Review Paper:

Forensic Analysis of a Distressed Railroad Embankment

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Abstract

Land subsidence is becoming a prevalent worldwide occurrence, perhaps with a devastating impact on civilian lives. Moreover, natural and man-made slopes formed are susceptible to damage unless there is adequate stability. The bulk of the slope failures is due to intensive rains. Examination of slope stability due to massive rains is an important issue to inspect in the area with high precipitation. This study is aimed at exploring the effects of severe flooding on the stability of the slope. A 30 m long railroad embankment failure that happened on May 25, 2011, in the city of Ann Arbor, Michigan, is introduced. The collapse happened due to the rainy season that brought about ponding water against the embankment and sufficiently high-water pressures that brought about the instability of the railroad embankment.

The back investigation is a much more dependable and predictable strategy to evaluate the shear parameters in situ. The back investigation of a slope is solved using the Resistance Envelope method wherein the embankment is divided through a certain number of slices. Forces on each slice are estimated and the potential failure surface is identified. The shear parameters are extracted employing the resistance envelope method for the actual failure plane and are verified with the initial condition. This study aims to find the impact of precipitation on slope stability using Geostudio 2012 software.

Keywords: Embankment, Geostudio, Land Subsidence, Resistance Envelope, Seepage.

Introduction

An embankment is a structure built by placing and compacting the earthen material or soil to construct a roadway or a railway above the existing ground surface[2]. In this study, a collapsed embankment cross-section was taken to perform back analysis to determine the critical failure plane. The failure site is situated towards the north of downtown Ann Arbor in Michigan, USA. The failure occurred on the embankment that is making a beeline for Plymouth road and adjoining private structures. This occurred on the night of the 25th of May 2011, at 9:23 pm, during critical precipitation and no trains were in operational condition. A 30 m long segment of the embankment along the railroad hub slide and the sliding mass moved to the downslope, evacuating various trees which were present in the downslope side of the embankment between the railroad embankment and Plymouth road.[3,16]

To determine the shear strength parameters for homogenous soils, various back analysis methods of slopes were introduced[15]. Failure of the soil bank is associated with the formation of tension cracks and it can be avoided up to a certain extent by providing sandbags on the embankment slope as studied by Hossain et al[6]. Most of the damages of railway embankments are due to flooding of water during heavy rainfall[5]. Due to the increase in compaction of soil, the failure of slopes can be reduced up to some extent as per Liu et al[10]. The extreme intensity of rainfall can even cause an increase in pore pressure and a decrease in the bearing capacity of soil present in the slope or embankment Gunawan et al[4].

Various laboratory tests were conducted to investigate the seepage analysis of the embankment and it was observed that continuous immersion of the embankment in water leads to the formation of heave near the downstream toe as per Luo et al[11]. Embankments are susceptible to slope failure due to numerous reasons. One of the major causes is seepage and surface runoff during the rainy (monsoon) season. Erosion by gullying has been regarded as the most significant failure scar as described by Aqib et al[1].

Various authors conducted experimental tests and numerical analysis to find the reasons for the failure of various embankments subjected to heavy rainfall. It is found that the Fellinious method of analysis gives less factor of safety and FOS was higher for the slope of 1:3 but that slope covers a large ground area as per Moldovan et al[12]. By performing a stability analysis of a railway embankment, it was found that the pore water pressures increase rapidly during the rainy season which causes a lack of stability to the railway embankments.[13]

From various laboratory tests conducted for determining the behaviour of slope subjected to heavy rainfall, it was observed that as the slope angle is increased, the retention time of rainwater was less, as a result there will be less seepage of rainwater according to Jing et al[7].

By performing finite element modelling on railway embankment, it was concluded that the infiltration of rain water into saline soil embankment will be higher. As a result, the factor of safety of saline embankment gets decreased according to Kolahdooz et al[9]. Factor of safety of embankment can be improved by providing geogrids layers

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as per Jyothi et al[8]. Factor of safety was reduced by increasing the water level proportional to the number of days as per Sooksatra et al[14].

