EFFECTS OF FINES ON CRITICAL HYDRAULIC GRADIENT OF SOILS AT OPTIMUM MOISTURE CONTENT

ABSTRACT

Critical hydraulic gradient is an essential parameter for determining the factor of safety against piping failure of earthen dams, excavations, etc. Theoretically, the critical hydraulic gradient of a soil is taken as a function of the saturated unit weight of soil. The occurrence and development of piping is a very complex process due to complicated interactions between water and soil. It was observed that fines content and plasticity characteristics of soil affect the initiation of piping of soils. In addition, the above properties affect the roof supporting capabilities of soil, which is an essential criterion for propagation of piping. This paper is based on a study of the effect of fines content of soil on the initiation of piping at optimum moisture content.

Soil with particle size of 0.075 to 2 mm and fine sand with particle size of less than 0.075 mm were mixed at different mass percentages. By performing the proctor compaction test optimum moisture content was found. Sample was prepared at the optimum moisture content and placed in mould and immersed into stable water slowly to get saturated sample. Series of permeability tests were performed to measure the critical hydraulic gradient. The critical hydraulic gradient was greater than the theoretical critical hydraulic gradient and increased with the increment of fine percentage.

Keywords: Critical hydraulic gradient, piping, plasticity

INTRODUCTION

Problem Statement and Background

Failure of the earth embankments can be in different modes such as Overtopping, Uncontrolled Seepage and piping, Instability and Liquefaction. When analysing the world history, piping is the one of the main reasons for majority of dam failures. It occurs due to the constant migration of soil particles towards the free exits or into course openings. Soil piping causes lot of catastrophic failures of engineered earth structures such as water and tailing dams, agricultural retention pond dikes, levees and sanitary land fill liners. Piping failures in the dams causes billions of dollars per year worldwide and with occasionally resulting significant loss of life and long term environmental damage.

Table 1: Percentage of different modes of piping failure according to the results by University of New South Wales

Mode of Failure	% Total Failure	% Failure pre 1950	% Failure post 1950
Piping through Embankment	32.5%	29.3%	35.5%
Piping from embankment into foundation	1.7%	0%	3.4%
Piping through Foundation	15.4%	15.5%	15.3%
Total Piping	46.9%	43.1%	54.2%

The Data in the above table clearly indicates that majority of failures of Embankments and Foundations are due to Piping. Therefore, Piping is critical in Earth structures.

There are lot of factors that affect piping such as a) Erodibility of soil b) the fine particles and plasticity of soil c) degree of compaction of soil layers on the earth structure d) homogeneity and quality control on the construction process e) geometry of earth structure f)upstream water energy head as well as hydraulic gradient g) velocity inside the soil mass h) the type of preventive measures in downstream of an earth quake structure and i) the compaction control along the installation of pipeline conduits.

Research gap leading to the topic

Critical hydraulic gradient is an essential parameter for determining the factor of safety against piping failure of earthen dams, excavations, etc. Theoretically, the critical hydraulic gradient of a soil is taken as a function of the saturated unit weight of soil. However, it was observed that fines content and plasticity characteristics of soil affect the initiation of piping of soils. In addition, the above properties affect the roof supporting capabilities of soil, which is an essential criterion for propagation of piping.

Symbols

h - Water head

L - Length of the sample

i -Hydraulic gradient

i_{cr} -Critical hydraulic gradient

γ_{sat} -Saturated weight of soil.

γ_w -Weight of the water

W_1 -Weight of the mould

E/T -Ratio between experiment and theoretical values.

Terminology

To gain the knowledge about piping the few terminologies need to be identified clearly such as Internal Erosion, Piping, Backward erosion and Suffusion.

Internal Erosion It occurs when the soil particles within the embankment dam or its foundation carried towards downstream by seepage flow.

Piping It is one type of Internal Erosion which initiates due to the backward erosion results in the formation of tunnel known as Pipe from the downstream to Upstream at embankments.

Backward erosion It involves the detachment of soil particles when the seepage exits to a free surface such as ground surface downstream of soil foundation or the downstream face of homogenous embankment. The separated particles from the soil matrix are carried away by the seepage flow and this process gradually works its way towards upstream side of embankment or its foundation until a continuous pipe is formed.

Suffusion It is a form of internal erosion which involves selective erosion of fine particles from the matrix of a soil made up of coarser particles.

