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ABSTRACT

This study proposes a simple mathematic model for approximating the level of phreatic surface inside the protected zone in mechanical stabilized earth wall with back drain installation though the position of phreatic surface at the drainage interface (h_o) which reflects the maximum level of phreatic surface in the protected zone. The proposed model was established based on dataset taken from 180 simulation cases caried out in Plaxis environment. Regression results present a combination of significant effects and major role to maximum water level in the protected zone (h_o) of a ratio of length from upstream water to the drainage face to the wall height (L/H), a soil permeabilities coefficient (k) and a transmissivity of the drainage material (T_{net}). The proposed model can facilitate design of drainage material to achieve desired level of phreatic surface in the protected zone.

Keywords: MSE wall, protected area, maximum water level, geonet transmissivity, linear association

INTRODUCTION

Although drainage system was properly installed behind mechanical stabilized earth (MSE) wall, failures happened during long term rainfall have been mentioned in many reports (Yoo and Jung, 2006; Koerner and Koerner, 2018; Zhang et al., 2015; Koerner and Koerner, 2015; Vahedifard et al., 2017). The wide distribution of high water content in the protected zone was a major source for many types of failure (Zhang et al., 2015; Chinkulkijniwat et al., 2016). To narrow the high water content zone, the backfill soil must consist of least fine particle and the level of phreatic surface inside the protected zone must be minimized. Good estimation of phreatic level inside the protected zone is, therefore, vital for design of MSE wall. This study focuses accurate estimation of phreatic level inside the protected zone though the high of phreatic surface at the drainage interface in the protected zone (h_o). The h_o is considered as the maximum level of phreatic surface in the protected zone and reflects the effectiveness of the drainage system.

Previous reports, i.e. Koerner and Koerner (2018), Koerner and Koerner (2015). Vahedifard et al. (2017), indicated that there were many factors influencing the h_o variation such as soil hydrological properties, properties of drainage material, and the wall dimensions. However, none of the previous attempts had been devoted to estimate the magnitude of h_o comprehensively. To date, engineers design the required transmissivity of drainage layer using a classical Dupuit's formular with an assumption that the phreatic level inside the protected zone is zero. Previous study from the authors (Chinkulkijniwat et al., 2016, Bui Van et al., 2017, La Duong et al., 2021) reports none zero phreatic level inside the protected zone even after assigning transmissivity of drainage layer greater than that provided by Dupuit's equation. For a given wall geometry of homogeneous soil, La Duong et al. (2021) reported linear relationship between h_o and logarithm of geonet transmissivity (T_{net}). Furthermore, the gradient of the h_o-log(T_{net}) relationship was found governed by the permeability coefficient of the upstream soil. This paper extends this important finding to propose a closed form equation for h_o estimation. Data used in this study were gathered from 180 sets of numerical calculation extracted from well calibrated Plaxis-2D model (Chinkulkijniwat et al., 2016). Steady-state flow conditions were focused in this study to quantify the final state of ground water flow in MSE wall .The proposed equation will assist drainage design in MSE wall with back drain installation.

METHODOLOGY

Research background

Soil-water model is based on van Genuchten model (Eq .1a) (van Genuchten, 1981) and van Genuchten -Mualem model (Eq .1b), which is an integration of the van Genuchten model with the Mualem hypothesis (Mualem, 1976), were employed to approximate the water retention curve and permeability functions for every porous media in the MSE wall problem .The models gave the following equations :

$$S_e = \frac{S - S_{res}}{S_{sat} - S_{res}} = \left[1 + \left(\alpha \left|h_p\right|\right)^n\right]^{-m} \quad (1a)$$

$$k_r(S_e) = S_e^{0.5}[1 - (1 - S_e^{1/m})^m]^2 \quad (1b)$$

In the above equations, S_e is effective degree of saturation [-], S is degree of saturation [-], S_{res} is residual saturation at very high values of suction [-], S_{sat} is the degree of saturation at saturated state [-], h_p is matric suction head [m], and k_r is the relative permeability coefficient [m/sec], α [m^{-1}] and n [-] are fitting parameters which represent respectively the air-entry head of the soil and the rate of water extraction from the soil once the air entry head has been exceeded, while m [-] is assigned the value $1 - 1/n$ [7].

