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FINITE ELEMENT SIMULATIONS FOR SAND AND LIMESTONE POWDER OF DIFFERENT THERMAL CONDUCTIVITY

Fayek Hassona[1], PhD, and Beshoy M. Hakeem[2], PhD.

[1]Profosser,Civil Engineering Department, Faculty of Engineering, El-Minia University, El-Minia, Egypt. Email: Fhassona@gmail.com.

[2]Lecturer, Civil Engineering Department, Higher Institute of Engineering and Technology, El-Minia, Egypt. Email: civileng_beshoy@yahoo.com

ABSTRACT.

Thermal physical phenomenon of soils and rocks constitutes an important property for the planning of heat foundations and borehole heat exchange systems. To determine soil thermal properties considerable effort has gone into developing techniques in recent years. This paper attempts to simulate the effectiveness of using a soil with higher thermal conductivity compared to normal sand using GeoStudio 2018 Finite Element 2D program. GeoStudio was used to verify a physical laboratory model which was built to investigate the variation in soil temperature related to the proposed ambient temperature conditions **[1]**. In this research, two different backfilling soils were adopted to carry out this work. The results show excellent agreements between the laboratory model and numerical results. Ground temperature of sand backfill is affected by ambient temperature and reaches a constant value at depths below 1.0 m from ground surface. Limestone powder of higher thermal conductivity reaches a constant value at depths below 0.75 m from ground surface. The results show that using GeoStudio 2018 program to simulate the variation in soil temperature with depth for different types of soil is feasible.

Keywords:

GeoStudio 2018, Numerical analysis, Thermal conductivity, Sand soil, and heat capacity.

1. INTRODUCTION

Thermal conductivity of soil is tormented by many factors. Some of these factors are the soil itself such as the organic matter of the soil. Within the state of nature of the soil, the organic matter content is relatively fixed because it is in relative equilibrium with the biologic activity occurring inside the soil. Alternative factors influencing the thermal conductivity of soil can be managed externally. Bulk density and water content are some of these controlled factors. An increase in moisture content at a given density increased thermal conductivity **[2].** Achieving environmentally friendly and a lot of economical energy utilization, as well as more sustainable power generation and building heating/cooling, will be supported by geothermal energy systems **[3].** According to **[4]** the soil thermal properties are

very important during a sort of applications, such as geothermal heat pumps and thermal performance of buried pipelines. He concluded that to obtain variation in soil thermal conductivity with both soil saturation and voids ratio analysis of a simplified model of fluid behaviour at particle contacts can be used to predict the variation in soil thermal conductivity with both voids' ratio and soil saturation. He derived an equation to calculate thermal conductivity is necessarily somewhat complex relative to the empirically derived equations. Thermal conductivity tends to be low when the porosity is high and the amount of fine particles is low. Also, when the fine particles are small enough to fill the pore body of the larger particles, the thermal conductivity increases.

The effect of geotechnical properties on the thermal conductivity of soils was studied by **[5]**. They concluded that thermal conductivity expectedly increased with an increase in effective stress because of increasing grain-to-grain contact area, coordination number, and the decreased porosity.

For estimating soil thermal conductivity, a simple empirical model for estimating soil thermal conductivity was built by **[6]**. The new empirical model is able to estimate the thermal conductivity of soil over the entire range of water content for

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soils of varied porosities.

According to **[7]** soil thermal conductivity are useful in many subjects connected with energetics. The authors present a developed version of quick and efficient methodology that allows conducting serial measurements of thermal properties of cohesive and non-cohesive soil. After a series of measurements, the authors consider it necessary to prepare databases of thermal properties of soils in a regional approach.

A research which presents the development of an experimental set-up for measurements of thermal conductivity of soils and rocks is introduced in **[8]**. The thermal conductivity of thirteen rocky and soil samples was experimentally measured. They concluded that EED (Earth Energy Designer) software allowed highlighting the importance of knowing the thermal conductivity of the surrounding ground in a geothermal system.

According to **[9]**, characterization of differently textured porous materials as well as different volumetric porous media mixtures, in relation to mass and heat transport is vital for many engineering and research applications.

An improved model for predicting the thermal conductivity for soil from its water content was developed by **[10].** A new functional relationship between degree of saturation and the thermal conductivity was established for both coarse and fine soils. **[11]** concluded that the development of effective thermal conductivity models in particulate materials must recognize that inter particle contacts play a decisive role in heat transfer

In the present research, a 2-D FEM was built using GeoStudio 2018 program to simulate model for a physical laboratory model which was built by **[1]**. Physical laboratory model was built in order to investigate the variation in soil temperature related to the proposed ambient temperature conditions. To check the validity of the chosen computational procedures, experimental results were compared with the results obtained using finite element analysis.