Research significance: Embankment failures generally lead to huge damage. In this study, an attempt has been made to evaluate the *in situ* shear strength parameters for a failure zone of the embankment using the resistance envelope method. The key parameters which adversely affect the embankment, have been found. In order to decide the critical failure surface of the embankment, Geostudio software was used. The results obtained through the form of critical failure surface extracted from the Geostudio and analytical approach, were compared.

Geometry of embankment

The embankment is having 9.3 m top width and height 8.2 m made up of silty sand resting on silty clay (native soil). The water has accumulated on the left of the embankment up to a depth of 1.4 m due to heavy rainfall as shown in fig. 1.

Resistance envelope approach: Critical failure surfaces can be retrieved by evaluating the embankment in various software. Investigating the slope of an embankment in an analytical approach is the latest or evolving methodology. In this research, the task is to find out the potential failure surface using an analytical concept called resistance envelope approach as shown in fig. 2.

STEP 1: The cross-section of embankment is drawn in Auto-cad 2019 and weak surface is picked which is originating from the left of an embankment and terminating near the foot of the embankment as shown in fig. 3.

STEP 2: The failure region is divided into 10 counts of slices and then all the measurements of slices are noted as shown in fig. 4.

STEP 3 - Ordinary method of slices: In this method, the forces on the sides of the slice are neglected as shown in fig. 5.