Simulation scenarios for linear association analysis

Well calibrated MSE wall with back drain installation model in Plaxis environment (Figure 1) reported by Chinkulkijniwat et al. (2016) was employed to approximate the maximum phreatic level in the protected zone of MSE wall (h_o). The upstream water level in all calculations was set equal to the wall height to imitate vital scenario of the MSE wall in mountainous terrain, where heavy rainfall could raise the upstream water level to equal heigh of the wall. In this study, the upstream-, foundation-, and backfill-soils were assigned identically. Six soil types; including coarse sand (Konukcu et al., 2004), sandy soil (Chinkulkijniwat et al., 2016), clayey soil (Szymkiewicz et al., 2015), lateritic soil (Bui Van et al., 2017) and clay (Koerner and Koerner, 2015), were assigned to perform the calculation. Saturated permeability coefficient and van Genuchten parameters these soils are given in Table 1. As for the wall dimensions ratio; including the distance from the wall base to the impervious boundary to the wall height (D/H), the protected zone width to the wall height (W/H), and the distance from the upstream water source to the drainage face to the wall height (L/H), La Duong et al. (2021) reports that except the dimension ratio L/H, other wall dimension ratios play small to negligible role to the magnitude of h_o/H. Accordingly, for wall dimension set up in this study, the wall height (H), distance from the wall base to the impervious boundary (D), and the protected zone width (W) were fixed at 2.0 m, 0.8 m, and 2.0 m, respectively. The shape parameter L was varied in range from L/H of 1.0 to L/H of 2.5 as stated in Table 2. Geonet transmissivity was controlled by geonet thickness (t_{net}) and geonet permeability (k_{net}) through the relationship written in Eq. 2,

$$T_{net} = k_{net} \times t_{net} \quad (2),$$

where T_{net} is geonet transmissivity (m^2/sec), t_{net} is geonet thickness (m) and k_{net} is geonet permeability (m/sec**).** The assigned hydrological properties of geonet as thickness (t_{net}), permeability (k_{net}) are also given in **Table 2**. Totally, 180 calculation cases were conducted in this study. Within this dataset, 18 calculation results yielding h_o value of 0.001 m were eliminated from the analysis. Since the smallest h_o readable from the calculations was 0.001 m, including this dataset might deviate the analyzed result.

RESULTS AND DISCUSSION

The relationships between h_o and $\log(T_{net})$ for coarse sand, sandy soil, clayey sand, lateritic soil, and clay extracted from Plaxis calculation are respectively shown in **Fig. 2a, 2b, 2c, 2d, and 2e**. The drop of h_o with the increase of $\log(T_{net})$ reflects the greater amount of water allow to flow along the drainage channel. Linear regression was employed to fit the h_o - $\log(T_{net})$ relationship. All plots reflect themselves best fit with linear association via the coefficient of determination r^2 greater than 0.96. Although the variation of h_o with $\log(T_{net})$ was well fitted through linear regression, no further correlation was found along these plots. Since the permeability coefficient of the upstream soil (k) plays important role to the drop of h_o with increasing T_{net} (La Duong et al, 2021), the permeability coefficient (k) was included in the T_{net} term as $\log(T_{net}/k)$ and plotted with $\log(h_o)$ as shown in **Figure 3**. The plots exhibit similar pattern for all values of shape parameter L, hence the shape parameter L must be included to normalize the data. After trial and error, the term $\log(T_{net}/k)$ was transformed to $\log(T_{net}/k^{(10+L/H)/10})$ and the variation of $\log(h_o)$ with $\log(T_{net}/k^{(10+L/H)/10})$ exhibit unique relationship with the coefficient of determination r^2 of 0.93 as shown in **Figure 4**. The equation for h_o estimation in MSE wall with geocomposite back drainage is, hence, delivered as:

$$\mathrm{Log}(h_o) = -0.16-0.56\log(T_{net}/k^{(10+L/H)/10}) \qquad (3)$$

To verify the above equation, 12 extra Plaxis calculations having the influence variables were randomly assigned to the model. **Table 3** presents variation of influence variables and the corresponding h_o values extracted from these extra calculations. The h_o values yield from Eq. 3 are also presented in this table. Comparison between ho values calculated from Plaxis and that from Eq. 3 is shown in **Figure 5**. The coefficient of determination r^2 along 1:1 line is 0.96 indicating level of accuracy of the h_o prediction using Eq. 3.

CONCLUSION

Following points are drawn from this study:

- Simple mathematic model for approximating the maximum water level in the protected zone (h_o) for mechanical stabilized earth wall with back drain installation was established through dataset calculated from a well calibrated model in Plaxis environment.
- Based on previous report (La Duong et al., 2021), important parameters playing role to the change of h_o are 1) permeability coefficient of upstream soil (k), 2) transmissivity of the back drain (T_{net}), and 3) a ratio of the distance from the upstream water source to the drainage face to the wall height (L/H). Hence, the model was established based on variation of these 3 parameters.
- The proposed equation was established based on identical soil at the upstream- and protection-zones. In practical situation, the soil located in protected zone always possesses its permeability coefficient no less than that of the upstream soil. According to Bui Van et al. (2017) and La Duong et al. (2021), if the soil in the protected zone possesses more permeable than the soil in the upstream side does, the flow path reflection results in the lower phreatic surface in the protected for the more permeable soil in the protected zone than that for the less permeable soil in the protected zone. As such, magnitude of h_o approximated from the proposed equation is conceptually no lower than that take place in MSE wall having higher soil permeability in the protected zone than that in the upstream side, i.e. the propose equation yields conservative results.

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STATEMENT FOR CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest

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Table 1. Permeability coefficient and van Genuchten parameters of the studied materials.

Material	Permeability (m/sec)	α (m^{-1})	n (-)	S_{sat} (-)	S_{res} (-)
Coarse sand	1.3×10^{-3}	49.36	1.53	1.0	0.002
Sandy soil	1.97×10^{-4}	20	1.5	1.0	0.03
Clayey sand	4.1×10^{-5}	12.4	2.28	1.0	0.14
Lateritic soil	4.0×10^{-6}	0.8	1.4	1.0	0.03
Clay	5.56×10^{-7}	0.08	8.0×10^{-5}	0.74	0.12
Geotextile	0.023 (0.0037)[a]	20	2.5	0.8	0.03
Geonet	0.8	600	40	1.0	0.0

[a] Permeability of geotextile in lateral direction.

Table 2. Variable setup of 180 simulations in Plaxis environment

Scenario	Prescribed soil	Reference
A	Coarse sand	Konukcu et al. (2004)
B	Sandy soil	Chinkulkijniwat et al. (2016)
C	Clayey sand	Szymkiewicz et al. (2015)
D	Lateritic soil	Bui Van et al. (2017)
E	Clay	Koerner and Koerner (2015)

Fixed parameter		
W (m)	Protected zone width	1.6
H (m)	MSE wall height	2.0
D (m)	Distance from the wall base to the impervious boundary	0.8
Varied parameter	Definition	Varied value
L (m)	Length from upstream water to the drainage face	2.0, 3.0, 4.0, 5.0
t_{net} *(mm)*	Geonet thickness	10, 15, 20
k_{net} *(m/sec)*	Geonet permeability	0.8, 0.08, 0.008

Upstream water level (H_w) is kept as constant 2.0 for all simulation cases

Table 3. Assigned variables in 12 verified cases and the corresponding h_o values from Plaxis calculation and that from the proposed equation.