2. NUMERICAL SIMULATION:

Eltohamy (2019)[1] proposed a physical laboratory model consist of a pipe that was used as a soil container as shown in Figure 1. A heat source was adopted on top of soil surface attached to the covering plate of the pipe. The adopted ambient temperature (recorded by a probe at soil surface) values were specified according to the monthly mean temperature along the year at northern Upper Egypt. He considered two mean maximum temperature ranges during four days. The first from (36 to 39 Cº) and the second from (25 to 27 Cº) to simulate the relatively hot and moderate temperature range at study area. This model was used to verify the results of a theoretical study using GeoStudio 2018. Then the results of the experimental and numerical model were discussed.

2.1. Geometry of the 2D Problem.

In the present study, numerical analysis was performed using 2-D Finite Element program GeoStudio 2018. The geometry of the numerical 2D model is presented as shown in Figure 2.

2.2. Boundary Conditions and Mesh Generation.

Boundary conditions were assigned as temperature function at the soil surface to simulate heat source, and constant temperature at the bottom and sides of pipe to simulate the room temperature as shown in Figure 3. When the geometry model is completed, the finite element model (or mesh) can be generated, See Figure 3.

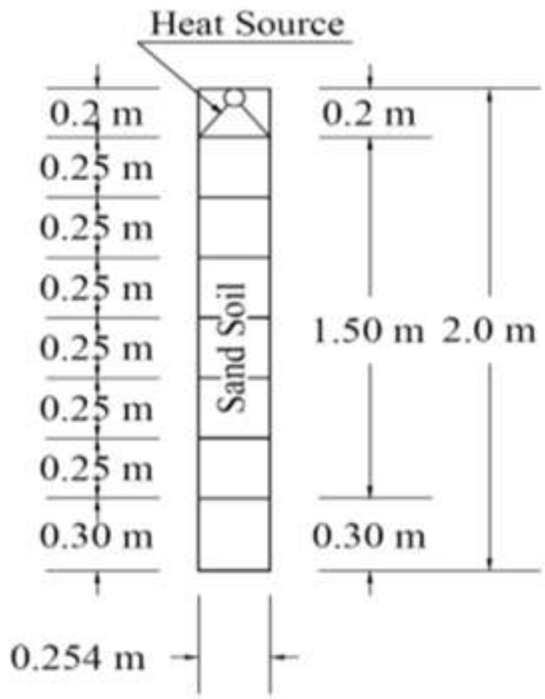

Figure 1. Cross Section of physical laboratory model **(After Eltohamy, 2019)[1]**.

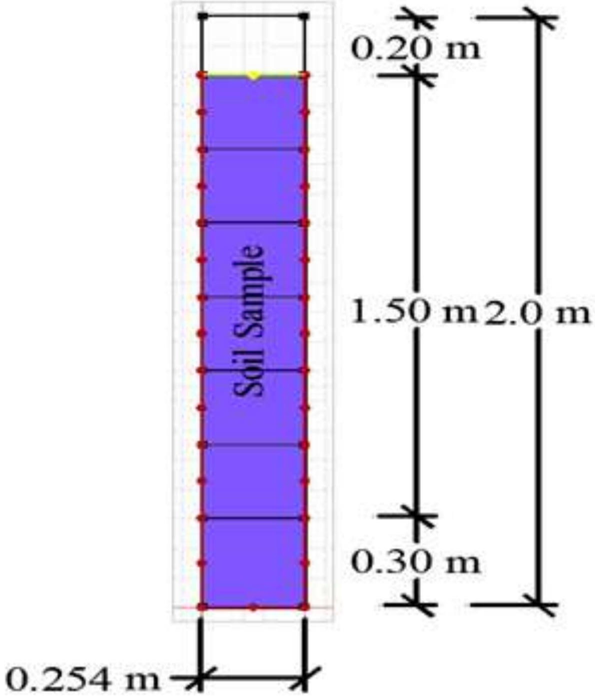

Figure 2. Physical laboratory model Using GeoStudio 2D program

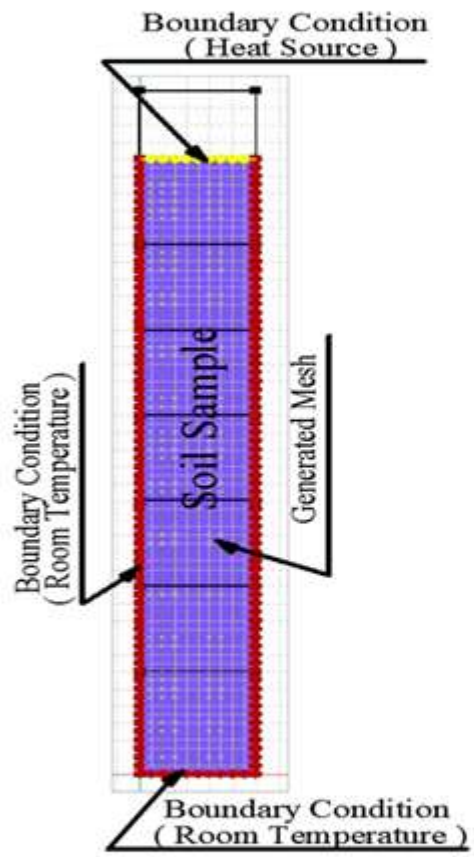

Figure 3. Generated mesh and boundary conditions for finite element analysis.

