EFFECT OF GROUNDWATER DRAWDOWN ON DISTRIBUTION OF LAND SUBSIDENCE IN LAYERED SOILS

Tran Van Tuan[1], Truong Quynh Nhu[2]
[1] Lecturer, Department of civil engineering, Can Tho university, Can Tho, Viet Nam
[2] Bachelor student, Can Tho university, Can Tho, Viet Nam

Received 10/8/2020, Revised 25/9/2020, Accepted 11/12/2020

Abstract
The objective of this study is focused on the effect of groundwater lowering on distribution of land subsidence in layered soils and developing charts which present the distribution of land subsidence with vertical directions when lowering the hydraulic heads. Authors used the expression for 1D water flow theory and Riley's method to calculate the land subsidence for two cases of layered soils: hypothetical soil (2 layers) and soil in My Thuan Bridge (4 layers), Vinh Long Province. Besides, the study used the finite element method (Plaxis 2D) to simulate the land subsidence. The results showed that 1D water flow theory and Riley's method presented the relationship between land subsidence with depth (Z). All 2 cases, the land subsidence was a function of local position as well as soil properties and this relationship is nonlinear with the curve is different in each soil layer. Settlement of soil near the surface is larger than settlement of soil at larger depth.
Keywords: *heterogeneous soil, groundwater, land subsidence, layer soils, settlement*

1. Introduction

Groundwater plays a role in a variety of geomechanical processes which is a convenient water supply and is a valuable resource both in the Viet Nam and throughout the world. For a groundwater source, it is important to have a sufficient number of observation wells, both local to the production wells and regionally throughout the groundwater basin. Many areas of the Viet Nam are experiencing groundwater depletion.

Land subsidence can cause other associated problems, such as changes in elevation and gradient of stream channels, ill drainage, other water transporting facilities, damage to civil engineering structures, private and public buildings. Land subsidence occurs when large amounts of groundwater have been withdrawn from certain types of soils, such as fine-grained sediments from the point of view of hydrology, these phenomena have had what may be called catastrophic results.

The water table has been constantly lowering and urbanization has been rapidly developing during the last decades… due to the strong groundwater extraction has led to the subsidence of some areas in the Ho Chi Minh (HCM) city. Land deformation at the rate of few centimeters per year can be measured at the heavy groundwater pumping stations. Groundwater exploitation in HCM city passed 600,000m^3/day, while the amount of water replenished below 200,000m^3/day that lead to lower groundwater levels of aquifers. The reduction of groundwater of aquifers, together with the rapid development of terrestrial constructions, caused the terrain surface deformation (subsidence) occurring in many places area (Trung et al., 2008).

In the lower Mekong Delta, most of which lies <2m above sea level, over-exploitation is inducing widespread hydraulic head (i.e., groundwater level) declines. InSAR-based on subsidence

rates, if pumping continues at present rates, ~0.88m (0.35–1.4m) of land subsidence is expected by 2050, that proves Mekong Delta will likely experience ~1m (0.42–1.54m) of additional inundation hazard (Erban et al., 2014). Therefore, it can say that groundwater extraction is a major cause of land subsidence which has a variety of hazards associated with naturally occurring.

The overall objective of this study is focused on the effect of groundwater lowering on distribution of land subsidence in layered soils. Developing charts which present the distribution of land subsidence with vertical directions when lowering the hydraulic heads.

Scopes of study are Riley's method is used for the analysis of land subsidence; the soil used for case study collects from My Thuan bridge project; Plaxis 2D and 1D water flow theory is also used in this research.

2. Riley's method

This study will use Riley's method in 1969 (Riley, 1969).

$$\Delta b = S_s \times b \times \Delta h \quad (1)$$

in which Δb is the change in layer thickness, b is the full thickness of the layer, Δh is the change in hydraulic head, or drawdown. The total head is calculated from elevation head and pressure head.

$$h_t = h_e + h_p \quad (2)$$

in which, h_e and h_p are elevation head and pressure head respectively.

