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Research Article

Numerical Modelling of Flood Induced Seepage Under Levees

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Abstract

Flood creates the most complex problems of engineering hydrology and extreme flood contains the crucial risk for urban areas, infrastructure, industry and agriculture. The aim of this paper is to study the transient flow caused by flood for levee of Filyos River. Numerical modeling based on finite element method was performed in the analyses. PlaxFlow which is an add-on module to Plaxis 2D, is used for the time variation of seepage in several points of interest within the levee. Exit velocity at several points of interest within the levee and degree of saturation of levee and hydraulic gradient were investigated. In addition, under seepage of water through different soil types underneath Filyos levee was examined. The results of transient flow analyses when piping occurred and sand boil formed were presented for different soil types.

Keywords: Seepage, Transient Flow, Levee, Flood, Finite Elements Method.

Sedde Altında Taşkın Kaynaklı Sızmanın Nümerik Modellenmesi

Öz

Taşkın, mühendislik hidrolojisinin en karmaşık sorunlarını meydana getirir ve aşırı taşkın, kentsel alanlar, altyapı, sanayi ve tarım için hayati riskleri içerir. Bu makalenin amacı, Filyos Nehri seddesi üzerinde taşkınların neden olduğu düzensiz akışı incelemektir. Analizlerde sonlu elemanlar yöntemine dayalı sayısal modelleme yapılmıştır. Plaxis 2D'ye bir eklenti modülü olan PlaxFlow, program dahilindeki çeşitli ilgi noktalarında sızıntının zaman değişimi analizi için kullanılır. Seddenin çeşitli ilgi noktalarında çıkış hızı, hidrolik eğim ve doygunluk derecesi incelenmiştir. Ayrıca Filyos seddesinin altındaki farklı zemin türleri için su sızıntısı da incelenmiştir. Borulama meydana geldiğinde ve oluşan kum kaynamasında meydana gelen düzensiz akış analizlerinin sonuçları farklı zemin tipleri için sunulmuştur.

Anahtar Kelimeler: Sızma, Düzensiz Akış, Sedde, Taşkın, Sonlu Elemanlar Methodu.

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1. Introduction

Floods are one of the most complex and important problems of engineering hydrology. It is a widespread problem in many countries, including Turkey. They form the risk for urban areas, infrastructure, industrial structures and agriculture. Filyos River basin covers area of 13.300 km^2 in the Western Black Sea region in Zonguldak (Figure 1). The project area is 203 km at the east-west direction, at 120 km north-south direction and the slope of the river is quite small. Project area is located at the Filyos river in the north of the area of rainfall and Filyos River flood plain of a north-south direction is 33.35 km long. Filyos river and tributaries of the river as Yenice, Devrek, Soganlı and Arac river form water sources of project area. Yenice River is the biggest tributary of the Filyos River Side.

Figure 1. Filyos River Basin (Atış, 2019)

2. Material and Method

Levees are embankments constructed of compacted earthen material. These materials can be impervious and semi-impervious but sometimes there may be pervious levee fill such as sands or gravels. Levees are generally constructed for floods of range of frequencies 50 years (average between 25 or 100 years). Slope of levee outline is choosen as equal slope of water surface during flood. Phreatic line of filling determines the size of levee. The flood protection project of Filyos River included the construction of a total 7 km of levee, and these levees are 3.5 km long along the right and left shore. Distance between two levees is approximately 300 m and the levee height is 6.7 m (Figure 2).

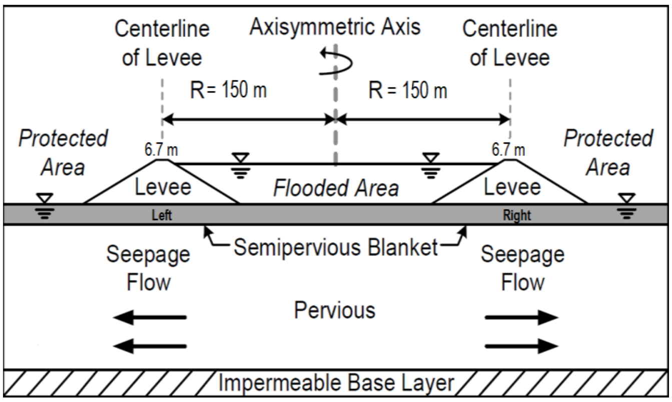


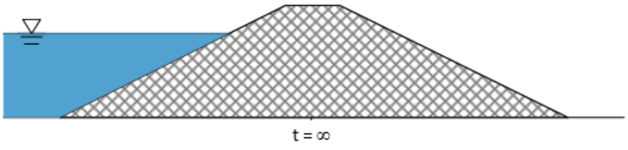
Figure 2. Filyos River Levees

The most important parameters for designing a levee are the precipitation and runoff of rivers. The relation between the time and height of the water was assummed as stable while Filyos levee is designed. In other words, a steady-state seepage occurs when hydraulic head, flow rate or given soil hydraulic properties are not changing with time. In transient flows, the variables depend on time (Figure 3). Steady-state seepage as a "saturated" flow condition and transient seepage as a "partially saturated or unsaturated" flow condition. Transient analyses can be successful to estimate the development of the uplift forces, exit gradients for the factor of safety against uplift, or the heave pressures acting on the base of a top stratum in regard to hydrograph for the flood event (Tracy et al., 2016). Transient flow is determined in an isotropic and homogeneous soil domain by the following partial differential equation.

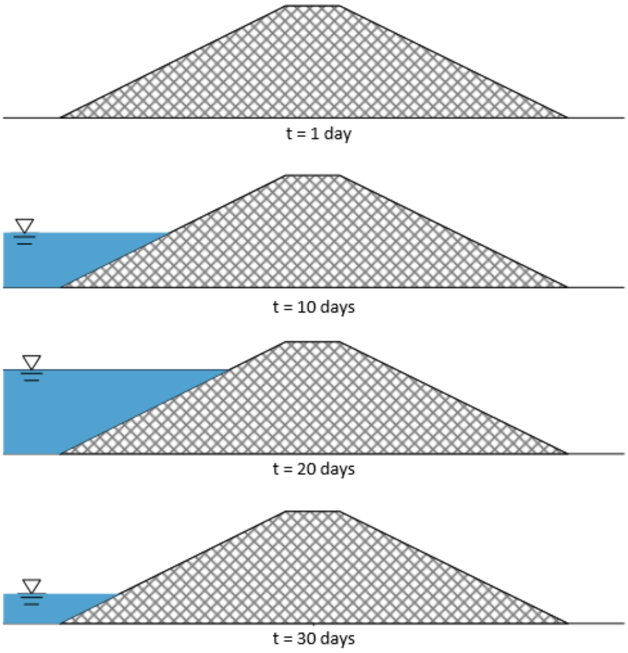
$$\mathrm{div}[\mathrm{k}\,\mathrm{grad}(\mathrm{h})] + \mathrm{c}\frac{\partial \mathrm{h}}{\partial \mathrm{t}} = \mathrm{Q} \qquad (1)$$

where;
k =hydraulic conductivity of soil
h =hydraulic head
c =specific capacity of soil
t =elapsed time
Q=discharge quantity