2.3. Material Model Parameters.

Soil thermal properties used in this model are listed in Table 1. The model was adjusted to simulate the variation of soil temperature with depth for high mean temperature ranges during four days of (36 to 39 C°) and (25 to 27 C°) in the same way of **[1]**. Sand used in back filling (BFS) was obtained from a construction site and backfilling lime powder (BFLP) is obtained from commercially available lime powder stacks obtained from Minya, Egypt. Soil mechanical properties used in this study are listed in Table 2. Particle size distribution for used soil as shown in Figure 4.

According to USCS ASAND classified as poorly graded sand (SP). Numerical analysis was performed via physical model. Finally, physical model measurements were compared to the numerical results.

Table 1. Thermal properties of soils.

Material		**Properties**	
		Thermal Conductivity	Volumetric Heat Capacity
Sand Soil	Value	2.9	1.9
	Unit	W m^{-1} K^{-1}	MJ / m^3 / K
	Reference	**[12]**	**[13]**
Limestone Powder Soil	Value	4.6	2.4
	Unit	W m^{-1} K^{-1}	MJ / m^3 / K
	Reference	**[14]**	**[14]**

Table 2. Mechanical properties of soils.

Material		**Properties**	
		Sand Soil	Limestone Powder Soil
Uniformity coefficient Cu	Value	3.33	20
	Unit	-----	-----
Coefficient of gradation Cc	Value	1.52	0.613
	Unit	-----	-----
Specific gravity	Value	2.65	2.7
	Unit	-----	-----
Max. dry density γ_{dmax}	Value	16.45	-----
	Unit	kN/m^3	kN/m^3
Min. dry density γ_{dmin}	Value	14.1	-----
	Unit	kN/m^3	kN/m^3

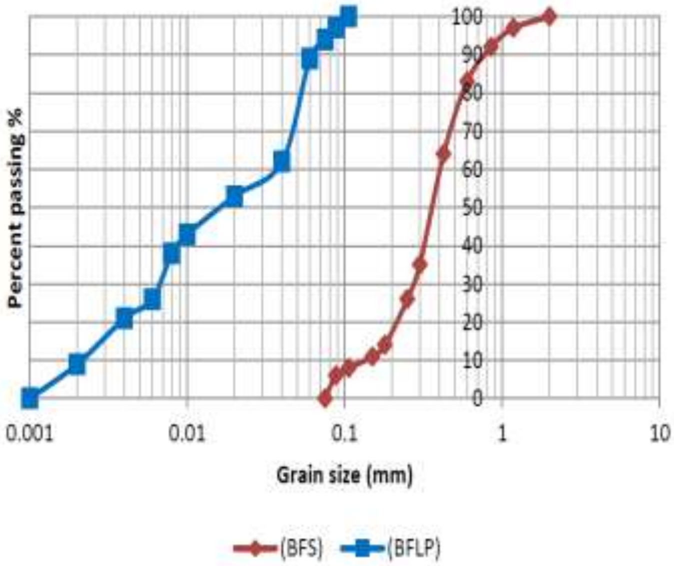

Figure 4. Grain size distribution of backfilling soils.

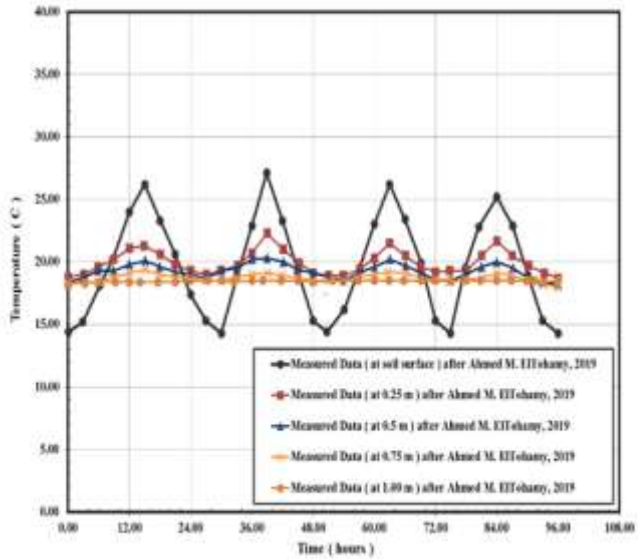

Figure 6. Relation between soil temperature and depth for high temperature of (25 to 27 Cº) **(After Eltohamy, 2019) [1]**.

3. RESULTS AND DISCUSSION.

3.1. Comparison between numerical and experimental results.

Figure 5. and Figure 6. show the variations of soil temperature at different depths along four days operation period at maximum temperature from (36 to 39 Cº), and from (25 to 27 Cº), respectively which measured in physical laboratory model by **[1]**. The estimated of this relationship by numerical model was illustrated as shown in Figure 7. and Figure 8. The difference between numerical analysis results and those of experimental model as indicated in Figures 9 to 14 for high maximum temperature (36 to 39 Cº), and Figures 15 to 19 which illustrate the difference for low maximum temperature (25 to 27 Cº).