Hydraulic Gradient

The Hydraulic gradient is given by the difference of water head h_1 at the entrance and water head h_2 at the exit of soil section divided by the length of soil sample (i.e. hydraulic head loss per unit length of soil sample).

$$i = \frac{h1-h2}{L} \quad [i]$$

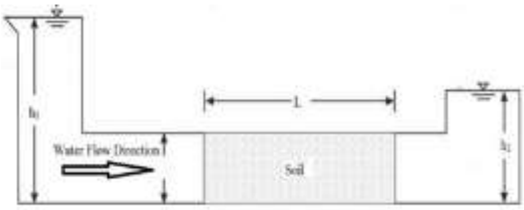

Figure 1: Hydraulic gradient Apparatus

Critical Hydraulic Gradient The existence of a hydraulic gradient that makes the effective stress of soil particles become zero in such a way that the friction resistance forces against erosion become nullified. The smallest hydraulic gradient that makes the stress zero is called as Critical Hydraulic Gradient.

Critical hydraulic gradient is an essential parameter for determining the factor of safety against piping of earth dams and excavations etc. Theoretically the critical hydraulic gradient of soil is taken as the function of saturated unit weight of soil.

$$i_{cr} = \frac{\gamma_{sat}-\gamma_w}{\gamma_w} \quad [ii]$$

LITERATURE REVIEW

According to the history of earth in 19th and 20th century, Dam structures were facing the threat due to piping since the early structure was constructed around 2900 BC. In the early ages our ancestors did not know about the seriousness of piping and did not consider the effects of seepage or proper zonation of materials to provide adequate filters in dams. With the experience of successful construction of dams on variety of foundation materials empirically successful dam design emerged by the first millennium AD as evidenced by 200 year service life of Prosepina Dam constructed by Romans. Shortly after Henry Darcy (1856) found the relationship between head, a length of flow and fluid velocities in granular media and methods were developed to evaluate piping potential from the length of flow path under dams.

Three types of piping are identified such as Heave piping, Backward Piping and Internal Erosion. According to the piping failure case histories, piping failure in dams were broadly categorized as failures at foundations, conduit and Internal erosion failures, backward erosion and suffusion failures and biological activities. Nearly one third of all piping (33.1%) could be associated with classic backward erosion model of piping or suffusion. But according to history the failures caused by backward erosion were significantly lower. The majority of activity of piping failures may be attributed to a variety of other causes, such as piping along conduits and internal erosion (49.8%), into or along foundation (15%) and piping due to biological activities (4.1%)

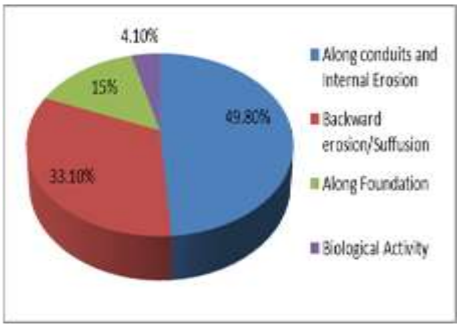

Figure 2: Percentage of types of piping failure *(Robin FELL and Chi Fai WAN, 2005)*

According to the history the piping might occur in river banks also. This is due to the rapid variation (filling and drawdown) of water in the river and seepage forces generated by the high instance of rainfall. These actions make the river bank soil unstable depending on the soil material type causing piping and landslides.

Figure 3: Occurrence of piping and landslides at river bank

Piping Process

Piping process can be considered into four main Stages as given below in Fig 4.

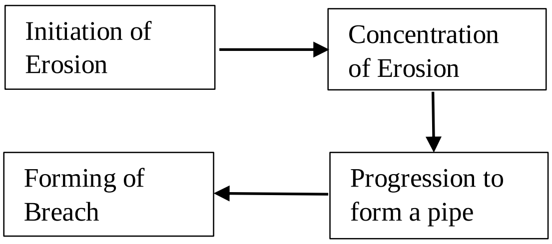

Figure 4: Process of piping

Initiation of piping in the foundation due to backward erosion

The pressure is higher at the upstream of embankment than the downstream. Due to the pressure difference there is always hydraulic gradient across the foundation. If the hydraulic gradient is greater than Critical hydraulic gradient particles at the foundation try to move. This is the initiation process of Piping. The continuation of the Erosion happens due the backward erosion until it meets the upstream and form a pipe. Backward erosion can be initiated in different places of the foundation such as at the ground surface downstream of the embankment, the surface of a cohesion less soil underlying a cohesive soil at the downstream toe of the embankment following heave and cracking of the cohesive soil, interface of a fine soil and a coarse soil, or fine soil and open jointed rock in the foundation and the interface of coarse downstream embankment fill and underlying soil or erodible weathered rock.