Unit hydrograph is the most popular method and widely used one for predicting flood hydrograph. It must be obtained for transient seepage analyses. There are widely used flood estimation methods such as statistical, rational, Mockus and Synder methods (Gulbahar, 2016). Every method has some significant limited conditions and these methods can give different results even for the same basin. A suitable method should be selected according to meteorological, hydrologic, topographic conditions of a basin.



(a) Steady State Analysis



(b) Transient Analysis

Figure 3. Steady-state and transient boundary conditions on riverside of levee (Tracy et al., 2016)

2.1. Determining Unit Hydrograph and Flow Hydrograph

Unit hydrograph is the most popular method and widely used method for predicting flood hydrograph. Synder method is used due to the fact that flood basin of Filyos river is larger than 1000 km^2.The basin characteristics which are area, shape, topography, channel slope, stream density are affected the shape of unit hydrograph is the main idea of this method. The unit hydrograph graph is obtained with the help of (q_v) yield value. Figure 4 is used to find width of hydrograph. 0.75 q_p and 0.50 q_p is equal to Tw_{75} and Tw_{50} to obtain unit hydrograph. Peak discharge is calculated according to equation 7.

L= 195 km
L_c= 92 km
t_p = C_t*(L*L_c)0,3 = 30.8 hr (2)
t_r = t_p / 5.5 = 5.5 hr (3)
q_p = 2760 * C_p / t_p = 54.8 (lt/s/km^2/cm) (4)
Q_p = q_p * A * 10^{-3} = 72.8 (m^3/s/mm) (5)
N = 0.9*A*0,2 = 6 days (6)
Q_p = q_p * A * 10^{-3} = 72.8 (m^3/s/mm) (7)
Tw_{50} = 58 hr 1/3.Tw_{50} = 19.3 hr 2/3.Tw_{50} = 38.7 hr
Tw_{75} = 35 hr 1/3.Tw_{75} = 12 hr 2/3.Tw_{75} = 23 hr

where;
L = Length of levee
L_c = Length of between the centry of gravity of basin and exit point of basin
C_t = Basin coefficient
C_p = Basin coefficient
t_p = The time of duration for peak discharge
t_r = The time of effective precipitation
q_p = Peak discharge per unit area
A = Area of basin
N = Fall time of the flood level

Table 1.Filyos River Flood Peak Calculation

Filyos River Flood Peak Calculation	
100-Year Precipitation Height of the Basin (mm)	85.82
Critical Rainfall Time (hr)	24
Total Flow (mm)	29.12
Q_p (m^3/s/mm)	72.8
Peak Discharge of Hydrograph (m^3/s)	2120

Figure 4 shows a relation between the discharge and time. Figure 5 presents relation river level and time during the flood. Peak discharge is 2120 m^3/s at 6.5 meter high of levee and the time of duration for peak discharge (T_p) completed 30.8 hours (Akdeğirmen et al., 2008). The fall time of the flood level is 144 hours. Time of duration of hydrograph of Filyos River approximately completed 7.5 days. The levee height is designed as 6.7 meters and air share of levee is 0.2 meters. The maximum discharge reaches 6.5 meters of the levee. In PlaxFlow, data of the change of flood height depending on time was entered. Consequently, seepage was investigated the change of flood height depending on time (transient analysis) in Filyos levees. Therefore, in each seepage analysis, flood height-time graph data is used.

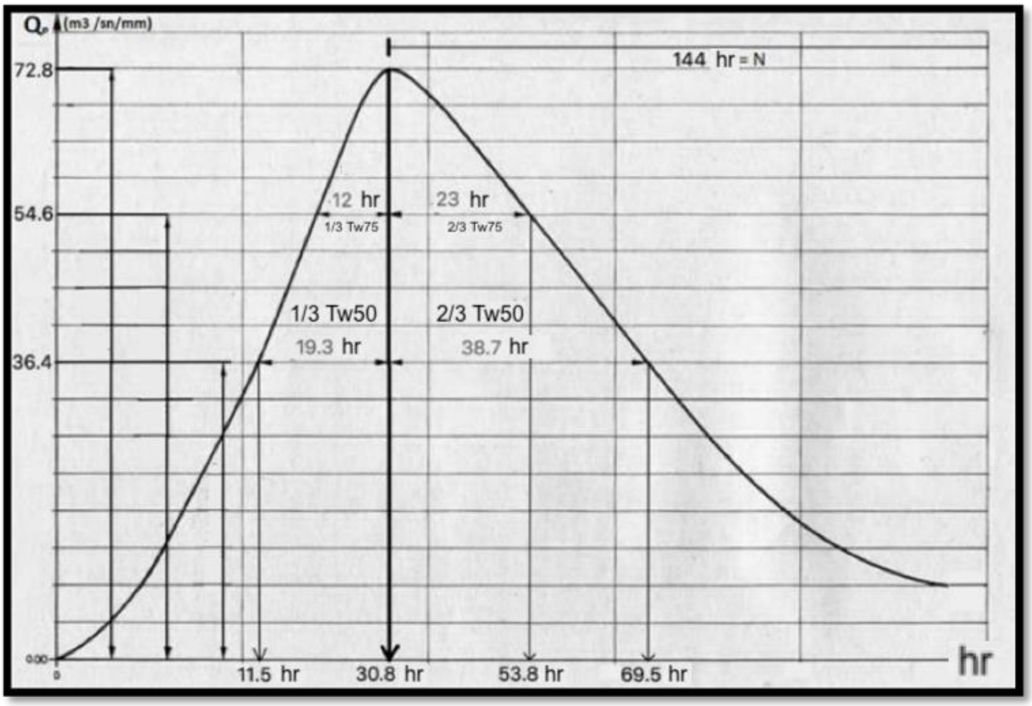


Figure 4. Unit Hydrograph of Snyder Method (Çelik, 2012)