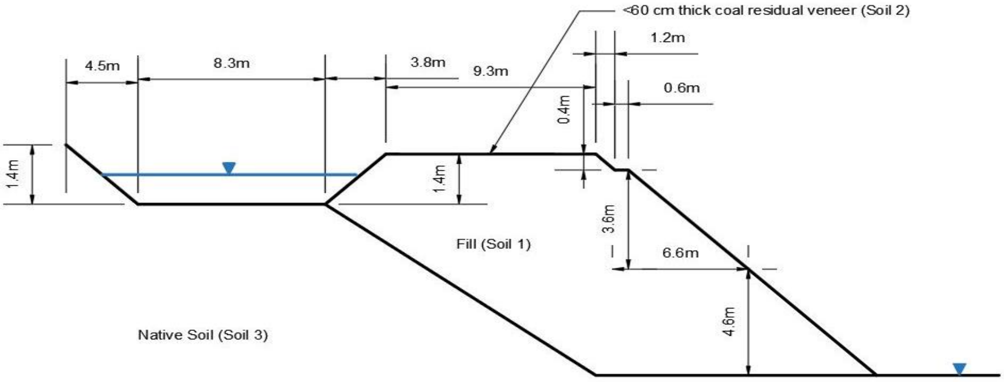

Figure 1: Embankment model

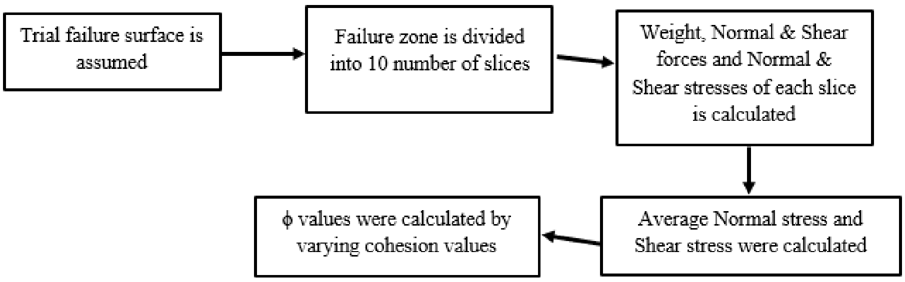

Figure 2: Stepwise process to find Ø value

Figure 3: Assumed failure region of an embankment

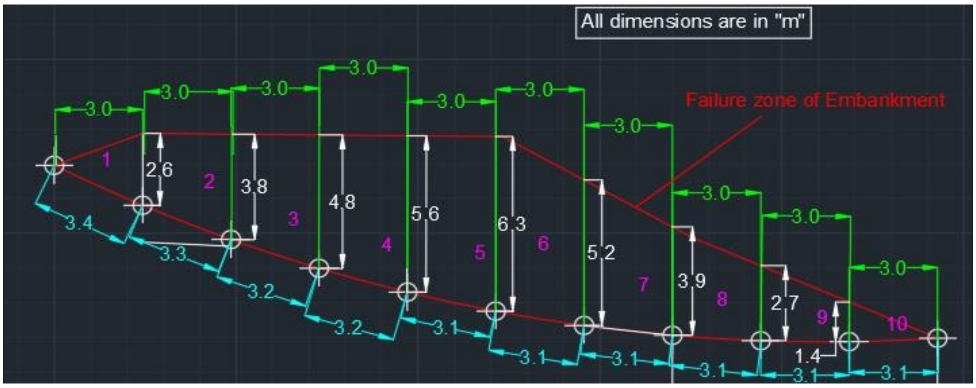

Figure 4: Failure zone divided into 10 number of slices in Auto-cad 2019

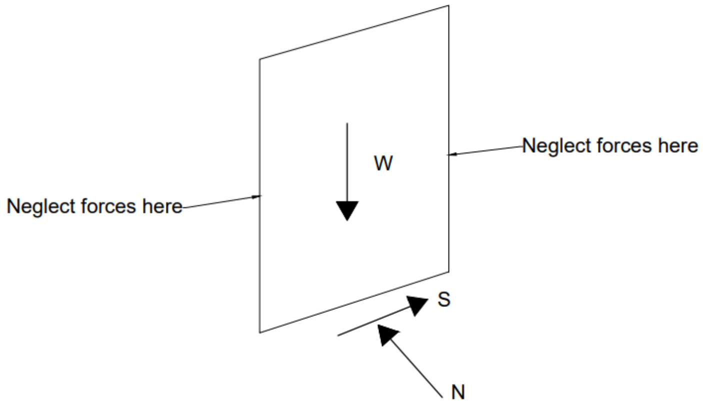

Figure 5: Slice with forces

Table 1
Normal and Shear stresses using Ordinary method of slices

Unit weight of soil in kN/m³	Slice No.	Area (m²)	Weight (kN)	Normal force N (kN)	Shear force, T (kN)	Base Area (m²)	Normal stress, σ (kN/m²)	Shear stress, τ (kN/m²)
20	1	3.90	78	62.40	46.80	3.4	18.35	13.8
	2	9.60	192	165.12	84.48	3.3	50.04	25.6
	3	12.90	258	232.20	90.30	3.2	72.56	28.2
	4	15.60	312	290.16	109.20	3.2	90.68	34.1
	5	19.60	392	372.40	117.60	3.1	120.13	37.9
	6	17.25	345	327.75	103.50	3.1	105.73	33.4
	7	13.35	267	253.65	80.10	3.1	81.82	25.8
	8	9.75	195	185.25	58.50	3.1	59.76	18.9
	9	6.15	123	116.85	36.90	3.1	37.69	11.9
	10	2.10	42	39.90	12.60	3.1	12.87	4.1
Average							65	23

Area of slice (A) = Height of slice * Width of slice
Volume of slice (V) = Area of slice * 1 m length of slice
Weight of slice (W) = Volume of slice * Unit weight of slice
Normal Force (N) =W cosα
Shear Force (S) = W sinα
α = Angle between the horizontal and base of a slice (Degrees)

$$\text{Normal Stress } (\sigma) = \frac{\text{Normal Force}}{\text{Base Area}}$$

$$\text{Shear Stress } (\tau) = \frac{\text{Shear Force}}{\text{Base Area}}$$

The normal and shear forces and normal and shear stresses are estimated at the base of each slice through an ordinary method of slices as shown in table 1.