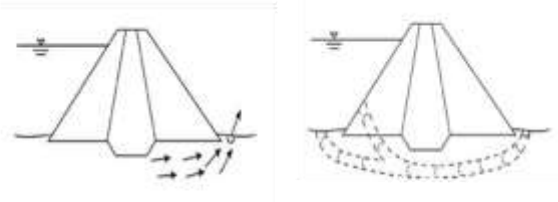

Figure 5: Initiation and Progression in the foundation

Initiation of Piping from the Embankment to Foundation due Backward Erosion

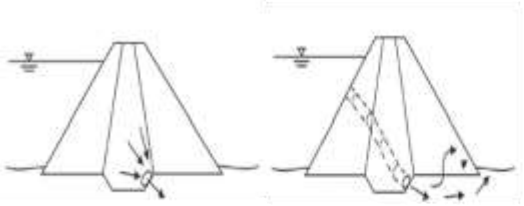

Figure 6: Initiation and Progression of piping from Embankment to foundation

For this type of piping failure to occur importantly embankment should have a concentrated leakage and at the same time the foundation should also have joints or defects or foundation with coarse gravel soil. This type of failure will occur if the foundation and embankments have defects. If leakage exits and seepage pressure is more than critical hydraulic pressure piping will occur.

Initiation of Piping due to Concentrated Leak in the Embankment

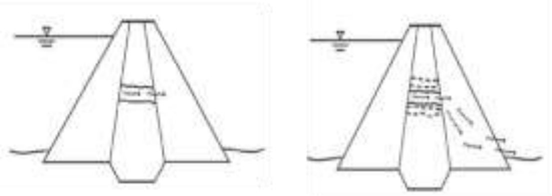

Figure 7: Initiation and Progression of piping through concentrated leak

In the embankments due to the different settlements, biological activities and defects through the cracks concentrated leakage should initiate in the embankment. If the hydraulic difference across the embankment is more than the critical hydraulic gradient the initiation of piping occurs at the embankment and due to backward erosion and suffusion continuation of erosion towards the upstream takes place forming a pipe.

Progression to Form a Pipe

Progression of piping is initiated by the three ways such as backward erosion, suffusion and concentrated leak.

Progression of internal erosion caused by backward erosion

The Backward erosion, to form a pipe, depends on a number of factors:

a) If the seepage gradient at exit point of downstream continues to exceed the critical hydraulic gradient to move particles. Sometimes gradient at the toe of the embankment will be high, and then progression will be self-limited.

b) It is very much depend on the flow of velocity in the pipe. The velocity should be sufficient enough to erode and enlarge the pipe. The phenomenon is considered into two situations.

- Before the pipe is fully developed between the reservoirs and downstream, velocities are comparatively low because there is no specific path to flow and soil particles are acting as obstruction against the flow in this condition.
- After the pipe is fully developed. Water flows with high velocity, the resistance force is only by the surrounding area of pipe, if the velocity is sufficient it enlarges the area of the pipe by eroding.

c) Whether the pipe which is developing will stay open or it will hold a roof. Cohesive soils, and silt sands/sandy silts with > 15% fines passing 0.075mm are likely to hold a roof (Foster 1999).

d) Limitations to flow of water may occur due to the presence of coarse soils.

Progression of internal erosion caused by suffusion

Suffusion is a special case in which selective removal of fine particles from the matrix of coarse particles. The formation of piping is not sure by suffusion. Sometimes erosion may progress to that extent that locally at least all fine particles are eroded without pipe being formed. For the formation of pipe to occur the seepage gradient should be greater than the critical hydraulic gradient for the backward matrix of coarse particles. Sometimes gradient at the toe of the embankment will be high then progression will be self-limited.

Progression of internal erosion caused by a concentrated leak

Given that the erosion has initiated through the concentrated leak and with the absent of embankment filters or natural filters in hydraulic flow, then there will be high possibility of formation of piping. The hydraulic gradient, geometry of the hole and Erodibility of soil are three main parameters affecting the rate of formation of the piping.

Breach of Embankments due to Piping

A breach is defined as an opening in a dam that prevents the dam from impounding a significant amount of water. A breach extends from the upstream side of the embankment to the downstream side. Internal erosion initiated by backward erosion or erosion through concentrated leak may form the breach by uncontrolled water flow by

1) Gross enlarge of pipe leading to uncontrolled loss of water.