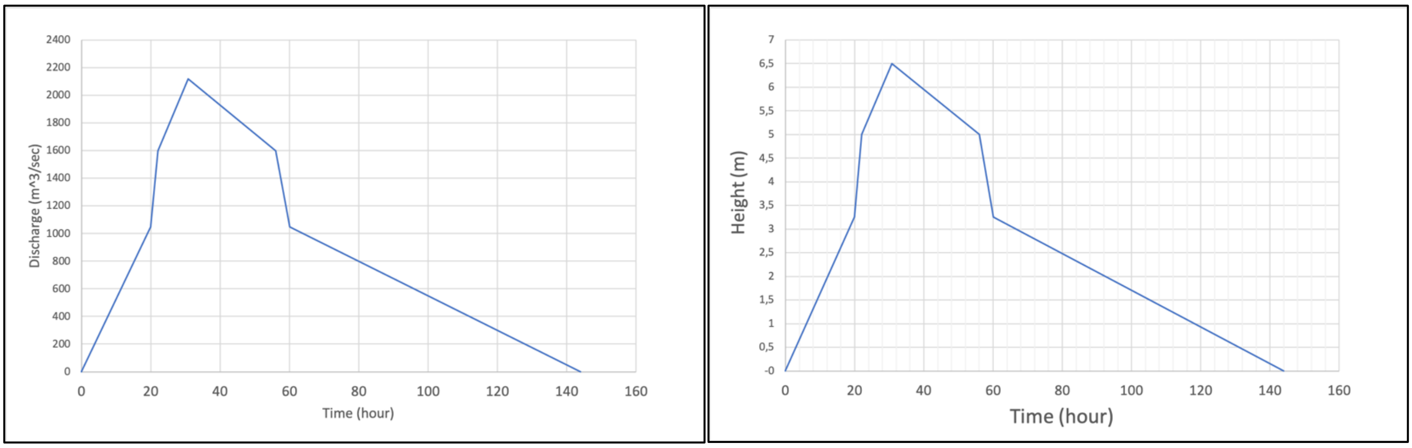


Figure 5. Flow hydrograph relation between the river height, discharge and time

2.2. Permeability of Soils

Soil permeability is a property of the soil transmitting water and it is one of the most important qualities to consider for seepage analyses. The permeability of soils is really important to determine the effect on stability of foundations, seepage loss through embankments of reservoirs, drainage of subgrades, excavation of open cuts in water bearing sand, rate of flow of water into wells and many others. Soil permeability is influenced by many factors such as pore size, particle shape, particle density, fluid density and number of pores. In 1856, Darcy found a linear relationship between the seepage velocity and hydraulic gradient.

$v = k.i$ (Terzaghi et al, 1996) (8)

where;
v = seepage velocity (m/s)
k = soil permeability (m/s)
i = Hydraulic gradient

2.3. Seepage and Erosion

The interaction between soils and percolating water influences the design of foundations and earth slopes and the quantity of water that lost by leakage through some hydraulic structures (Murthy, 2018). Foundation failures happens due to excess pressure of water which tries to lift up the soil on downstream sides of some hydraulic structures. Erosion is called that soil particles are removed and carried with the water flow deu to the fact that erosion resistant forces are less than seepage forces (Lopez et al., 2010). The soil erosion problems may occur in river banks and factors affecting soil erosion are the erodibility of the soil, the water velocity inside the soil mass or the water velocity on a river and geometry of levee (Lopez et al., 2010). If the hydraulic gradient reaches the critical hydraulic gradient, the balance in the soil mass is distorted and it moves up (Lopez et al., 2010). The soil surface floots and the soil – water mixture exits on the surface. This is called piping or internal erosion. Heaving can be observed when seepage forces push the substrata upward.

$$i_c = \frac{\gamma'}{\gamma_w} = \frac{G_s-1}{1+e} \qquad (9)$$

where;
i_c=critical hydraulic gradient
γ'=effective unit weight of soil
γ_w=unit weight of water
G_s=specific gravity of soil
e= void ratio of soil

2.4. Development of Underseepage and Sand Boils

During a flood, holes or cracks under the levee structure occur due to increasing in water pressure. Thus; piping through sand, silty sand, sandy silt and silty soils happens because of underseepage at the levee. A sand boil forms that water seeps through pipes from the water side to the land side of the levee and carries levee foundation material out from underneath of the levee. The critical gradient is the important parameter to cause sand boils or heaving. Critical gradients for silty clay and clay are 0.8 and for silty sands and silts are 0.85.

2.5. Investigation Soil Properties for Piping

Piping can be observed in sandy gravelly soils that have small quantities of fine particles and for these soils d_{10}=0.25 mm, C_u>20, C_c>3 for the piping. In general, higher critical exit gradients are observed for the coarser and the denser sand (Ozkan, 2003). Ozkan S. (2003) observed that 98 % by weight of eroded grains were smaller than 0.125 mm in diameter for sand boil formation during Mississippi River flood of 1993. Sherard et al. (1972) showed that non cohesive silt, rock flour and very fine sands disperse in water and may be highly erosive (Ozkan, 2003).

3. Materials

Drilling must be made in order to know the soil properties by using SPT testings. Since the alluvium forming the basement floor is very variable in Filyos basin, it was better to perform shallower and frequent foundation drilling. Six drillings were drilled at 30 meters deep on the left shore and, on the right shore, a total of five drillings were drilled at depths of 30 m depend on project. Table 2 presents the depth and locations of the drilled wells. Table 5 presents the soil properties of Filyos River basin. As an example, Table 6 presents the soil properties along a depth of TSK-1 drilled well. TSK- X is called name of drillings points that is stayed landside. Tests of determining the mentions soil parameter are gravity of soil solids by water pycnometer; relative density test; standard test for density of soil in place by the drive-cylinder method.