STEP 4: Initially, shear stress against the normal stress component is plotted. Shear stress intercept (Cohesion intercept) is managed to keep at zero and a line is crossed drawn from zero and finishing at (τ Vs σ) coordinate. Similarly, the shear stress intercept differed by five variables and lines are created to cross the (τ Vs σ) coordinate. The slopes of all the lines are evaluated and that implies the angle of shearing resistance (ø) as shown in fig. 6. The angle of shearing resistance is estimated by differing cohesion intercepts starting from zero as shown in table 2.

It is asserted that perhaps the failure surface selected is not really the actual critical failure surface as the value of the angle of internal friction acquired is 20º at nil cohesion. However, the exact value of the angle of internal friction at the loosest state is ø=45º. To really get the exact failure surface, various textures are chosen and the same process is managed to carry out.

To figure out critical failure surface performing trial and error is rather complicated. Initially the embankment safety is checked by using Geostudio 2012. The failure surface produced in Geostudio is analysed further again by the resistance envelope method.

Stability and seepage analysis

Slope/W analysis: Slope stability analysis is conducted using the Geostudio 2012 program in which the embankment is having 2 distinct layers of different cohesion, shearing friction inclination and unit weight measurements as shown in table 3. For such a research scenario, the stability analysis is carried out using Geostudio 2012 software. The approach used for slope stability analysis is Morgenstern-Price approach to determine the factor of safety and Mohr-coulomb material model is used to model the soil materials using Geostudio (2012). The factor of safety obtained for critical failure surface is obtained as 2.26 as shown in fig. 7.

SEEP/W analysis: Seepage analysis of embankment is undertaken using Geostudio software (2012) by using the required parameters as shown in table 4. The volume of flow going via the embankment cross section is identified by adding the segment flux.

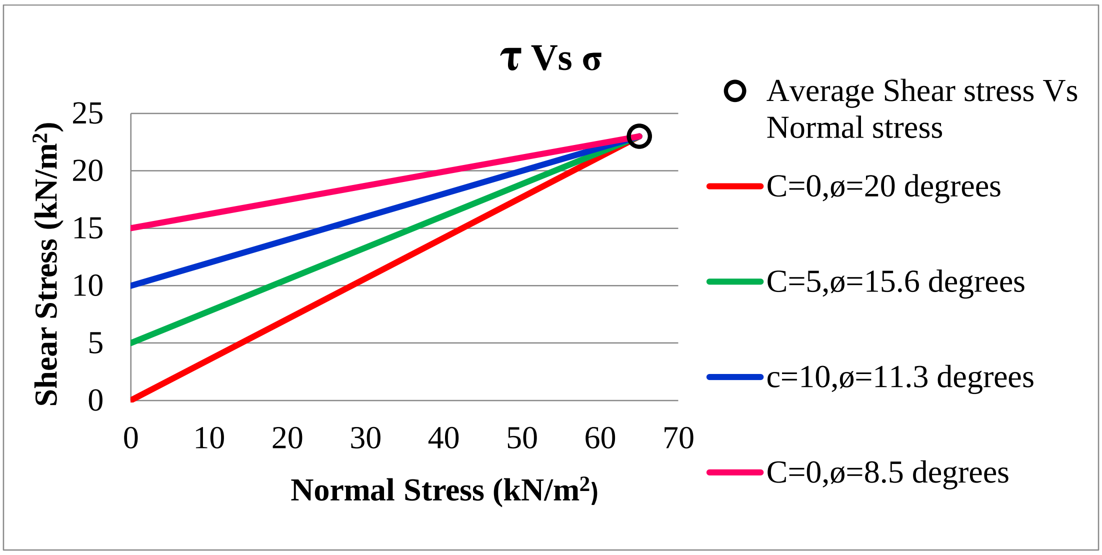

Figure 6: Graphical representation of (ø) angle of shearing resistance value obtained by varying (c) the cohesion

Table 2
Angle of shearing resistance (ø) values obtained by varying the cohesion(c)

