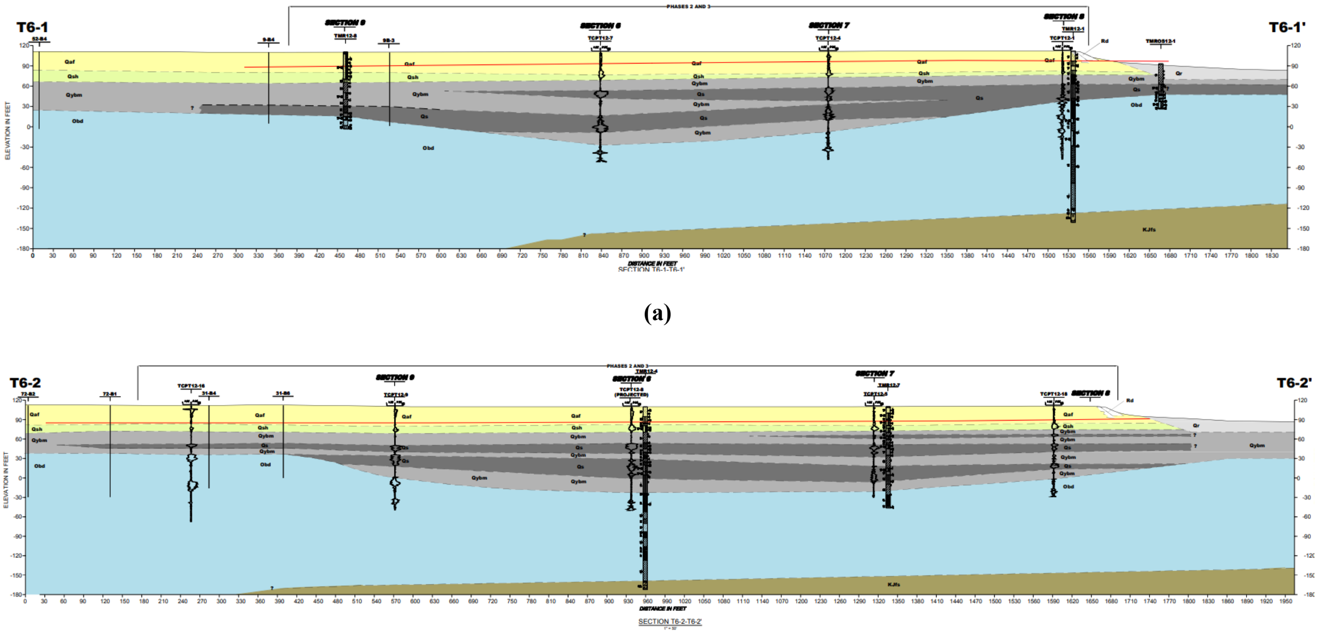


Figure 3: Section location plan for cross-section views (ENGEO Inc., 2019)



(a)

(b)

Figure 4: Cross sectional profiles of sections T6-1 and T6-2. Note that the elevation datum applied to the cross sections is the North American Vertical Datum of 1988 (NAVD88) plus 100 feet.

For simplifying the establishment of the complicated community-scale FE model, some formations with similar soil properties are combined and five layers are obtained. Digitization of the selected cross-section views started by selecting the side of island neighboring `Clipper Cove` as the base. After an exhaustive stage of digitization, coordinate points are imported to COMSOL in order to create solid volumes from them. As the final product, the three-dimensional view in Figure 5 is generated using COMSOL.

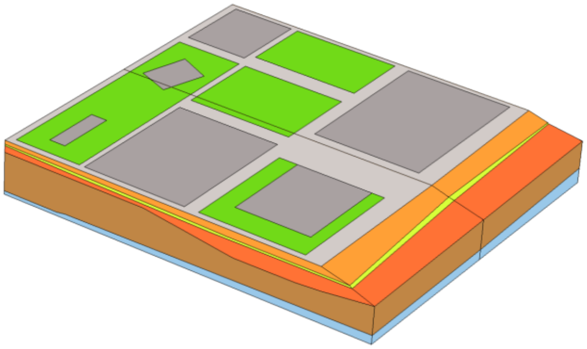


Figure 5: Three-dimensional model of Treasure Island

In Figure 5, the color grey at the ground represents the footprint of buildings. In the same figure, the color green represents grassy areas where no buildings are currently located. The ground surface of the three-dimensional model needs to be updated in the future depending on the new proposals for the real estate development on the island.

For the underground geology, starting from the ground, the color orange represents the hydraulic fill that was placed during the initial construction of the island. Beneath the hydraulically placed fill, a thin layer of sand-shoal deposits is observed, which is represented with color green. Young Bay mud lies beneath the sand-shoal deposits and it is colored with red. Old bay deposits, which are mainly composed of clay, are overlain by the Young Bay mud. At the bottom of the underground profile, the Franciscan rock formation is denoted by the color blue. Depending on the location, the Franciscan rock formation is observed at a depth of 70-80 m beneath the ground surface throughout the island.

Running the developed three-dimensional model requires the input of hydrothermal properties of the corresponding soil types. Thermal properties for the soil types observed in Treasure Island has not been extensively studied and hence, values in literature for this location were not found. It is expected that the geotechnical consulting partner will run tests on the soil samples collected from the island in order to calculate the hydrothermal properties.