Table 2. Depth and location properties of foundation drilling wells

No	Drilling No	Well Point	Locations (km)	Depth (m)
1	TSK-1	Left Shore	0+044.24	30
2	TSK-2	Left Shore	0+511.29	30
3	TSK-3	Left Shore	1+010.63	30
4	TSK-4	Left Shore	1+513.22	30
5	TSK-5	Left Shore	2+005.66	30
6	TSK-6	Left Shore	2+501.94	30
7	TSK-9	Right Shore	0+271.05	30
8	TSK-10	Right Shore	0+758.18	30
9	TSK-11	Right Shore	1+256.40	30
10	TSK-12	Right Shore	1+762.17	30
11	TSK-13	Right Shore	2+327.64	30

Table 3. Specific Gravity Standard (Hosni, 2015)

Soil Type	G_S values
Sand	2.63-2.67
Clay	2.65-2.7
Clay and Silty Clay	2.67-2.9
Organic soil	Less than 2

Table 4. Void Raito-Unit Weight Standards (Han, 2018)

Soil Type	e (void ratio)	γ_{sat} (kN/m^3)	γ_d (kN/m^3)
Uniform sand	1.0 - 0.40	13.2-21.4	13-18.5
Silty Sand	0.9 - 0.3	13.8-22.3	13.7-19.9
Clean, well-graded sand	0.95 - 0.2	13.5-23.2	13.4-21.7
Silty Sand and Gravel	0.85 - 0.14	14.1-24.3	14.0-22.9
Sandy or Silty Clay	1.8 - 0.25	15.7-23.1	9.4-21.2
Well Graded Sand, Gravel, Silt and Clay Mixture	0.7 - 0.13	19.6-24.5	15.7-23.2

Table 5. Soil Properties Of Filyos Basin

Soil Type	G_S (Specific Gravity	e (void ratio)	γ_{sat} (kN/m^3)	γ_s (kN/m^3)
Clayey Silt	2.70	0.90	18.6	26.5
Silty Clay	2.75	1.78	16.0	27.0
Clayey Sand	2.67	0.43	21.3	26.2
Sand	2.68	0.55	20.4	26.3
Gravelly Sand	2.66	0.62	19.9	26.1
Gravel	2.65	0.27	22.6	26.0
Silty Sand	2.69	0.43	21.4	26.4
Sandy Silt	2.68	0.85	18.7	26.3
Sandy Clay	2.72	0.47	21.3	26.7
Sandy Gravel	2.65	0.50	20.6	26.0
Clay	2.80	1.85	16.0	27.5
Silt	2.70	1.10	17.8	26.5
Gravelly Clay	2.71	0.80	19.1	26.6
Gravelly Silt	2.69	0.75	19.3	26.4

Table 6. Soil Properties of TSK-1

Depth(m)	Soil Type	Permeability(k) (m/sec)	Specific Gravity (G_s)	Void Ratio (e)
0.0-6.0	Clayey Silt	$1x10^{-7}$	2.70	0.90
6.0-27.5	Silty Clay	$5x10^{-8}$	2.75	1.78
27.5-29.0	Clayey Silt	$1x10^{-7}$	2.70	0.90
29.0-30.0	Silty Clay	$5x10^{-8}$	2.75	1.78

Table 7. Soil Properties of TSK-2

Depth(m)	Soil Type	Permeability(k) (m/sec)	Specific Gravity (Gs)	Void Ratio (e)
0.0-2.0	Clayey Sand	$1x10^{-6}$	2.67	0.43
2.0-3.0	Silty Clay	$5x10^{-8}$	2.75	1.78
3.0-3.5	Clayey Sand	$1x10^{-6}$	2.67	0.43
3.5-10.0	Silty Clay	$5x10^{-8}$	2.75	1.78
10.0-10.5	Sand	$1x10^{-4}$	2.68	0.55
10.5-12.0	Silty Clay	$5x10^{-8}$	2.75	1.78
12.0-12.5	Clayey Sand	$1x10^{-6}$	2.67	0.43
12.5-13.5	Silty Clay	$5x10^{-8}$	2.75	1.78
13.5-14.0	Clayey Sand	$1x10^{-6}$	2.67	0.43
14.0-14.50	Silty Clay	$5x10^{-8}$	2.75	1.78
14.5-18.5	Gravelly Sand	$5x10^{-4}$	2.66	0.62
18.5-19.0	Silty Clay	$5x10^{-8}$	2.75	1.78
19.0-20.0	Gravelly Sand	$5x10^{-4}$	2.66	0.62
20.0-20.5	Silty Clay	$5x10^{-8}$	2.75	1.78
20.5-23.0	Gravelly Sand	$5x10^{-4}$	2.66	0.62
23.0-23.5	Gravel	$1x10^{-2}$	2.65	0.27
23.5-30.0	Gravelly Sand	$5x10^{-4}$	2.66	0.62

Table 8. Soil Properties of TSK-3

Depth (m)	Soil Type	Permeability(k) (m/sec)	Specific Gravity (Gs)	Void Ratio (e)
0.0-0.6	Silty Clay	$5x10^{-8}$	2.75	1.78
0.6-4.0	Silty Sand	$1x10^{-6}$	2.69	0.43
4.0-8.0	Gravel	$1x10^{-2}$	2.65	0.27
8.0-10.0	Silty Sand	$1x10^{-6}$	2.69	0.43
10.0-20.0	Sand	$1x10^{-4}$	2.68	0.55
20.0-28.0	Clayey Silt	$1x10^{-7}$	2.70	0.90
28.0-29.0	Silty Clay	$5x10^{-8}$	2.75	1.78
29.0-30.0	Clayey Silt	$1x10^{-7}$	2.70	0.90

Table 9. Soil Properties of TSK-4

Depth(m)	Soil Type	Permeability(k) (m/sec)	Specific Gravity (Gs)	Void Ratio (e)
0.0-2.0	Sand	$1x10^{-4}$	2.68	0.55
2.0-2.5	Sandy Silt	$1x10^{-7}$	2.68	0.85
2.5-3.5	Sandy Clay	$1x10^{-6}$	2.72	0.47
3.5-7.0	Gravelly Sand	$5x10^{-4}$	2.66	0.62
7.0-10.0	Sand	$1x10^{-4}$	2.68	0.55
10.0-12.0	Gravelly Sand	$5x10^{-4}$	2.66	0.62
12.0-14.0	Silty Sand	$1x10^{-6}$	2.69	0.43
14.0-17.5	Silty Clay	$5x10^{-8}$	2.75	1.78
17.5-18.5	Sandy Clay	$1x10^{-6}$	2.72	0.47
18.5-20.5	Clayey Sand	$1x10^{-6}$	2.67	0.43
20.5-23.0	Sand	$1x10^{-4}$	2.68	0.55
23.0-24.0	Silty Clay	$5x10^{-8}$	2.75	1.78
24.0-24.5	Sand	$1x10^{-4}$	2.68	0.55
24.5-25.5	Silty Clay	$5x10^{-8}$	2.75	1.78
25.5-28.5	Sand	$1x10^{-4}$	2.68	0.55
28.5-30.0	Silty Clay	$5x10^{-8}$	2.75	1.78