Trial No.	Average Normal stress (σ) in kN/m²	Average Shear stress (τ) in kN/m²	Cohesion kN/m²	Angle of shearing resistance (ø) Degrees
1	65	23	0	20
2			5	15.6
3			10	11.3
4			15	8.5

Table 3
Variables used in Slope/w analysis

S.N.	Layers	Parameters		
		Unit Weight (kN/m³)	Cohesion (c) (kPa)	Angle of Shearing resistance (ø) (Degrees)
1	Native soil	21	18	30
2	Embankment fill	20	0	45

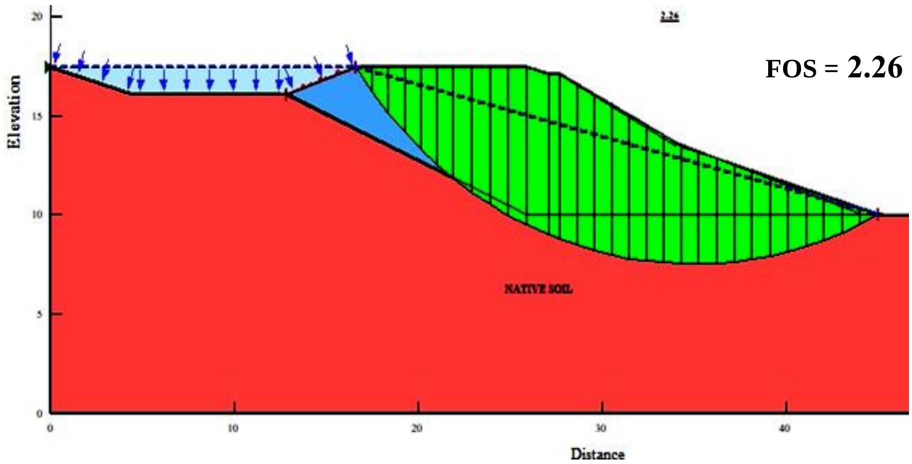

Figure 7: Slope/w analysis of embankment

Table 4
Variables used for Seep/w analysis

S. N.	Soil layers	Material	Saturated water content (m^3/m^3)	Sample material	Residual water content (m^3/m^3)	k (at saturation), m/sec
1	Native soil	Saturated/ Unsaturated	0.35	Silty clay	0.02	1e-0.009
2	Embankment fill	Saturated/ Unsaturated	0.5	Silty sand	0.05	5.1e-0.07