S_s is the layer's specific storage $(1/L)$, a metric related to the compressibility of both the sediment and water that expresses the volume of water released from storage per unit volume of water-bearing layer per unit decline in hydraulic head.

3. Finite element method

3.1 Plaxis 2D

Plaxis 2D version 8.2 (Brinkgreve, R. B. J. et al, 2007) is a finite element program which has been written for analysis geotechnical problems including settlement of soil under drawing down water table. It can generate a large 2D finite element meshes. The mechanical behavior of soils can be modeled by several models (e.g. Mohr-Coulomb model) for different analyses. The incremental effective stress and contour of total incremental displacement of homogeneous soil can be simulated via this program.

3.2 Mohr-Coulomb model

The Mohr-Coulomb model is an elastic perfectly plastic model which is a constitutive model with a fixed yield surface and the behavior of points within the yield surface is purely elastic. Based on the basic principal of elastoplasticity, equation (3.1) can be written as:

$$\dot{\sigma}' = D^e\left(\dot{\varepsilon} - \dot{\varepsilon}^p\right) \quad (3)$$

Where $\dot{\varepsilon}^p$ is the plastic strain rate component which is defined by:

$$\dot{\varepsilon}^p = \lambda \frac{\partial g}{\partial \sigma'} \quad (4)$$

Where λ is the plastic multiplier which is defined from the yield function, f, as below:

$$\lambda = 0 \text{ for: } f < 0 \text{ or: } \frac{\partial f^T}{\partial \sigma'} D^e \dot{\varepsilon} \leq 0 \text{ (Elasticity)} \quad (5a)$$

$$\lambda > 0 \text{ for: } f = 0 \text{ and: } \frac{\partial f^T}{\partial \sigma'} D^e \dot{\varepsilon} > 0 \text{ (Plasticity)} \quad (5b)$$

g is the plastic potential function which is introduced to fix the problem of theory of associated plasticity in estimating dilatancy. Non-associated plasticity is denoted as $g \neq f$.

Therefore, the relationship between effective stress rates and strain rates can be expressed as

$$\dot{\sigma}' = \left(D^e - \frac{\alpha}{d} D^e \frac{\partial g}{\partial \sigma'} \frac{\partial f^T}{\partial \sigma'} D^e\right)\dot{\varepsilon} \quad (6a)$$

In which α = 0 (elasticity) and α = 1 (plasticity)

$$d = \frac{\partial f^T}{\partial \sigma'} D^e \frac{\partial g}{\partial \sigma'} \quad (6b)$$

For multi surface yield contour, the above equations should be extended as:

$$\dot{\varepsilon}^p = \lambda_1 \frac{\partial g_1}{\partial \sigma'} + \lambda_2 \frac{\partial g_2}{\partial \sigma'} + \lambda_3 \frac{\partial g_3}{\partial \sigma'} + \ldots \quad (7)$$

Where λ_i (i = 1, 2, 3,…) can be defined from the yield functions f_i (i = 1, 2, 3,…), respectively.

The yield condition used in Mohr-Coulomb model is an extension of Coulomb's friction law to general states of stress. In principle stress space, this condition consists of six yield functions as below:

$$f_{1a} = \frac{1}{2}(\sigma'_2 - \sigma'_3) + \frac{1}{2}(\sigma'_2 + \sigma'_3)\sin\phi - c\cos\phi \leq 0 \quad (8a)$$

$$f_{1b} = \frac{1}{2}(\sigma'_3 - \sigma'_2) + \frac{1}{2}(\sigma'_3 + \sigma'_2)\sin\phi - c\cos\phi \leq 0 \quad (8b)$$

$$f_{2a} = \frac{1}{2}(\sigma'_3 - \sigma'_1) + \frac{1}{2}(\sigma'_3 + \sigma'_1)\sin\phi - c\cos\phi \leq 0 \quad (8c)$$

$$f_{2b} = \frac{1}{2}(\sigma'_1 - \sigma'_3) + \frac{1}{2}(\sigma'_1 + \sigma'_3)\sin\phi - c\cos\phi \leq 0 \quad (8d)$$

$$f_{3a} = \frac{1}{2}(\sigma'_1 - \sigma'_2) + \frac{1}{2}(\sigma'_1 + \sigma'_2)\sin\phi - c\cos\phi \leq 0 \quad (8e)$$

$$f_{3b} = \frac{1}{2}(\sigma'_2 - \sigma'_1) + \frac{1}{2}(\sigma'_2 + \sigma'_1)\sin\phi - c\cos\phi \leq 0 \quad (8f)$$