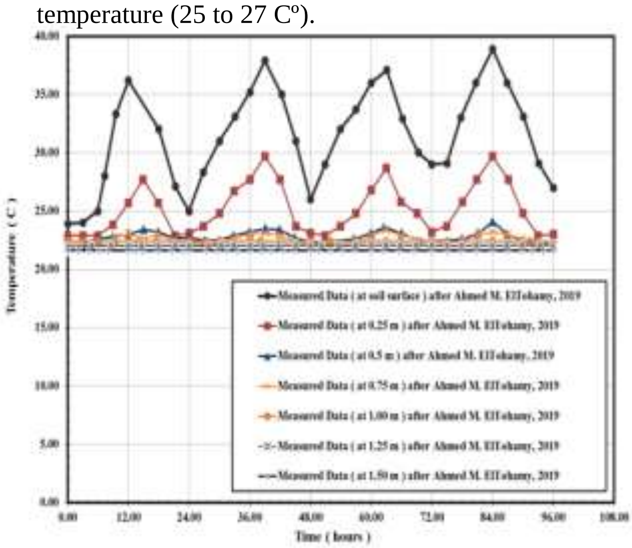

Figure 5. Relation between soil temperature and depth for high temperature of (36 to 39 Cº) **(After Eltohamy, 2019) [1]**.

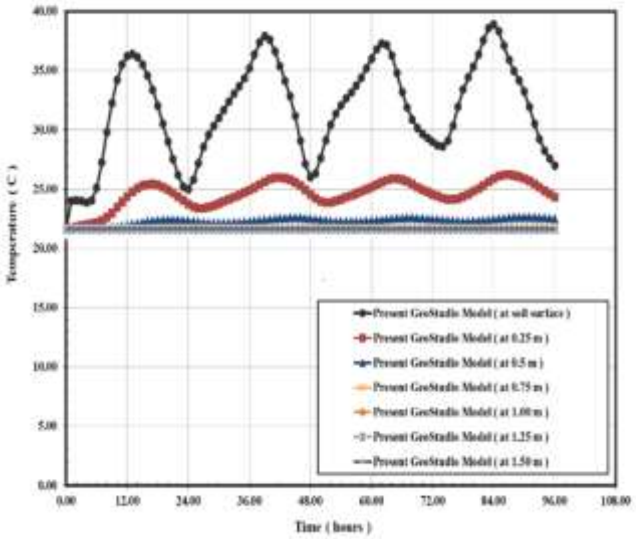

Figure 7. Relation between soil temperature and depth for high temperature of (36 to 39 Cº) using GeoStudio 2D program.

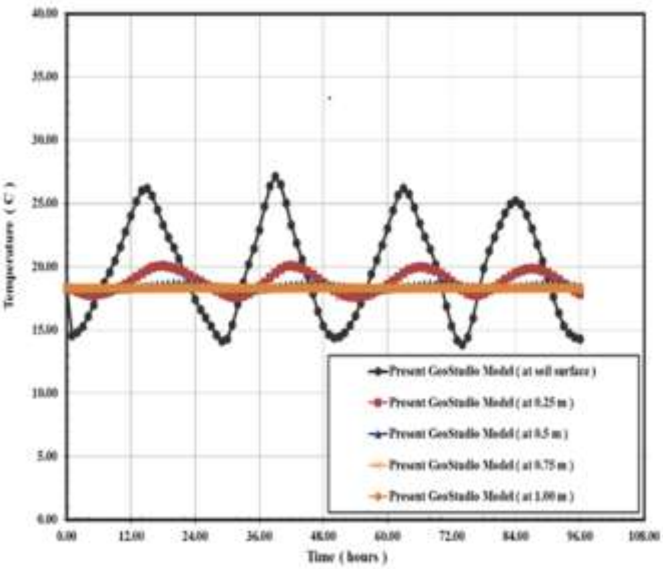

Figure 8. Relation between soil temperature and depth for high temperature of (25 to 27 Cº) using GeoStudio 2D program.

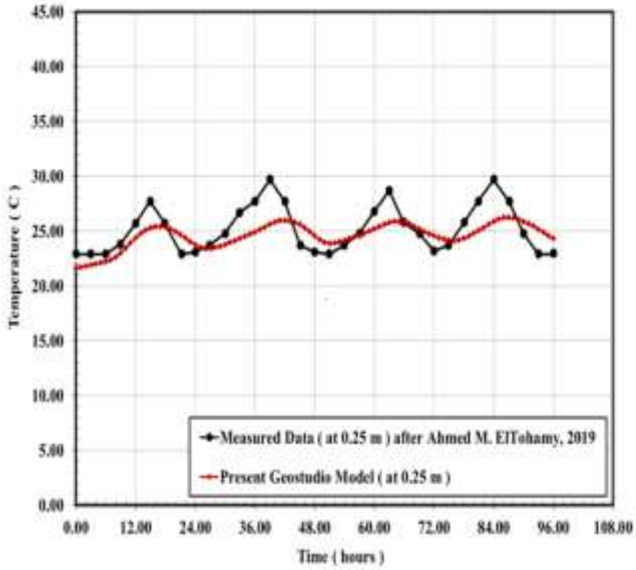

Figure 10. Relationship between the variation of soil temperature (36 to 39 Cº) along four days at 0.25 m.