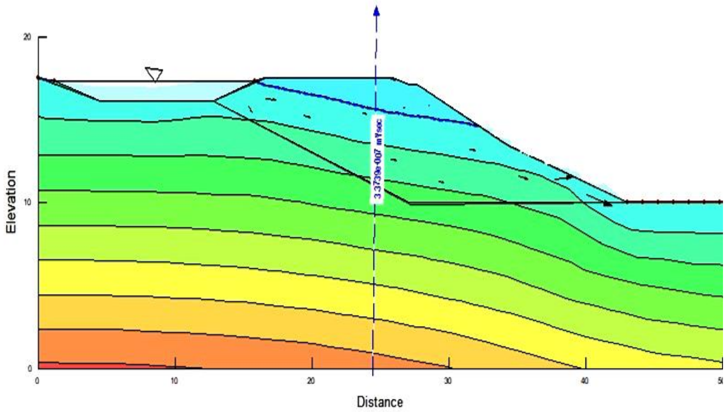

Figure 8: View of Pore water pressure

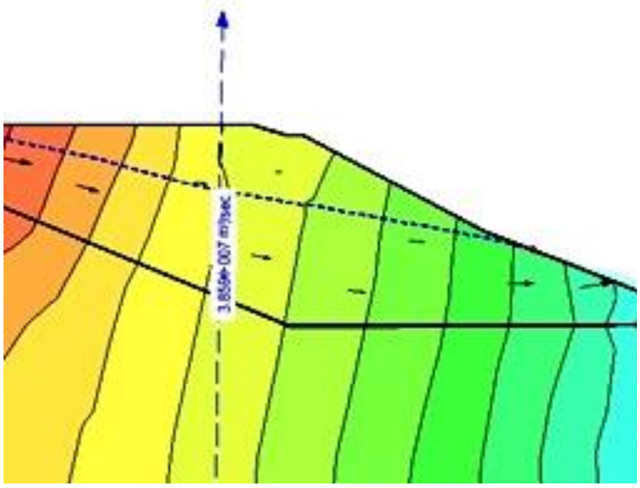
Figure 9: View of Flux section

The seepage study has been carried out with the use of tools from Geostudio 2012. The results are estimated for the volume of flow that crosses the segment of the embankment. The volume of flow that crosses the embankment segment, is estimated as 3.859e-007 m^3/sec as shown in fig. 7 and fig. 8. Flux section view is shown in fig. 9. Across the height of the embankment of 18 m, the pore water pressure profile is illustrated in fig. 10.

By varying the height of the embankment by 2 units, pore water pressure is drawn. The fluid pressure gradually decreases from 150 kPa to 99 kPa at 0 m to 5.5 m height and is stable at 0.7 m height and yet again decreases sequentially from 99 kPa to 15 kPa at 6.2 m to 13.9 m. This pressure rises again from 18 kPa to 30 kPa at 14 m height and then next it gradually decreases from 14 m to 18 m to 0 kPa. From the slope stability analysis of the embankment by using the Geostudio software, the potential failure layer starts from the upper left corner of the embankment, passes via the layer 1 (bank fill) to the layer 2 (native soil) and ends at the toe of the layer 1. The critical failure plane acquired utilizing the Geostudio software is picked up and the shear variables are discovered using an analytical method and both the failure planes are compared.

The critical surface generated from the software is taken, evaluated and authenticated using analytics. The critical failure plane is validated analytically using the Resistance Envelope method. In this approach, the shear strength variables are evaluated and compared with the original parameters. The cross-section of the embankment is drawn in AutoCAD 2019 and the critical surface is taken from Geostudio which is originating from the left of the dike and terminating near the foot and is drawn as shown in fig. 11. Failure region is divided into 10 counts slices and then all the measurements of slices are noted as shown in fig. 12.

The normal and shear forces along with normal and shear stresses are calculated at the base of each slice by using the Ordinary method of slices. In this, the forces on the sides of the slice are neglected. Area, volume, weight, normal and shear force, along with normal and shear stresses are calculated using an ordinary method of slices as shown in table 5.

Initially shear stress against the normal stress component is plotted. Shear stress intercept (Cohesion intercept) is managed to keep as zero and a line is crossed glancing from zero and finishing at τ Vs σ coordinate. Similarly, the shear stress intercept is differed by five variables and lines are created to cross the τ Vs σ coordinate. The slopes of all the lines are evaluated and they imply the angle of shearing resistance (ø) as shown in fig. 13.