Soil type and its permeability	Case no.	H (m)	L (m)	T_{net} (m^2/sec)	h_o (m) (Plaxis)	h_o (m) (Proposed model)
Soil type 1 k = 1.97 × 10^{-4} m/s	1	3.5	6.5	3.0×10^{-3}	0.0875	0.1070
	2	4.5	3.5	6.0×10^{-3}	0.0585	0.0704
	3	4.2	0.5	8.0×10^{-3}	0.126	0.0821
	4	3.2	3.0	1.7×10^{-3}	0.192	0.1322
Soil type 2 k = 2.23 × 10^{-3} m/s	1	3.1	2.1	3.0×10^{-3}	0.5857	0.4648
	2	2.2	5.5	6.0×10^{-3}	0.1751	0.1691
	3	3.8	7.7	8.0×10^{-3}	0.1311	0.1692
	4	4.3	5.0	2.7×10^{-2}	0.1514	0.1150
Soil type 3 k = 3.0 × 10^{-6} m/s	1	4.7	2.6	3.0×10^{-3}	0.0141	0.0097
	2	4.4	4.5	6.0×10^{-3}	0.0044	0.0047
	3	3.1	2.8	8.0×10^{-3}	0.0031	0.0043
	4	2.6	4.2	1.2×10^{-3}	0.0104	0.0076

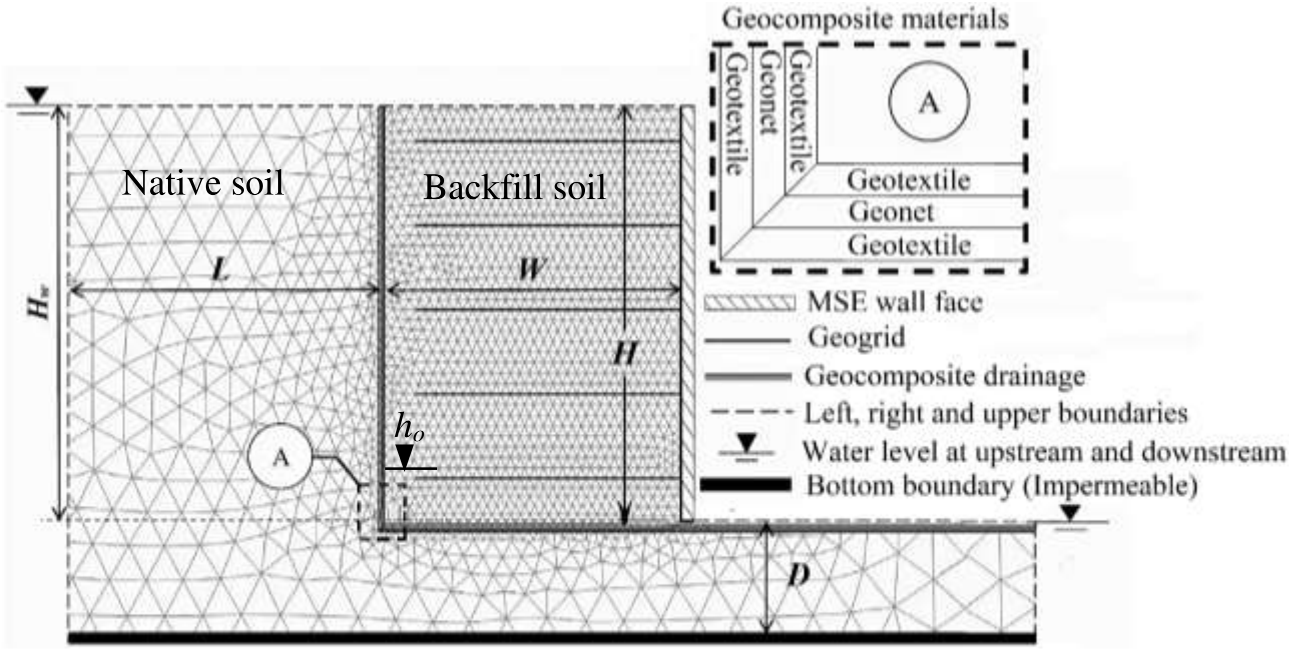

Fig 1. Plaxis model of mesh discretization with h_o and the relevant shape parameters of MSE wall with back drain using geocomposite (adopted from Chinkulkijniwat et al. 2016).