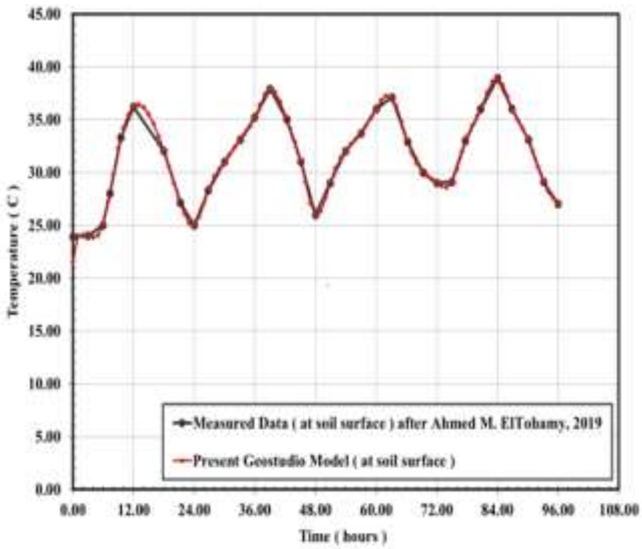

Figure 9. Relation between the variation of soil temperature (36 to 39 Cº) along four days at soil surface.

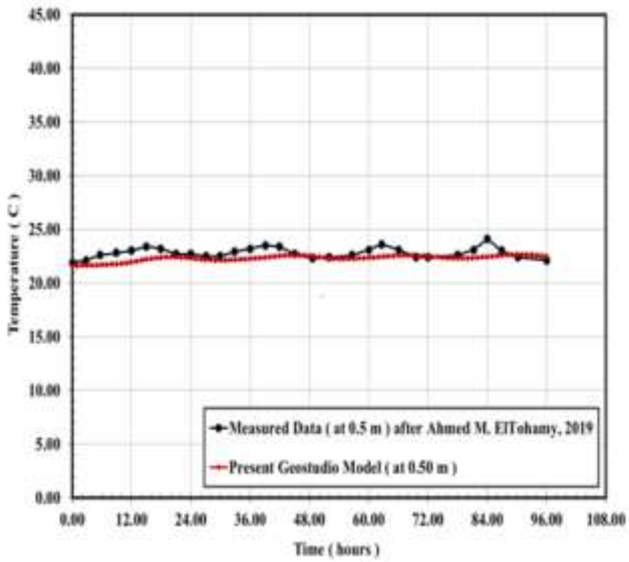

Figure 11. Relation between the variation of soil temperature (36 to 39 Cº) along four days at 0.50 m.

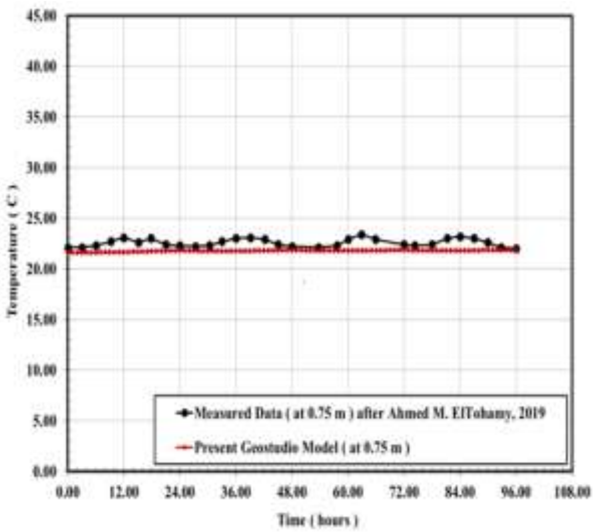

Figure 12. Relation between the variation of soil temperature (36 to 39 Cº) along four days at 0.75 m.

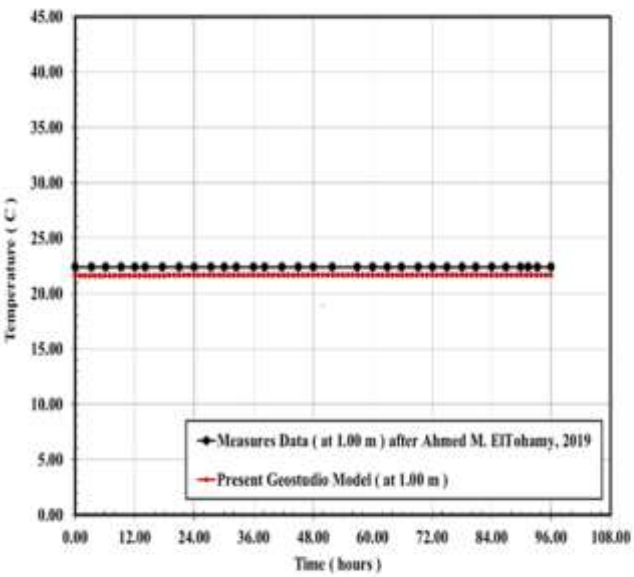

Figure 13. Relation between the variation of soil temperature (36 to 39 Cº) along four days at 1.00 m.