Where ϕ, c are the friction angle and cohesion of the soil respectively. The condition $f_i = 0$ for all yield functions together give a hexagonal cone as shown in Figure 1.

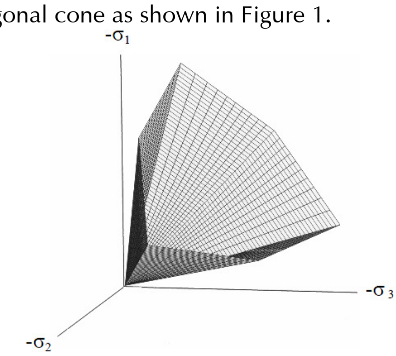

Figure 1. The Mohr-Coulomb yield surface in principal stress space for $c = 0$.

The plastic potential functions of Mohr-Coulomb model are defined as below:

$$g_{1a} = \frac{1}{2}(\sigma'_2 - \sigma'_3) + \frac{1}{2}(\sigma'_2 + \sigma'_3)\sin\psi \quad (9a)$$

$$g_{1b} = \frac{1}{2}(\sigma'_3 - \sigma'_2) + \frac{1}{2}(\sigma'_3 + \sigma'_2)\sin\psi \quad (9b)$$

$$g_{2a} = \frac{1}{2}(\sigma'_3 - \sigma'_1) + \frac{1}{2}(\sigma'_3 + \sigma'_1)\sin\psi \quad (9c)$$

$$g_{2b} = \frac{1}{2}(\sigma'_1 - \sigma'_3) + \frac{1}{2}(\sigma'_1 + \sigma'_3)\sin\psi \quad (9d)$$

$$g_{3a} = \frac{1}{2}(\sigma'_1 - \sigma'_2) + \frac{1}{2}(\sigma'_1 + \sigma'_2)\sin\psi \quad (9e)$$

$$g_{3b} = \frac{1}{2}(\sigma'_2 - \sigma'_1) + \frac{1}{2}(\sigma'_2 + \sigma'_1)\sin\psi \quad (9f)$$

Where ψ is the dilatancy angle of the soil. Hence, there are five parameters including c, ϕ and ψ for plasticity and E and ν for elasticity are required for Mohr-Coulomb model.

4. Considered cases

The heterogeneous soil in My Thuan bridge, Vinh Long province (Figure 3), which across the Tien Giang branch of the Mekong River is located 125 km south-west of Ho Chi Minh City on National Highway No 1, the main highway through the Mekong Delta. Figure 4 presented generalized soil profile. The soil profile at the bridge site can be summarized as follow: (i) First Clay Layer, (ii) First Sand Layer, (iii) Second Clay Layer, (iv) Second Sand

Layer, (v) Third Clay Layer, (vi) Third Sand Layer (Mitchell et al., 1994).

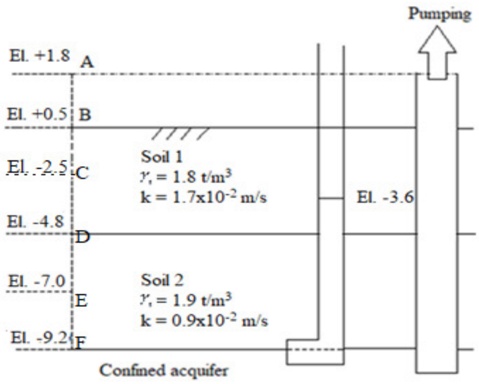

Figure 2. Hypothetical heterogeneous soil in flood zone (2 layers).