Table 10. Soil Properties of TSK-5

Depth(m)	**Soil Type**	**Permeability(k) (m/sec)**	**Specific Gravity (Gs)**	**Void Ratio (e)**
0.0-4.0	Sandy Silt	$1x10^{-7}$	2.68	0.85
4.0-8.0	Silty Sand	$1x10^{-6}$	2.69	0.43
8.0-28.0	Silty Clay	$5x10^{-8}$	2.75	1.78
28.0-30.0	Clayey Silt	$1x10^{-7}$	2.70	0.90

Table 11. Soil Properties of TSK-6

Depth(m)	**Soil Type**	**Permeability(k) (m/sec)**	**Specific Gravity (Gs)**	**Void Ratio (e)**
0.0-2.0	Silty Sand	$1x10^{-6}$	2.69	0.43
2.0-3.0	Silty Clay	$5x10^{-8}$	2.75	1.78
3.0-4.0	Gravel	$1x10^{-2}$	2.65	0.27
4.0-12.0	Gravelly Sand	$5x10^{-4}$	2.66	0.62
12.0-12.5	Gravel	$1x10^{-2}$	2.65	0.27
12.5-15.5	Gravelly Sand	$5x10^{-4}$	2.66	0.62
15.5-16.5	Gravel	$1x10^{-2}$	2.65	0.27
16.5-23.0	Gravelly Sand	$5x10^{-4}$	2.66	0.62
23.0-28.5	Silty Clay	$5x10^{-8}$	2.75	1.78
28.5-30.0	Silty Sand	$1x10^{-6}$	2.69	0.43

Table 12. Soil Properties of TSK-9

Depth(m)	**Soil Type**	**Permeability(k) (m/sec)**	**Specific Gravity (Gs)**	**Void Ratio (e)**
0.0-2.5	Silty Clay	$5x10^{-8}$	2.75	1.78
2.5-4.0	Silty Sand	$1x10^{-6}$	2.69	0.43
4.0-8.0	Sandy Gravel	$5x10^{-3}$	2.65	0.50
8.0-10.0	Sand	$1x10^{-4}$	2.68	0.55
10.0-12.0	Sandy Gravel	$5x10^{-3}$	2.65	0.50
12.0-14.0	Silty Clay	$5x10^{-8}$	2.75	1.78
14.0-15.0	Gravelly Silt	$5x10^{-6}$	2.69	0.75
15.0-18.0	Gravelly Sand	$5x10^{-4}$	2.66	0.62
18.0-20.0	Silty Clay	$5x10^{-8}$	2.75	1.78
20.0-28.0	Clayey Silt	$1x10^{-7}$	2.70	0.90
28.0-30.0	Clayey Sand	$1x10^{-6}$	2.67	0.43

Table 13. Soil Properties of TSK-10

Depth(m)	**Soil Type**	**Permeability(k) (m/sec)**	**Specific Gravity (Gs)**	**Void Ratio (e)**
0.0-4.0	Clayey Silt	$1x10^{-7}$	2.70	0.90
4.0-6.0	Gravel	$1x10^{-2}$	2.65	0.27
6.0-8.0	Silty Sand	$1x10^{-6}$	2.69	0.43
8.0-13.0	Silty Clay	$5x10^{-8}$	2.75	1.78
13.0-14.0	Clayey Silt	$1x10^{-7}$	2.70	0.90
14.0-15.0	Silty Clay	$5x10^{-8}$	2.75	1.78
15.0-23.5	Clayey Silt	$1x10^{-7}$	2.70	0.90
23.5-30.0	Silty Clay	$5x10^{-8}$	2.75	1.78

Table 14. Soil Properties of TSK-11

Depth(m)	Soil Type	Permeability(k) (m/sec)	Specific Gravity (Gs)	Void Ratio (e)
0.0-4.0	Clayey Silt	$1x10^{-7}$	2.70	0.90
4.0-6.0	Gravel	$1x10^{-2}$	2.65	0.27
6.0-8.0	Silty Sand	$1x10^{-6}$	2.69	0.43
8.0-13.0	Silty Clay	$5x10^{-8}$	2.75	1.78
13.0-14.0	Clayey Silt	$1x10^{-7}$	2.70	0.90
14.0-15.0	Silty Clay	$5x10^{-8}$	2.75	1.78
15.0-23.5	Clayey Silt	$1x10^{-7}$	2.70	0.90
23.5-30.0	Silty Clay	$5x10^{-8}$	2.75	1.78

Table 15. Soil Properties of TSK-12

Depth(m)	Soil Type	Permeability(k) (m/sec)	Specific Gravity (Gs)	Void Ratio (e)
0.0-4.0	Clayey Silt	$1x10^{-7}$	2.70	0.90
4.0-8.0	Sandy Gravel	$5x10^{-3}$	2.65	0.50
8.0-10.0	Silty Clay	$5x10^{-8}$	2.75	1.78
10.0-14.0	Sandy Clay	$1x10^{-6}$	2.72	0.47
14.0-18.0	Clay	$1x10^{-8}$	2.80	1.85
18.0-20.0	Silty Clay	$5x10^{-8}$	2.75	1.78
20.0-22.0	Gravelly Clay	$5x10^{-7}$	2.71	0.80
22.0-30.0	Clay	$1x10^{-8}$	2.80	1.85

Table 16. Soil Properties of TSK-13

Depth(m)	Soil Type	Permeability(k) (m/sec)	Specific Gravity (Gs)	Void Ratio (e)
0.0-2.0	Clayey Silt	$1x10^{-7}$	2.70	0.90
2.0-4.0	Sand	$1x10^{-4}$	2.68	0.55
4.0-6.0	Gravel	$1x10^{-2}$	2.65	0.27
6.0-14.0	Sand	$1x10^{-4}$	2.68	0.55
14.0-18.0	Clayey Silt	$1x10^{-7}$	2.70	0.90
18.0-20.0	Silt	$5x10^{-7}$	2.70	1.10
20.0-24.0	Sand	$1x10^{-4}$	2.68	0.55
24.0-30.0	Silty Clay	$5x10^{-8}$	2.75	0.90

3.1. Safety Factors

Soil erosion causes by the underseepage may occur due to several mechanism. Firstly, the seepage exits the soil (exit gradient) is larger than the gradient required to cause erosion of the soil at the location (critical gradient). The soil particles will be eroded from the exit location. This mechanism is commonly named as piping. A second mechanism may be observed when high-hydraulic conductivity soils on the landside of the levee are overlain by a soil layer having lower hydraulic conductivity (Rice et al., 2012). Assesment of exit hydraulic gradients at the toe of levees in water drawdown conditions (López et al., 2015). Due to the lower hydraulic conductivity, water pressure is created at the base of the top layer. If the water pressure grows great enough, it may lift the top layer upward. This is generally called as heave. Then, the top layer may crack and sand boil formation can occur. In the first failure mechanism case, the safety factor against the erosion piping is expressed as follows.