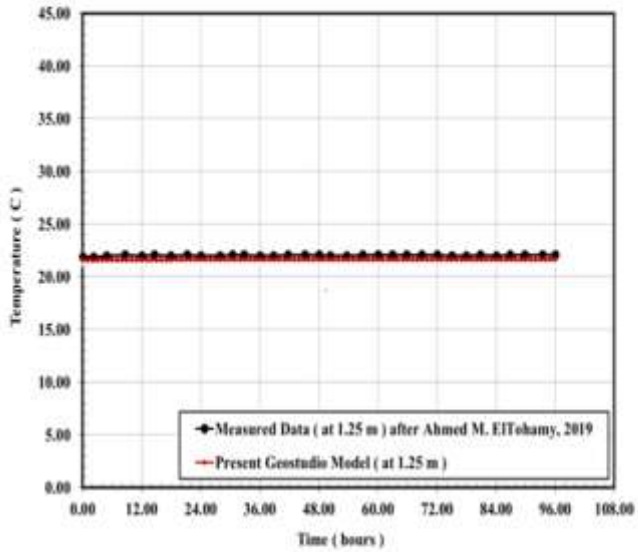

Figure 14. Relation between the variation of soil temperature (36 to 39 Cº) along four days at 1.25 m.

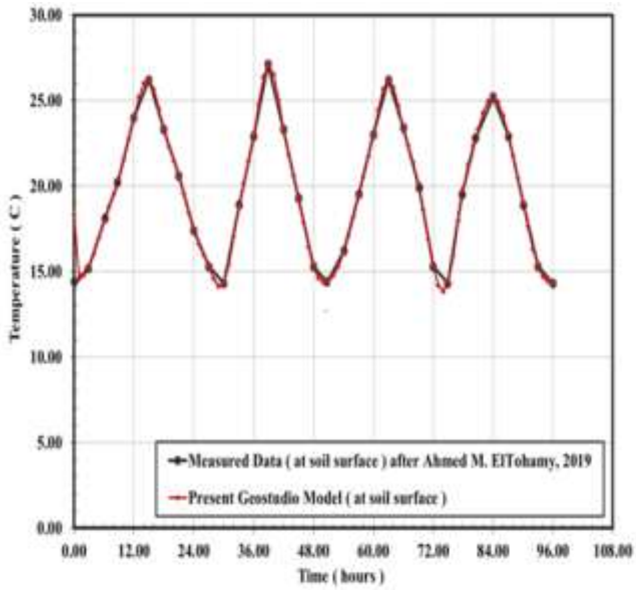

Figure 15. Relation between the variation of soil temperature (25 to 27 Cº) along four days at soil surface.

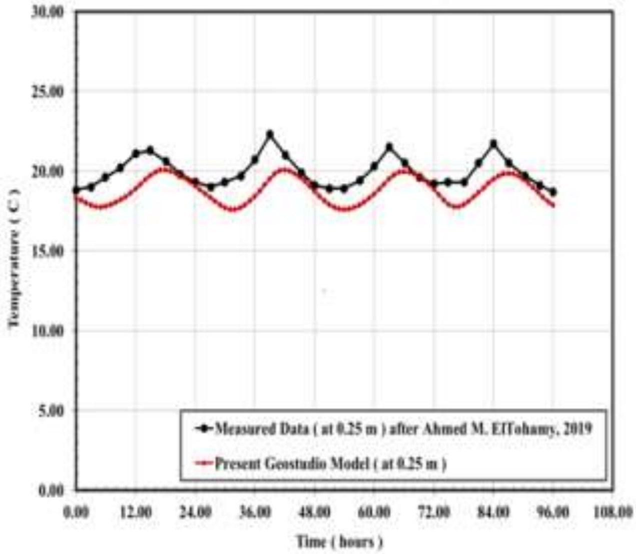

Figure 16. Relation between the variation of soil temperature (25 to 27 Cº) along four days at 0.25 m.

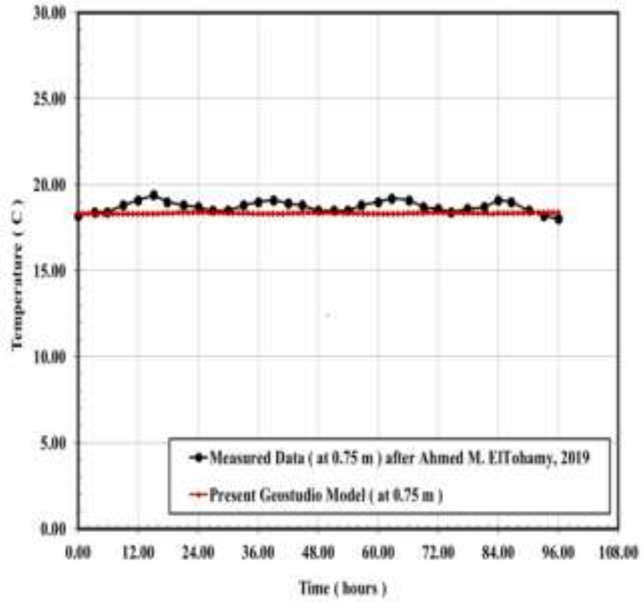

Figure 18. Relationship between the variations of soil temperature (25 to 27 Cº) along four days at 0.75 m.