In order to assign the hydrothermal properties of soils in the three-dimensional model, a literature review has been performed to assign representative values for similar materials. The soil descriptions provided by ENGEO Inc. (2019) are used as the benchmark for obtaining the hydrothermal properties of similar soils.

Young bay deposits are described as medium-stiff fat to lean, normally consolidated clays with interbedded lenses of silty and clayey sand. Britto et al. (1989) used a similar clay for their study on numerical and centrifuge modelling of coupled heat flow and consolidation around hot cylinders buried in clay. Hence, thermal properties for Young Bay mud are referenced from this study. Nguyen's (2006) study on Bay Mud is utilized for adopting the hydraulic conductivity value of both Young Bay mud and Old Bay deposits.

ENGEO Inc. (2019) describes the old bay deposits as interbedded stiff to hard, low to bluish-gray to greenish-gray high plasticity clays, dense to hard fine silty and clayey sands. Misra et al. (1995) developed a theoretical model for predicting the thermal conductivity of an ideal soil mainly based on the degree of saturation of the soil, which is taken as the reference study for the thermal conductivity value evaluation for old bay deposits. The Old Bay deposit's heat capacity value is taken from Goto et al. (2017), which focused on the thermal properties of mud-dominant marine sediments that share a similar classification with the Old Bay deposits.

The shoal deposits on the island are classified as silty to clayey sand (ENGEO Inc., 2019). For those sand deposits encountered on the island, Misra et al.'s (1995) study is also taken as the reference for calculating the thermal conductivity value through the use of proposed empirical relationships. Heat capacity for sand is obtained from Russo and Civita's (2009) work involving clayey sand in the development of open-loop groundwater heat pumps for large buildings. For the hydraulic conductivity of sandy shoal deposits, values from Phillips' (1993) study on the groundwater in San Francisco is adopted.

The Franciscan Formation bedrock encountered in deep borings across the Island consists of dense, weathered dark gray sandstone and shale. For that formation, thermal properties are interpolated from Maqsood and Kamran (2004) using the thermophysical properties of porous sandstones. Due to the assumption of a specific porosity, further site and laboratory testing is required for getting an accurate state representation of the Franciscan Formation. Konakova (2013)'s dataset for thermal properties of various sandstones is adopted for the heat capacity value of Franciscan Formation. Pokar et al. (2008) gives a range for the hydraulic conductivity of sandstones in which the average of those values is adopted in the three-dimensional model.

The hydrothermal properties gathered from the literature are summarized in Table 1.

Table 1: Model parameters

Type	Thermal Conductivity	Heat Capacity	Hydraulic Conductivity
Young Bay Mud	1.5 W/mK	3.3×10^6 J/m^{3}K	1.45×10^{-4}m/day(vertical)
Old Bay Deposits	1.7 W/mK	3.5×10^6 J/m^{3}K	1.45×10^{-4}m/day(vertical)
Sandy Shoal Deposits	2.2 W/mK	2.5×10^6 J/m^{3}K	3 m/day(horizontal)
Franciscan Bedrock	3.2 W/mK	2.0×10^6 J/m^{3}K	0.1 m/day(horizontal)

The ground temperature of Treasure Island is required for obtaining the temperature gradient and ambient temperature of the aquifer. Temperature values in Figure 6 are adopted from U.S. National Weather Service in which the weather is data reported for San Francisco International Airport for the years of 1985-2015. The distance between San Francisco International Airport and Treasure Island is about 14 km and therefore, the seasonal temperature values for the airport can be used as the same for the Treasure Island shallow geothermal energy model.

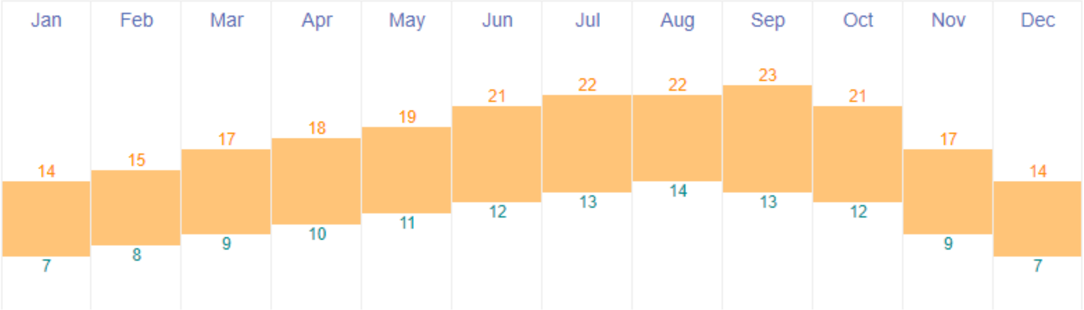


Figure 6: Annual average temperature at San Francisco International Airport

4. CONCLUSION

The cross section from ENGEO can describe in detail the subsurface lithological profile of Treasure Island. However, the hydrothermal properties are not included in their data. Based on the soil properties shown in the dataset, a literature review was conducted to obtain representative values for thermal conductivity, heat capacity and hydraulic conductivity. The 3D geometry of the fully coupled model is built using COMSOL. For the future work, the size of the current three-dimensional model of Treasure Island will be extended. Laboratory tests are also being planned to generate accurate hydrothermal properties for samples collected from the island. The three-dimensional model will be complemented with the development of a high-performance computing based finite element code. HPC efforts are expected to aid in the city-scale simulations of the coupled building physics-subsurface heat transfer calculations for future scenarios.

5. ACKNOWLEDGEMENTS

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