2) Due to the collapse of pipes, the crest settlement and over topping of the embankment will happen.

3) Due to piping the water may wet the downstream slope and causing slope instability.

4) Local collapse of pipe leading to formation of sinkhole up to the crest of the embankment and lead to the loss of freeboard.

According to Von Thun’s report (1985) (Robin FELL and Chi Fai WAN, 2005) Due to the poor filter design 26% of piping failures were occurred.30.5% of all dam failures were due to the piping through embankment, 14.8% were due to piping through foundation and 1.6% were from piping into foundation. According to past history, 35% of piping failures through embankment occurred more than after first filling and 59% occurred during the first 5 years.

The piping problem was first analysed by two engineers known as Blight (1910) and Lane (1935) by considering the percolation factor (C).They considered the path of flow through soil, Type of the soil and the water difference between upstream and downstream. But these empirical methods have a significant shortcoming; they are based on seepage flow paths consistent with internal erosion and do not adequately address the potential for backwards erosion.

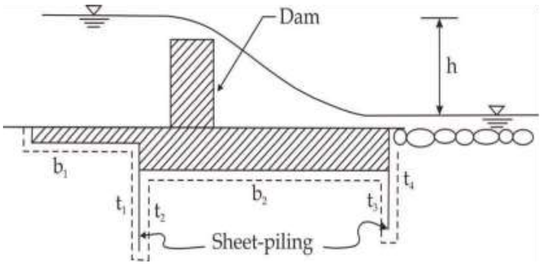

Figure 8: Dam example given by Blight (1910) to define the percolation factor CB (Casagrande,

1968)

The equation found by Blight was given as

$$C_b = \frac{\sum b + \sum t}{h}[iii]$$

The equation by Lane was given as

$$C_L = \frac{1/3 \sum b + \sum t}{h}[iv]$$

In Both methods the minimum value of Percolation factors were given for different soil types. According to that minimum values the dimension b ant t were selected.

Table 2: Minimum values of percolation factor(C) to avoid piping (Casagrande, 1968)

Material	Blight Criteria C_B	Lane Criteria C_L
Fine Sand and Silt	18	8.5
Coarse Sand	12	6
Gravel and Sand	9	3
Boulders Gravel and Sand	4	2.5

In 1967 Sherard at el did an experiment related to piping and published a table about the properties of soil related to piping which was fully empirical. This table roughly gives the soil type and there resisting ability of piping in the earth embankments. According to this table, well compacted high plasticity soils have greater piping resistance, well graded coarse sand and gravel mixture have the intermediate resistance and uniform cohesion less sand have least piping resistance.

In 2001 Schmertmann (Kevin S. Richards,Krishna R. Reddy) defined the Piping by using maximum global gradient (Ipmt) and Coefficient of uniformity (Cu).But the Ipmt value must be corrected according to the field condition such as layer depth, density, anisotropy, pipe length, permeability of layer below and roof above. According to past researches, it reveals that piping occurs at low critical hydraulic gradients. According to Sherard (Kevin S. Richards,Krishna R. Reddy) (1979) piping initiates with boiling at critical hydraulic gradient within the range of 0.3 to 0.8.According to Schmertmann the piping initiates at critical hydraulic gradient range of 0.3 to 0.6.

In 1970's first standardized laboratory piping test was developed to evaluate piping potential in earthen dams commonly known as pinhole test and the double hydrometer test (Sherard et al.,1976, Decker and Dunnigan, 1977).The tests were specifically developed to evaluate a soil's piping potential in areas with dispersive soils. Dispersive soils are highly prone to piping failure (Aitchison, et al., 1963) (Kevin S. Richards,Krishna R. Reddy)

Terzaghi (1922) (Kevin S. Richards,Krishna R. Reddy) developed the classic theory of heave, which is based on theoretical application of soil mechanics. This theory is mainly used to evaluate piping potential but there are some drawbacks in this method. In this method it does not consider properties of the soils that influence piping potential. No standardized laboratory tests have been developed to assess piping potential in non-cohesive soils that could be used to evaluate piping potential in a way that would take all these other factors into account.

EXPERIMENTAL ANALYSIS

In earth dam embankment construction, the dams are constructed at the optimum moisture content of soil to obtain high degree of compaction. So it's very important to find the relationship between the critical hydraulic gradient and varying fine percentage at the optimum moisture content.

Aim of the experiment

The Aim of the experiment is to find the relationship between critical hydraulic gradient and the percentage of fines starting from 0 to 30 per cent at the optimum moisture content condition.