$$\mathrm{F_{bep}} = \frac{\mathrm{i_c}}{\mathrm{i_e}} > 3 - 4 \tag{10}$$

F_{bep}= factor of safety against to erosion piping

i_e = exit graident calculated at the ground surface in the finite-element analysis

i_c = critical gradient of the eroding soil

The exit gradient is calculated using hydraulic head data from the top two to three rows of elements below the ground surface (Rice et al., 2012). In the second failure mechanism case, the safety factor against heave can be expressed as follows;

$$\mathrm{F_{heave}} = \frac{\mathrm{H}.\gamma_{\mathrm{sat}}}{\mathrm{h_m}.\gamma_{\mathrm{w}}} > 3.0 \tag{11}$$

$$\mathrm{i_{max}} = \frac{\mathrm{h_m}}{\mathrm{H}} \tag{12}$$

H = thickness of overlying top layer(m)

γ_{sat}= saturated unit weight of overlying top layer(kN/m^2)

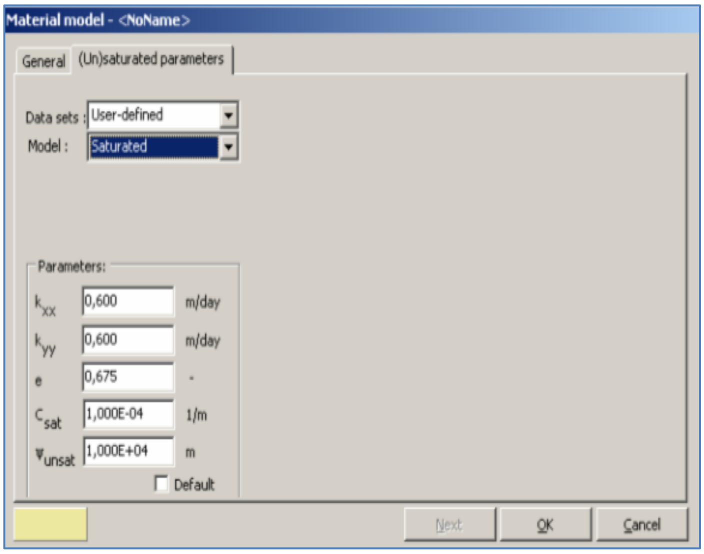
$\mathrm{h_m}$ = average hydraulic head at the point(m)

γ_{w}= water unit wight(kN/m^2)

$\mathrm{i_{max}}$= maximum exit gradient

4. Numerical Modelling

One of the Plaxis products is the PlaxFlow. It is a finite element software for groundwater flow analysis in geotechnical engineering. PlaxFlow enables many features for the analysis of transient groundwater flow problems with several conditions in time. Also, the time-dependent conditions are only used for transient analysis. Irregular variations in water levels are modelled using harmonic, linear or user-defined time distributions to enable time-dependent water level. Time -Water level (Figure 5) data are used for the transient seepage analysis by water level option in time – dependent selection. It solves groundwater flow as transient flow and steady state flow. It can consider unsaturated behavior and time-dependent boundary conditions, deformation and/or stress analysis and stability. It involves different models for saturated/unsaturated groundwater flow, using 'Van Genuchten' relations between pore pressures, saturation and permeability. Van Genuchten (1980) is a well known model that simulates unsaturated soil behavior. The basis of common soil classification systems (Hypres, USDA, Staring) can be selected for various types of soil and also, different types of soil are created using user-defined models relationships between groundwater head, permeability, and saturation. The other important parameter is the time-dependent conditions. It can be created by linear or harmonic function or by means of an input table (Spink, 1996). Output features are distributions of the groundwater head pore pressure, degree of saturation and Darcy flux. Plain strain model is selected to study 2D in all of the transient seepage analyses. Choose the fine option in element distribution in PlaxFlow menu and generate the mesh. Saturated and unsaturated soil behavior is presented in three different options such as standard, advanced, and expert. Expert option is used to define both saturated and unsaturated properties manually (Figure 6). Saturated and unsaturated properties of soils are defined according to groundwater level so user-defined was choosen. This option includes permeabilities, void ratio, c_{sat}(1e-4) and ψ_{unsat}(1e+4) (Brinkgreve et al, 2006). Unsaturated option in user-defined is selected for soil proporties of levee material.


Material model - <NoName>

Data sets : User-defined

Model : Saturated

Parameters:

k_{xx} 0,600 m/day

k_{yy} 0,600 m/day

e 0,675 -

c_{sat} 1,000E-04 1/m

ψ_{unsat} 1,000E+04 m

☐ Default

Figure 6. User-Defined Option

5. Analysis

Location of Filyos levee at 44.24 m on left shore is presented in Figure 7. Filyos levee includes gravelly sand soil type. There is a clayey silt layer under the levee and this layer is 6 m thick. It is seen that flow values are high at the critical region (red area) (Figure 8) in case h_{max} under the flow line according to PlaxFlow. There is a risk that is observed piping at these area.

5.1. Analysis of clayey silt below the levee

Figure 9 shows that location of points near the ground surface for finding extreme velocity and figure 10 presents that results of flow velocity at K, L, M, N, O, P, Q and R. One of the most important point is M points. M point is levee toe and K point is located upstream face region. L point is under the levee. According to Figure 10, max values of flow are K=7.6x10^{-8} m/s at time=38.9 hours; L=4.6x10^{-8} m/s at time=30.6 hours; M=1.6x10^{-8} m/s at time=66.7 hours; N, O, P, Q and R= 5.4x10^{-10} m/s at time=152.8 hours. Piping formations are simply compute as;

$$i_c = \frac{G_s - 1}{1 + e} = \frac{2.7 - 1}{1 + 0.9} = 0.89$$

v=flow velocity (m/sec)
k=permeabilty (m/sec)
i=hydraulic gradient
i_c =critical hydraulic gradient
G_s =specific gravity; 2.70 for clayey silt
e=void ratio; 0.90 for clayey silt

Critical hydraulic gradients is 0.89 for clayey silt. According to maximum flow velocity, piping is investigated at these points. Table 17 shows that piping is not observed at any points due to $i_{exit}<i_c$. In order for the sand boiling to occur, the piping must take place. As can be seen in Table 18, critical hydraulic gradient is 0.89 for clayey silt and it did not reach the critical hydraulic gradient for the formation of boiling.