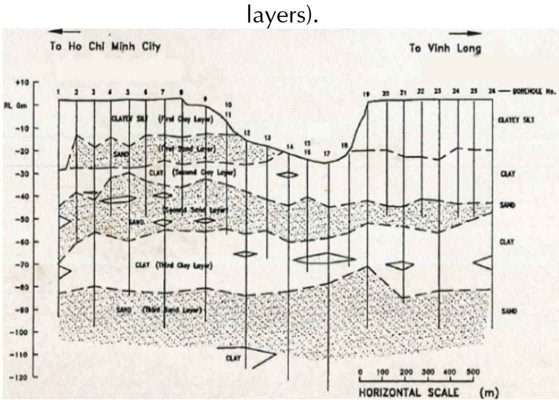

Figure 3. Soil profile in My Thuan bridge, Vinh Long province.

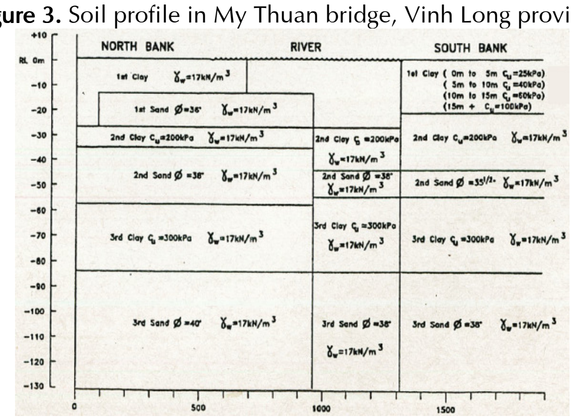

Figure 4. Geotechnical model in My Thuan bridge, Vinh Long province.

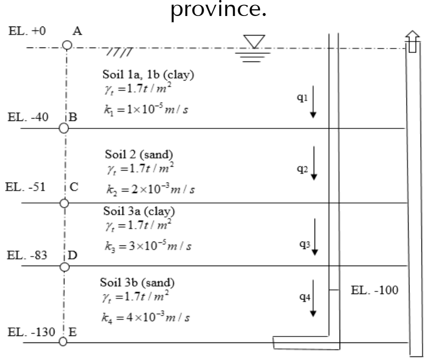

Figure 5. Heterogeneous soil in My Thuan bridge, Vinh Long province.

Considering a well in the layers of soil as shown in figure 5, specific location at My Thuan bridge (North Bank), Vinh Long province. Elevations of given points are also given in this figure. Calculating the distribution of subsidence 1 well in t = 1 year.

5. Geological parameters

Application of geological parameters of these soils, the geological parameters are as follows:

Table 1. Index of geological parameters of hypothetical heterogeneous soil in flood zone.

Parameters	Soil 1	Soil 2
Thickness (m)	40	11
Description	sand	sand
Model	Mohr-Coulomb	Mohr-Coulomb
γ_{unsat} (KN/m³)	18.000	19.000
γ_{sat} (KN/m³)	18.000	19.000
E_{ref}(KN/m²)	1.3E+04	1.3E+04
v	0.30	0.30
c_{ref} (KN/m²)	1.00	1.00
φ (⁰)	31.00	31.00

Table 2. Index of geological parameters of soil in My Thuan Bridge.

Parameters	Soil 1a, 1b	Soil 2	Soil 3a	Soil 3b
Thickness (m)	40	11	32	47
Description	clay	sand	clay	sand
Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
γ_{unsat} (KN/m³)	17.000	17.000	17.000	17.000
γ_{sat} (KN/m³)	17.000	17.000	17.000	17.000
E_{ref}(KN/m²)	1.0E+04	1.3E+04	1.0E+04	1.3E+04
v	0.35	0.30	0.35	0.30
c_{ref}(KN/m²)	5.00	1.00	5.00	1.00
φ (⁰)	25.00	31.00	25.00	31.00