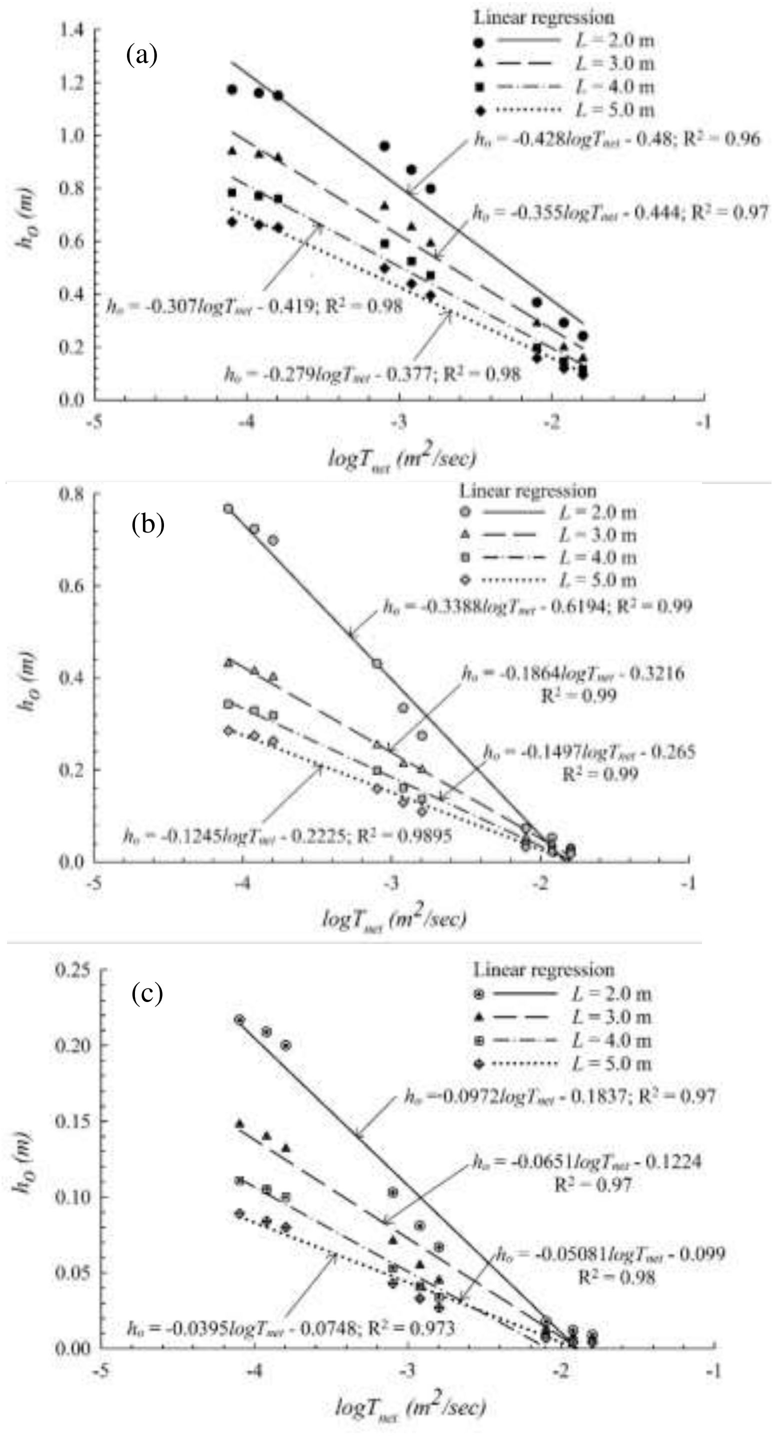

Fig. 2. Linear relationship of h_o subject to $logT_{net}$ and various shape parameter L values for (a) coarse sand, (b) sandy soil and (c) clayey sand (e) lateritic soil, and (f) clay.