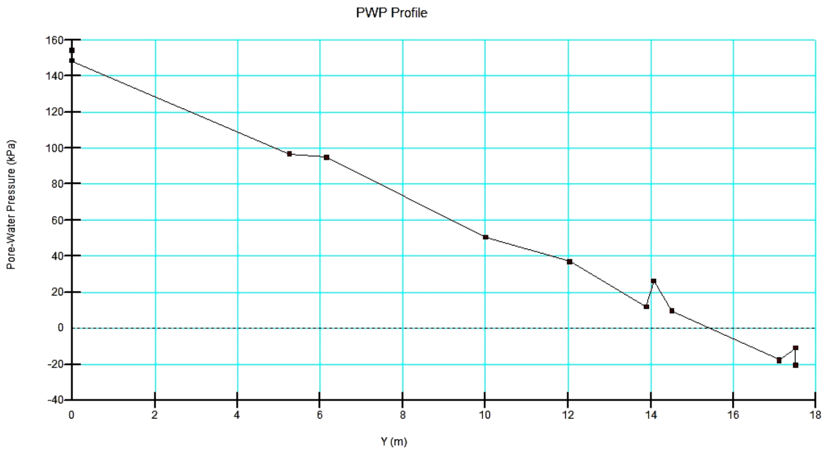

Figure 10: Pore water pressure profile

Figure 11: Failure zone of embankment obtained from AutoCAD

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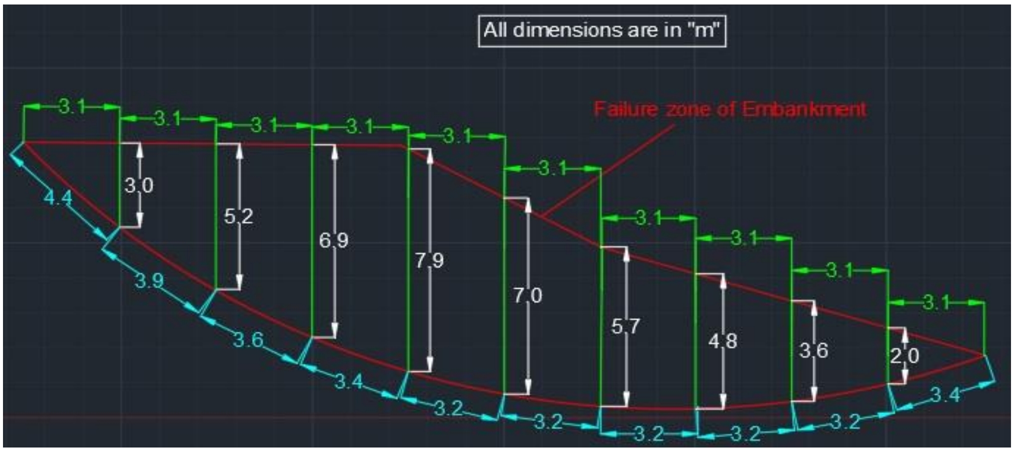

Figure 12: Failure zone divided into 10 counts of slices in Auto-cad 2019

Table 5
Normal and Shear stresses using Ordinary method of slices

Unit weight of soil in kN/m³	Slice No.	Area(m²)	Weight(kN)	Normal force, N (kN)	Shear force, T (kN)	Base Area (m²)	Normal stress, σ (kN/m²)	Shear stress, τ (kN/m²)
20	1	4.65	93	55.8	93.0	4.4	12.68	21.1
	2	12.71	254.2	152.5	254.2	3.9	39.10	65.2
	3	18.76	375.2	300.2	375.2	3.6	83.39	104.2
	4	22.94	458.8	426.7	321.2	3.4	125.50	94.5
	5	23.10	421.57	358.3	261.4	3.2	111.97	81.7
	6	19.53	356.42	303.0	221.0	3.2	94.69	69.1
	7	16.12	294.19	238.3	182.4	3.2	74.47	57.0
	8	13.18	240.535	194.8	149.1	3.2	60.88	46.6
	9	8.68	158.41	128.3	98.2	3.2	40.09	30.7
	10	3.10	56.575	45.8	39.6	3.4	13.47	11.6
Average							66	58