6. Calculation principles

6.1 Based on 1-D water flow theory in hypothetical heterogeneous soil in flood zone (2 layers)

1. Set datum line: $\rightarrow$ "h_e"

2. Calculate h_p, h_t at know points

$$h_p = u / \gamma_w \quad (10)$$

$$h_t = h_p + h_e \quad (11)$$

3. For water flow through different soil: Use "continuity equation" to solve problem.

4. For water flow through the same layer,

$k = const \Rightarrow i = const$

$$i = \Delta h_t / L = (h_{t2} - h_{t2}) / L_{21} = (h_{t3} - h_{t2}) / L_{32} = const \quad (12)$$

Can use "known i" to solve h_t at any point

(11) $\Rightarrow h_p = h_t - h_e$

(10) $\Rightarrow u = h_p \gamma_w$

5. Amount of flow

$q = kiA$

in which: $q =$ rate of water flow (m^3)

$k =$ Coefficient of permeability (ms^{-1})

$i =$ hydraulic gradient = (dimensionless)

$A =$ cross sectional area (m^2)

6. Pumping rate flow over time

$Q = qt$

in which: $Q =$ pumping rate of water flow (m^3)

$t =$ time (s)

6.2 Based on 1-D water flow theory in My Thuan bridge soil (4 layers)

According to the study of Laura E Erban in 2014, the subsidence of the Mekong Delta is within $\Delta b \approx 0 - 4$ cmyr^{-1} [Laura et al. 2014) an average of about 2 cmyr^{-1}.

Assume: for h_{tF} to $\Delta b \approx 2$ cmyr^{-1} $\Longrightarrow$ select $h_{pF} = 30$ m, elevation rise is El. = -100 m.

$\Longrightarrow h_{tF} = h_{pF} + h_{eF} = 30 + (-130) = -100$ m.

Assume the groundwater at the surface ground

$\Longrightarrow$At A: $h_{tF} = 0(m),\ h_{pF} = 0(m),\ h_{eF} = 0(m).$

$\Longrightarrow$At F: $h_{tF} = -100(m)\ h_{pF} = 30(\text{m}),\ h_{eF} = -130(m).$

According to 1D theory to calculate h_t; h_p; h_e at the remaining points and find the flow rate for a period of 1 year.

$q = kiA$

$Q = qt$

Appling to the formula for calculation of Riley method (1969), choose the coefficient of water discharge $S_s = 0.0004(m^{-1})$ (Ty *et al., 2017)* based on the study of Ty et al..

Preparing a summary table, the chart presents the relationship between settlement at each point. Develop a formula for calculating vertical distribution settlement (Z), which occurs due to groundwater pumping.

7. Results and discussions

Based on one-dimension water flow theory and Riley's method to calculate the land subsidence. Results of the land subsidence in hypothetical soil and in My Thuan Bridge soil are presented in Table 3 and Table 4 respectively.

Table 3. Results of land subsidence calculations due to lowering of groundwater level in hypothetical soil.

Component \ Point		A	B	C	D	E	F
Elevation		+1.8	+0.5	-2.5	-4.8	-7.0	-9.2
(1)	h_e (m)	1.8	0.5	-2.5	-4.8	-7.0	-9.2
	h_p (m)	0.0	1.3	3.1	4.5	5.0	5.6
	U (T/m^2)	0.0	1.3	3.1	4.5	5.0	5.6
	h_t (m)	1.8	1.8	0.61	-0.30	-1.95	- 3.6
	h_a (m)	1.8	1.21	0.15	-1.13	-2.78	- 3.6
(2)	h_e (m)	1.8	0.5	-2.5	- 4.8	- 7.0	- 9.2
	h_p (m)	0.0	1.3	2.8	3.9	4.5	4.9
	U (T/m^2)	0.0	1.3	2.8	3.9	4.5	4.9
	h_t (m)	1.8	1.8	0.31	-0.83	-2.54	-4.24
	h_a (m)	1.80	1.06	0.26	-1.68	-3.39	-4.24
ΔQ (m^3)		3.89x10^3					
Δh (m)		0	0.11	0.31	0.54	0.85	1.0
Δb (cm)		0	0.16	0.15	0.12	0.07	0.0

Table 4. Results of land subsidence calculations due to lowering of groundwater level in My Thuan bridge soil, Vinh Long Province.