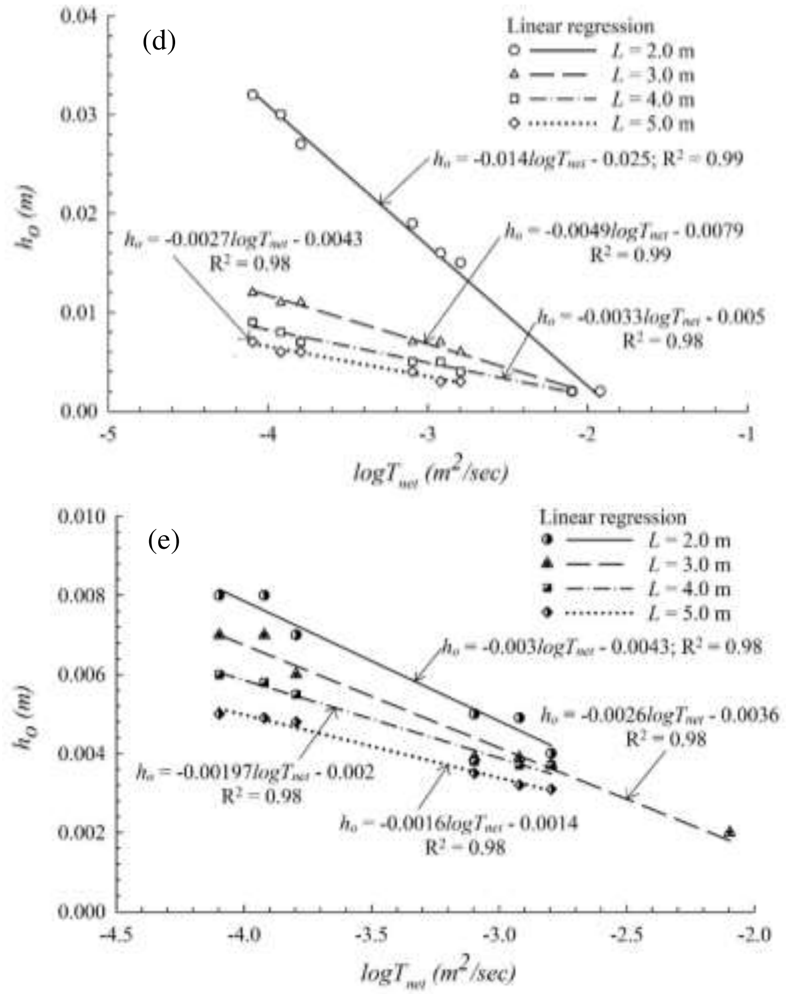

Fig. 2 (cont.). Linear relationship of h_o subject to $logT_{net}$ and various shape parameter L values for (a) coarse sand, (b) sandy soil and (c) clayey sand (e) lateritic soil, and (f) clay.