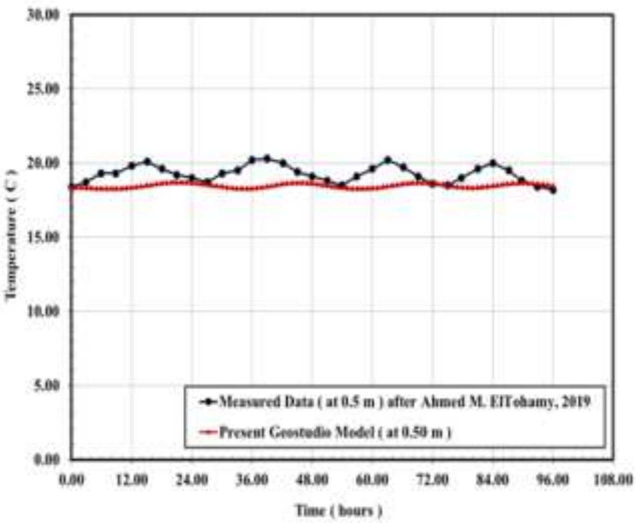

Figure 17. Relation between the variation of soil temperature (25 to 27 Cº) along four days at 0.50 m.

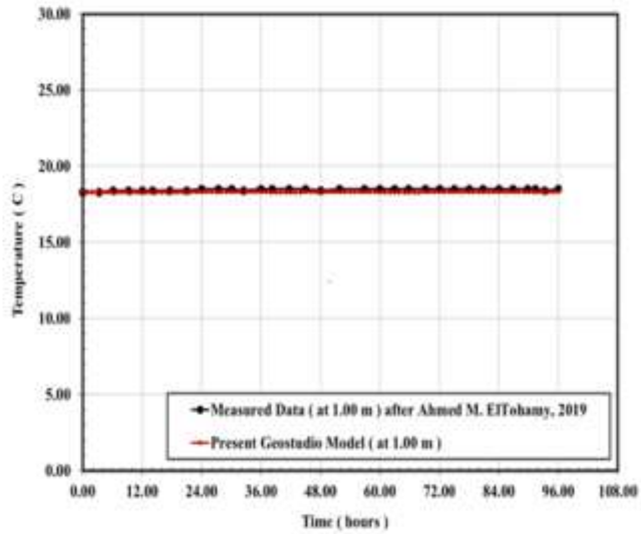

Figure 19. Relation between the variation of soil temperature (25 to 27 Cº) along four days at 1.00 m.

The above-mentioned illustrations indicate that:

For high mean temperature (36 to 39 Cº), an excellent agreement between experimental and numerical results has been noticed along operation time (96 hours), with a maximum difference of about 1.57 Cº (i.e., % Difference = 6.9 %) noticed at 0.5 m from ground surface after 84 hours as shown in Figure 4, Figure 6, and Figures from 8 to 13.

Also, a similar difference of about 1.33 Cº (i.e., % Difference = 7.2 %) is noticed at 0.5m from ground surface after 60 hours as shown in Figure 5, Figure 7, and Figures from 14 to 18 at low mean temperature (25 to 27 Cº).

According to the experimental results at simulated time (96 hours), for high temperature (36 to 39 Cº) the ground temperature variation with depth to a depth of 1.0 m then remains constant. This is also confirmed by the numerical analysis as indicated Figure 4 and Figure 6.

Experimental and numerical models show the vibration of ground temperature to a depth of 1.0 m then remains constant for low temperature (25 to 27 Cº) as indicated in Figure 5 and Figure 7.

In general, Figures 4 to 18 indicate that the developed GeoStudio 2D model satisfactorily estimated variation of temperature along the soil depth. The consistent difference of temperature values between physical model measurements and GeoStudio 2D model results, may be referred to some of the following factors: -

a-Perhaps due to some errors in the temperature measurement in laboratory monitoring.

b-May be instability of the heat source used during the operating period.

c-Probability of irregular distribution for sand density which was affected on thermal conductivity and volumetric heat capacity of sand soil.

3.2. Limestone Powder Backfilling Material Model Results.

As mentioned before, the results confirmed the possibility of using GeoStudio 2D program to determine the variation of temperature with depth at any time. Then sand soil was replaced by limestone powder as a backfilling material as the same way of **Eltohamy (2019) [1]**. Figure 20. and Figure 21. show the variation of soil temperature at different depths along four days operation period at temperatures from (36 to 39 Cº), and from (25 to 27 Cº).