Component \ Point		A	B	C	D	E
Elevation		0	-40	-51	-83	-130
(1)	h_e (m)	0	-40	-51	-83	-130
	h_p (m)	0	-38.90	-27.79	-16.77	30.00
	U (T/m^2)	0	-38.90	-27.79	-16.77	30.00
	h_t (m)	0	-78.90	-78.79	-99.77	-100.00
	h_a (m)	0	-40	-51	-83	-130
(2)	h_e (m)	0	-39.37	-28.26	-17.37	29.40
	h_p (m)	0	-39.37	-28.26	-17.37	29.40
	U (T/m^2)	0	-79.37	-79.26	-100.37	-100.60
	h_t (m)	0	-38.90	-27.79	-16.77	30.00
	h_a (m)	0	-38.90	-27.79	-16.77	30.00
ΔQ (m^3)		3.89 x 10^3				
Δh (m)		0.24	0.47	0.53	0.60	0.60
Δb (cm)		2.39	2.01	1.81	1.12	0.00

((1) Before pumping; (2) After pumping).

8. Figure of results

8.1 Analysis results

Figure 6 presents ground settlement is a function of depth and soil properties. This relationship is nonlinear and the curve is also different in each layer. Settlement of soil near the surface is larger than settlement of soil at larger depth.

Figure 7 shows for soil in My Thuan Bridge, ground settlement is a function of depth and soil properties. This relationship is nonlinear and the curve is also different in each soil layer. Settlement of soil near the surface is larger than settlement of soil at larger depth.

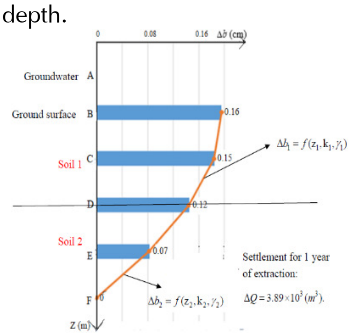

Figure 6. Relationship between Δb (cm) and Z in hypothetical soil.

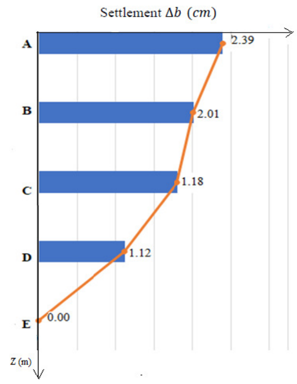

Figure 7. Relationship between Δb (cm) and Z in My Thuan Bridge soil.

Figure 8 shows the effective stress of before pumping, the value is -81.55kPa and after pumping, the effective stress is -91.55kPa. So, effective stress increases 10kPa. Therefore, this causes land subsidence.

8.2 Finite element method (Plaxis 2D) results

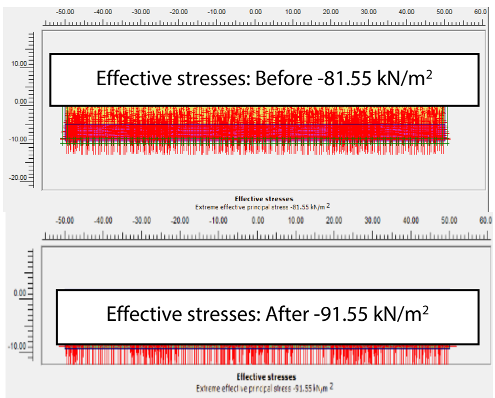

Figure 8. The water pressure before and after pumping of hypothetical soil.

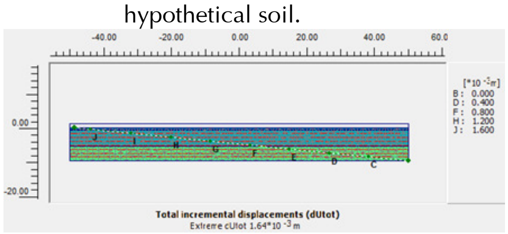

Figure 9. Distribution of ground settlement with depth of 2 layers soil.