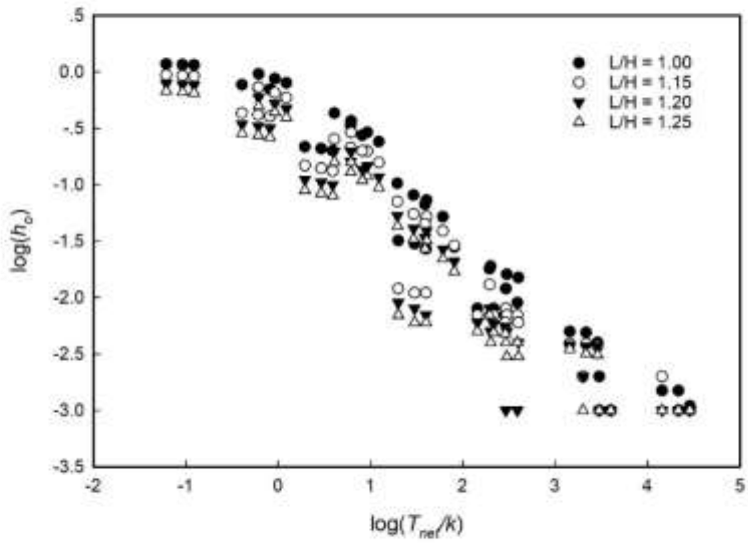

Fig 3. Variation of log h_o and log (T_{net}/k) for various L/H ratios

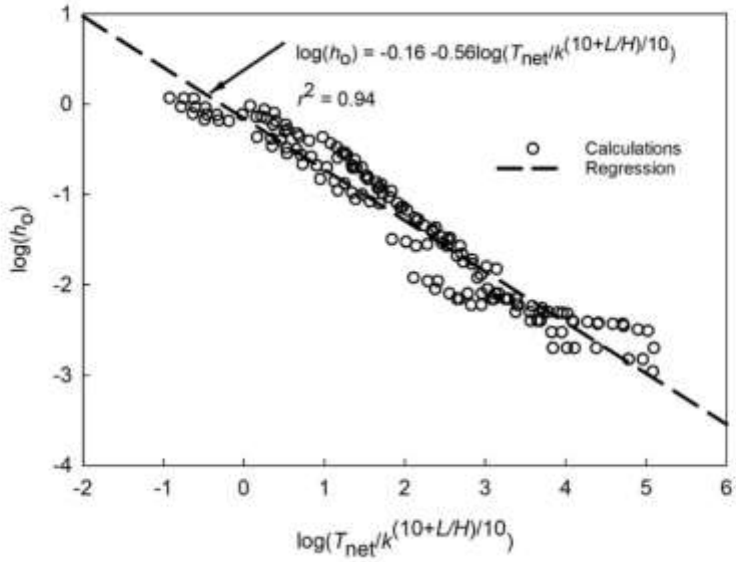

Fig 4. Relationship between log h_o and log ($T_{net}/k^{(10+L/H)/10}$) and regression result

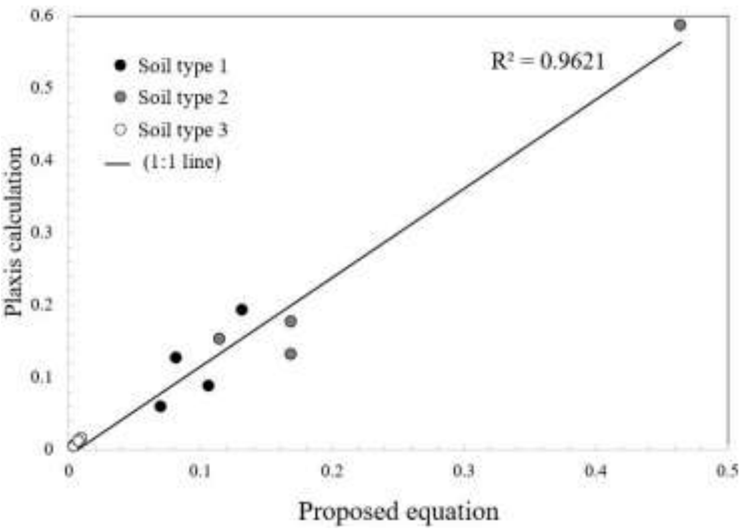

Figure 5. Comparison between h_o calculated from Plaxis and that from proposed equation.