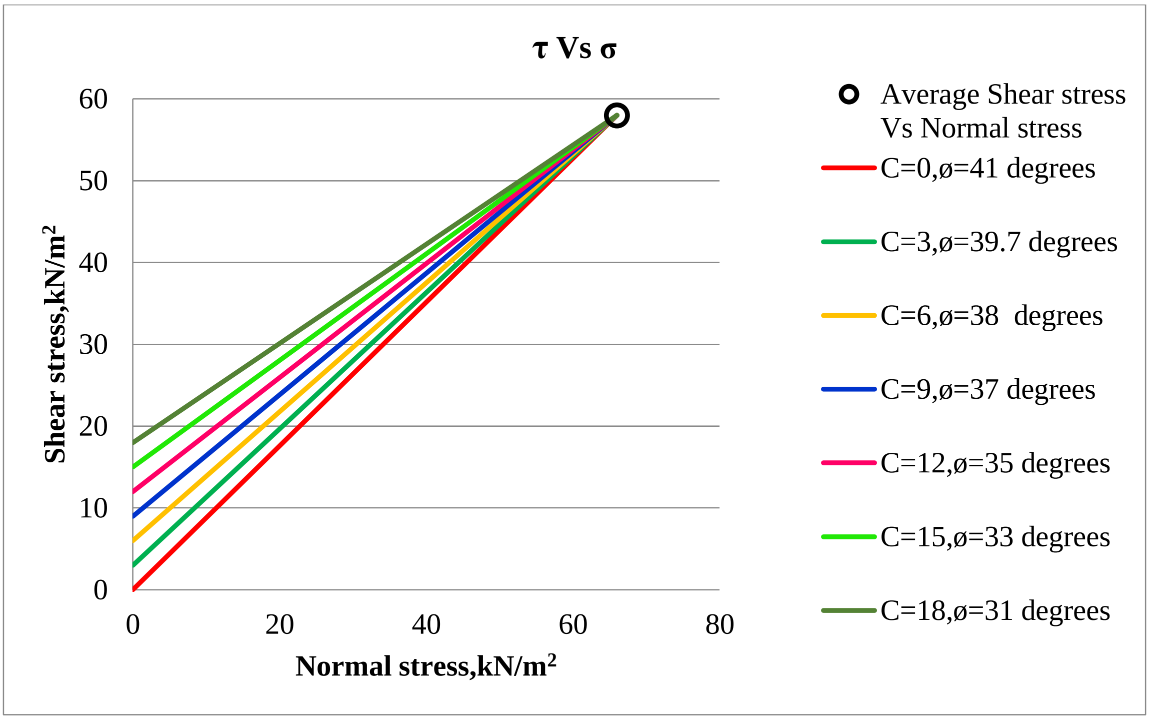

Figure 13: Graphical representation of (ø) angle of shearing resistance value acquired by varying (c)the cohesion

Table 6
(ø) Angle of internal friction values obtained by varying (c) the cohesion value

Trial No.	Average Normal stress (σ) in kN/m^2	Average Shear stress (τ) in kN/m^2	Cohesion kN/m^2	Angle of shearing resistance
				Degrees
1			0	41
2			3	39.7
3			6	38
4	66	58	9	36.9
5			12	35
6			15	33
7			18	31

Table 7
Results of c and ø

S.N.	Variable	Shallow failure plane	Critical failure plane	
1	Cohesion (kPa)	0	0	9
2	Angle of shearing resistance (Degrees)	20	41	37

The normal and shear stresses are estimated by using the formulae given and the average of these stresses is drawn. The angle of shearing resistance is estimated by differing cohesion intercepts getting started from zero as shown in table 6.

The results of the shallow failure plane and critical failure plane are evaluated and given as shown in table 7. Results also illustrate that the angle of shearing resistance is 20^o at zero cohesion for the shallow failure plane attempting to pass through soil layer 1 (Embankment fill) and the angle of shearing resistance is 41^o at zero cohesion for the critical failure plane. The angle of shearing resistance is 37^o which is the average of the two angles of shearing resistance i.e. 46^o and 30^o, provided for 2 layers at 9 kPa of cohesion which seems to be the average of the two cohesions i.e. 0 kPa and 18 kPa, indicated for 2 layers.

Conclusion

- The embankment has been destroyed due to the tremendous pressure triggered by the water on the dike as the acquired amount of fluid passing through the dike segment is 3.859e-007 m^3/sec.
- If the embankment consists of two layers, it is suspected that the shear strength variables are the average of 2 values of each layer for the critical failure plane.
- The analytical methodology used in this study is being used to estimate the *in situ* shear strength parameters for a failure zone of embankment without a realistic site visit.
- The failure plane identified by the analytical approach is exactly the same as the retrieved potential failure plane from Geostudio software.

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