The results show that, for high temperature (36 to 39 Cº), temperature has a constant value at a depth 0.75 m from ground surface as shown in Figure 20.

Also, numerical mode shows the vibration of ground temperature to a depth of 0.75 m then remains constant for low temperature (25 to 27 Cº) as shown in Figure 21.

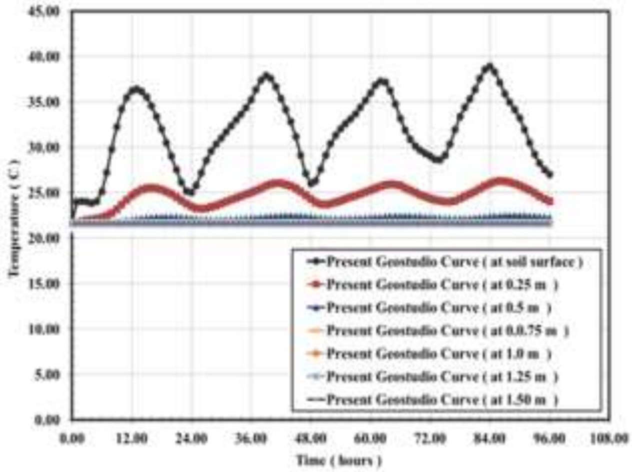

Figure 20. Variation of limestone powder temperature with depth for high temperature of (36 to 39 Cº) using GeoStudio 2D program.

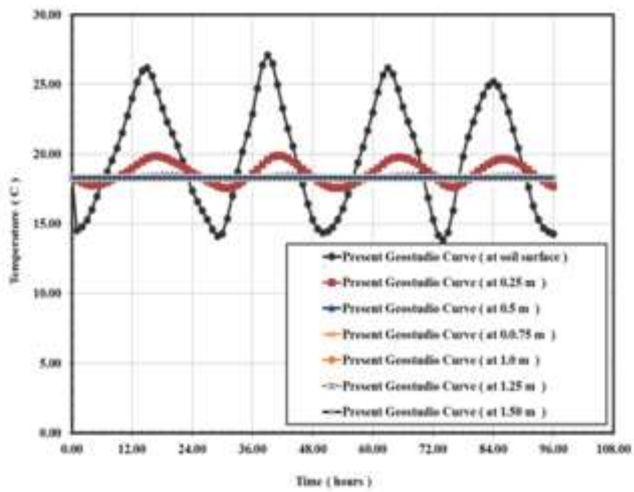

Figure 21. Variation of limestone powder temperature with depth for high temperature of (25 to 27 Cº) using GeoStudio 2D program.

4- CONCLUSIONS.

To simulate the variation of temperature with the soil depth. GeoStudio 2018 (Temp / W) finite element 2D program was adopted. The results showed that numerical model gives satisfactory results compared with the results of laboratory model. Comparing the laboratory measurements with the finite element model results allowed us to validate the proposed numerical model to obtain the temperature at any time for all backfilling soil.

When using sand soil, the ground temperature various with depth to a depth of 1.0 m then remains constant for high temperature (36 to 39 Cº), and for low temperature (25 to 27 Cº).

When limestone powder was used, the results show that for high temperature (36 to 39 Cº), and for low temperature (25 to 27 Cº) the temperature gives a constant value at a depth 0.75 m from ground surface.

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نمذجة الأنواع المختلفة من التربة ذات توصيل حراري مختلف باستخدام العناصر الغير محدودة

يشكل التوصيل الحراري للتربة والصخور خاصية هامة وحاسمة وذلك لمرفة التبادل الحراري للتربة والأنظمة، والخواص الحرارية للتربة مطلوبة في العديد من المجالات الهندسة وعلوم التربة. في السنوات الأخيرة تم بذل الكثير من الجهد في تطوير التقنيات المطلوبة للحصول علي هذه الخصائص للتربة.هذا البحث يهدف الي محاكاة للتربة ذات توصيل حراري أعلي مقارنة بالرمل العادي وذلك بإستخدام برنامج (GeoStudio 2018, 2D). تم إستخدام هذا البرنامج للتحقق من النتائج التي تم الحصول عليها من النموذج المعملي الذي تم إنشاؤه بواسطة (Eltohamy 2019,) لمعرفة مدي التغير الحراري للتربة مقارنة بالظروف المحيطة. في هذ البحث تم إستخدام نوعين مختلفين من التربة. وأوضحت النتائج أن هناك توافق كبير بين النتائج التي تم الحصول عليها من النموذج المعملي وما تم التوصل إليه من المحاكاه بإستخدام البرنامج النظري. وأوضحت النتائج أن درجة حرارة الرمل تتغير وتصبح ثابتة علي عمق واحد متر من سطح الأرض، وفي حالة إستخدام مسحوق الحجر الجير ذات التوصيل الحراي العالي أوضحت النتائج أن الحرارة تصبح ثابتة علي عمق 0.75 متر من سطح الأرض. بمناقشة ومقارنة النتائج أوضحت أنه يمكن إستخدام الربنامج في معرفة تغير درجة الحرارة لأي نوع من التربة علي أعماق مختلة.