8.3 Results of heterogenous soil (My Thuan Bridge, Vinh Long Province)

Figure 9 presents the water table decrease from +1.8m to -0.11m, the ground surface subsidence (N) is 0.16cm. It is the same with Riley's method (0.16cm).

Figure 10 shows the effective stress of before pumping, the value is -908.62kPa and after pumping, the effective stress is -924.62kPa. So, effective stress increases 16 kPa. Therefore, this causes land subsidence.

Figure 11 presents the water table degrease from 0m to -0.6m, the ground surface subsidence (N) is 2.39cm. It is the same as Riley's method (2.39cm).

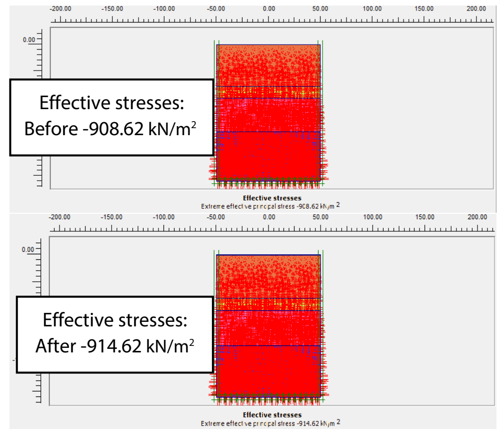

Figure 10. The water pressure before and after pumping of My Thuan Bridge soil.

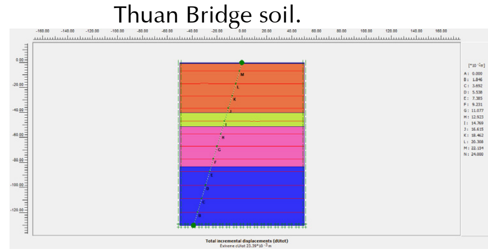

Figure 11. Distribution of ground settlement with depth of My Thuan bridge soil.

9. Conclusions

This research was based on 1D and Riley's method to calculate the land subsidence of two cases of layered soils: hypothetical soil and soil in My Thuan Bridge, Vinh Long Province. The results showed that ground settlement is a function of local position as well as soil properties and this relationship is nonlinear with the curve is different in each soil layer. Settlement of soil near the surface is larger than settlement of soil at larger depth. 1D and Riley's method can also capture the relationship between land subsidence with depth (Z). Finite element method (Plaxis 2D) can be used to simulate the effect of land subsidence due to groundwater pumping.

References

[1] R. B. J. Brinkgreve, et al. (2007). Plaxis user's manual, Version 8.2. Rotterdam: Balkema.

[2] L. E. Erban, S. M. Gorelick and H. A. Zebker., (2014). *Groundwater extraction, land subsidence and sea-level rise in the Mekong Delta*. Vietnam *Environ. Res. Left. 9*.

[3] L.V. Trung and H.D. Tống., (2008). *Ứng Dụng Kỹ Thuật Insar vi Phân Trong Quan Trắc Biến Dạng Mặt Đất Khu Vực Thành Phố Hồ Chí Minh*. Tạp chí phát triển khoa học và công nghệ, tập 1, số 12, 121–30.

[4] P. W. Mitchell and B. J. Harris., (1996). *Geotechnical Aspects of My Thuan Brige Project in Vietnam*. Geotechnical services, Rust PPK Pty. Ltd.

[5] M. F. Randolph., (2003). *Science and empiricism in pile foundation design*. Geotechnique 54, No. 1 444-444.

[6] F. S. Riley., (1969). *Analysis of borehole extensometer data from central California*. Int. Assoc. Sci. Hydrol. Publ

[7] 89 423-31.

[8] T. V. Ty and H. V. Hiep., (2017). *Trạng khai thác nước dưới đất và mối tương quan giữa hạ thấp cao độ mực nước và sụt lún đất: nghiên cứu tại Trà vinh và thành phố Cần thơ*. Tạp chí trường Đại học Cần Thơ, Môi trường và Biến đổi khí hậu 128-136.