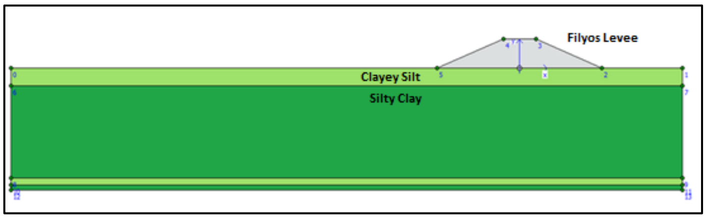


Figure 7. Filyos Levee at 44.24 m on left shore of Filyos River

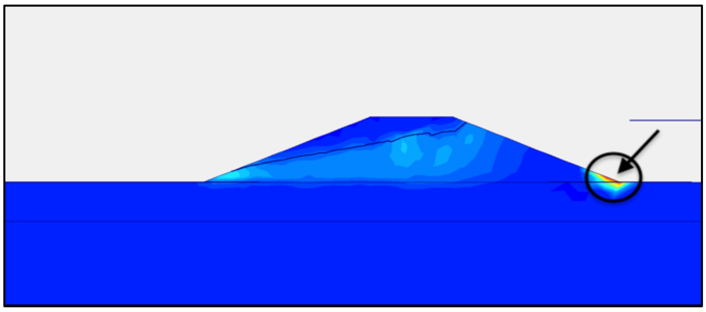


Figure 8. Flow field at 44.24 m on left shore of Filyos River during h_{max}

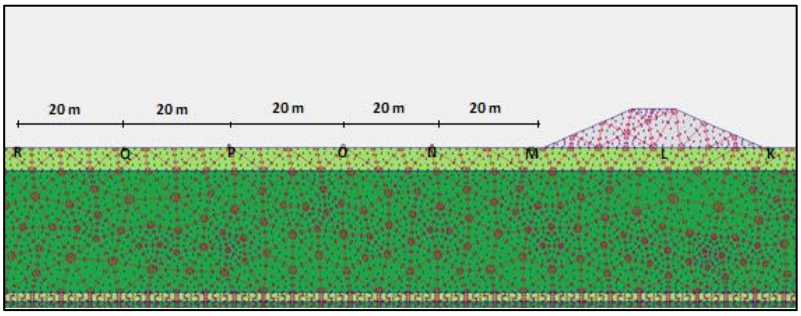


Figure 9. Location of points near the ground surface for finding extreme velocity

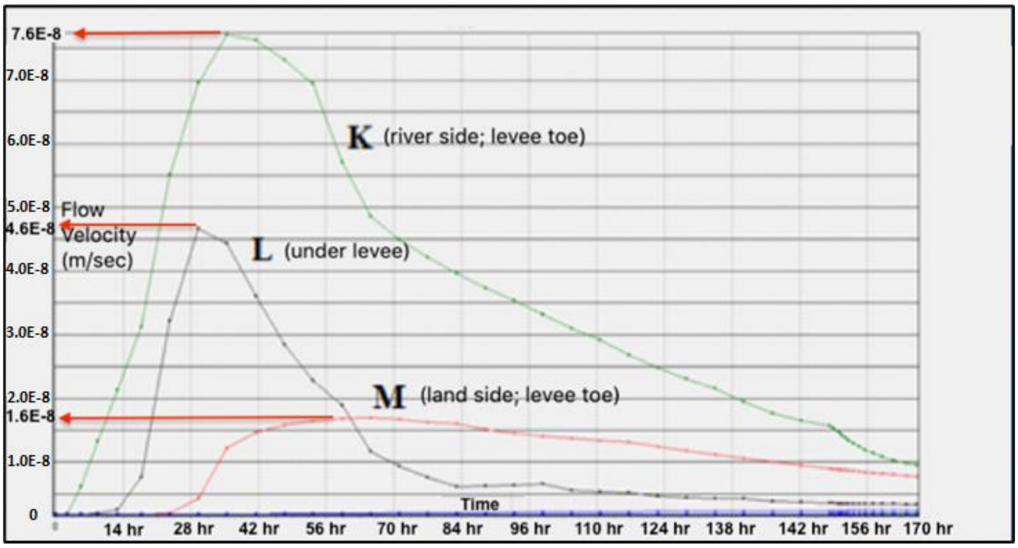


Figure 10. Extreme velocity graph relation time to seepage velocity

Table 17. Piping Status of location of points near the ground surface

Symbol	Max Seepage Velocity (m/s)	Permeability (m/s) (k)	Exit Gradient (i)	Piping
K	7.6×10^{-8}	1×10^{-7}	0.76	Not
L	4.6×10^{-8}	1×10^{-7}	0.46	Not
M	1.6×10^{-8}	1×10^{-7}	0.16	Not
N	5.4×10^{-10}	1×10^{-7}	0	Not
O	5.4×10^{-10}	1×10^{-7}	0	Not
P	5.4×10^{-10}	1×10^{-7}	0	Not
Q	5.4×10^{-10}	1×10^{-7}	0	Not
R	5.4×10^{-10}	1×10^{-7}	0	Not

Table 18. Sand Boil Status of location of points near the ground surface

Symbol	Max Seepage Velocity (m/s)	Permeability (m/s) (k)	Exit Gradient (i)	Sand Boil
M	1.6×10^{-8}	1×10^{-7}	0.16	Not
N	5.4×10^{-10}	1×10^{-7}	0	Not
O	5.4×10^{-10}	1×10^{-7}	0	Not
P	5.4×10^{-10}	1×10^{-7}	0	Not
Q	5.4×10^{-10}	1×10^{-7}	0	Not
R	5.4×10^{-10}	1×10^{-7}	0	Not

5.2. Analysis above the levee for gravelly sand soil type

Piping can only be observed at K, L and M points because these points are under the phreatic line. K, L, M points on the ground surface or levee are different from other analyses. K, L and M points are investigated in terms of piping formation and Figure 11 shows K, L and M points on downstream face of Filyos levee. According to Figure 12, maximum values of flow are K = 1.8x10^{-4}m/s at time=48.6 hours; L=2x10^{-4}m/s at time=48.6 hours; M=8.7 x 10^{-5}m/s at time=55.6 hours. Piping formations are simply compate as;

$$i_c = \frac{G_s - 1}{1+e} = \frac{2.66-1}{1+0.62} = 1.02$$

where;
v=flow velocity (m/sec)
k=permeabilty (m/sec)
i=hydraulic gradient
i_c=critical hydraulic gradient
G_s=specific gravity; 2.66 for gravelly sand
e=void ratio; 0.62 for gravelly sand

Table 19 shows that piping is not observed at any points due to $i_{exit} < i_c$.

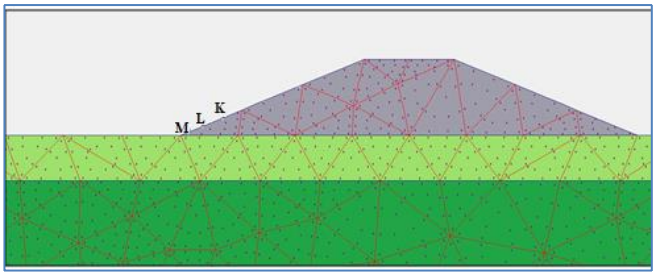


Figure 11. Location of points above the levee for finding extreme velocity

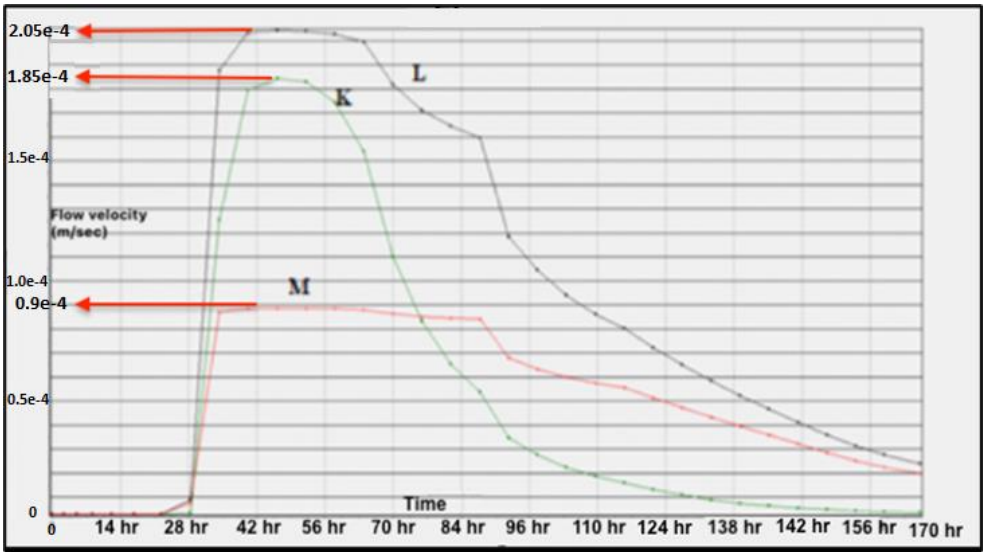


Figure 12. Extreme velocity graph relation time above the levee

Table 19. Piping Status of location of points above the levee

Symbol	Max Seepage Velocity (m/s)	Permeability (m/s) (k)	Exit Gradient (i)	Piping
K	1.85 x 10^{-4}	5 x 10^{-4}	0.37	Not
L	2.05 x 10^{-4}	5 x 10^{-4}	0.41	Not
M	0.9 x 10^{-4}	5 x 10^{-4}	0.18	Not

5.3 Safety factor against heave analysis for the top layer

Heaving potential is only observed at the ground surface hence a point is investigated at 1 m below the top layer, as seen in Figure 13. Heave is not observed due to the fact that F_{heave} is computed as being higher than 3.0.

6. Conclusions and Recommendations

The study is part of the research with the aim to reveal a methodology to simulate transient flow of levee during a flood. There are available inputs of hydrological and soil properties data for the transient analysis using PlaxFlow V.9. Filyos levees were designed as the steady state case but this study investigated transient effects of seepage flow on Filyos levees and under levees associated sand boil, piping and heaving formation (Ozkan, 2003). Table 20 shows that different drilling points are investigated according to heave and piping potential and conclusions are at below.

Following conclusions are drawn from this study:

1. Maximum exit gradient doesn not exceed critical hydraulic gradient, so sand boil formations are not observed at levee toe (Point M).
2. Piping formations are not observed under levee.
3. The maximum exit gradient are respectively 0.78 and 1.0 through levee and filling (silty sand layer), so piping formations are not observed.
4. Since the safety factor is heigher than 3-4, the heaving potential is not observed at the ground surface.

Overall, silty and sandy soils with (%5-%12) finer material have piping potential at K, L points under the levee. If the top layer is thin, it increases the risk of piping. The design of levee can be made for the steady state flow and it can also be valid for the transient flow. In addition, This study can be repeated frequently with up-to-date data. In future studies, current data can be compared to these data.

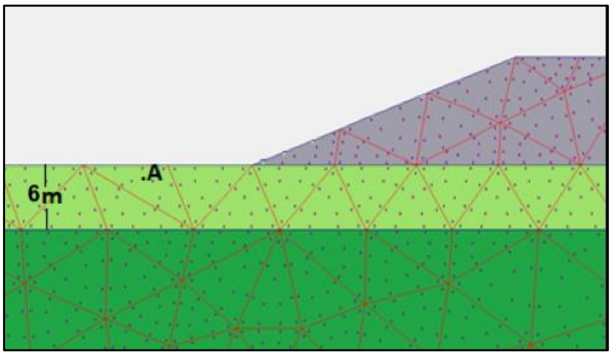


Figure 13. Analysis against to heave at A point 1 m below the top layer

Table 20. Conclusions of transient seepage analyses for different drillings

Drilling No	Soil Type on Top Layer	Max Exit Gradient K	Max Exit Gradient L	Max Exit Gradient M	Critical Exit Gradient	Heave Analysis on Top Layer
TSK-2	Silty Clay	1.90	0.85	0.45	0.63	F_{max} is higher than 3.0 .
TSK-3	Silty Clay	0	0	0	0.63	Since i_{max}=0, heaving is not likely to occur.
TSK-4	Sand	0.02	0	0	1.1	F_{max} is higher than 3.0 .
TSK-5	Sandy Silt	0.95	0.73	0.27	1.1	F_{max} is higher than 3.0 .
TSK-6	Silty Sand	0.36	0.66	0.09	1.2	F_{max} is higher than 3.0 .
TSK-9	Clayey Silt	2.1	2.7	0.02	0.89	F_{max} is higher than 3.0 .
TSK-10	Clayey Silt	0	0	0	0.89	Since i_{max}=0, heaving is not likely to occur.
TSK-11	Clayey Silt	0	0	0	0.89	Since i_{max}=0, heaving is not likely to occur.
TSK-12	Clayey Silt	2.40	2.40	0.4	0.89	F_{max} is higher than 3.0 .
TSK-13	Clayey Silt	3.26	3.21	0.06	0.89	F_{max} is higher than 3.0 .

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