Sample Collection

Experiments were conducted in our university premises. The fine sand and soil were collected in our university premises and the sand was placed into the oven for 24 hours to dry. For the dry sample sieve analysis was done from the sieve analysis Fines (sizes less than 0.075mm) and sand (size in between 0.075mm and 2mm) was collected.

Table 3: The particle size distribution

Pan size (mm)	Mass retained (g)	Retained Percentage (%)	Cumulative Percentage Retained (%)	Percentage Finer (%)
3.35	75.18	7.28	7.28	92.72
2.36	39.76	3.85	11.13	88.87
1.18	149.76	14.51	25.64	74.36
0.6	304.27	29.47	55.11	44.89
0.3	315	30.51	85.62	14.38
0.15	110.67	10.72	96.34	3.66
0.075	25.73	2.49	98.83	1.17
pan	12.1	1.17	100.00	0.00

Determination of Optimum Moisture Content and Density

The proctor Compaction test is used to determine the optimum moisture content to know which given soil type will become most dense and achieve its dry density. The optimum moisture and dry density were found by varying the fine sand percentage from 0% to 30% by increment of every 5%.Initially total capacity of mould was measured. First 5% of fine sand was measured and experiment sample was prepared. The standard proctor compaction test was performed for that sample to find optimum moisture content and maximum dry density.

Determination of Critical Hydraulic Gradient

A Steel filtration apparatus (diameter 10.7cm and height 10.2cm) is used for experimental work. The apparatus comprises of a water inlet pipe at the bottom and outlet pipe at the top. The soil sample was prepared by mixing 5% of fine sand and soil and the amount of water to achieve optimum moisture content was calculated. Then prepared sample was placed in the filtration apparatus in three layers. After placing each layer, 25 blows were applied to each layer. The weight of the sample was measured. Then the sample with apparatus was immersed in the water up to the top edge of cylinder (separate apparatus) to make the sample saturated. The bottom inlet was connected to the water column with scale. The water column height was steadily increased and the surface of the soil sample was carefully observed for piping.

Figure 9: Hydraulic gradient apparatus

RESULTS

Optimum Moisture Content

The below graph was obtained for five percentage of fines mixed with soil.

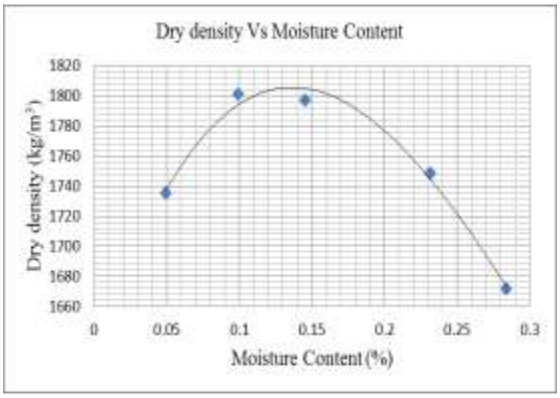

Figure 10: Dry density vs. Moisture content at fine percentage of 5

From the above graph (Refer the figure instead) the maximum dry density and optimum moisture content was obtained. Proctor test was carried out by varying the fine percentage in the soil sample and optimum moisture content was found for each sample.

Table 4: Optimum moisture content for varying fine percentage

Percentage of Fines (%)	Optimum Moisture Content (%)	Maximum dry density (kgm^{-3})
5	13.5	1804
10	15	1850
15	15	1884
20	16.5	1890
25	16	1870
30	15	1935

The experiment was carried out to the sample at optimum moisture content, to find the relationship Critical hydraulic gradient and varying fine percentage. By using the data obtained practically the critical hydraulic gradient was determined practically and theoretically critical hydraulic gradient (icr) was obtained from

$$i_{cr} = \frac{\gamma_{sat} - \gamma_w}{\gamma_w}$$

Table 5 Calculation of Critical hydraulic gradient

percentage of soil	Dry density (kg/m3)	Moisture (w)	Wet density (kg/m3)	Wet unit weight	Theoretical gradient i_{cr}	Hydraulic gradient
5	1795.666	0.1738	2107.75	20.677	1.107	6.308
10	1843.703	0.1744	2165.42	21.242	1.165	6.962
15	1865.434	0.1725	2187.26	21.457	1.187	8.738
20	1902.033	0.1826	2249.51	22.067	1.249	11.028
25	1924.908	0.1943	2299.05	22.553	1.299	13.084
30	1969.514	0.1951	2353.87	23.091	1.353	14.485

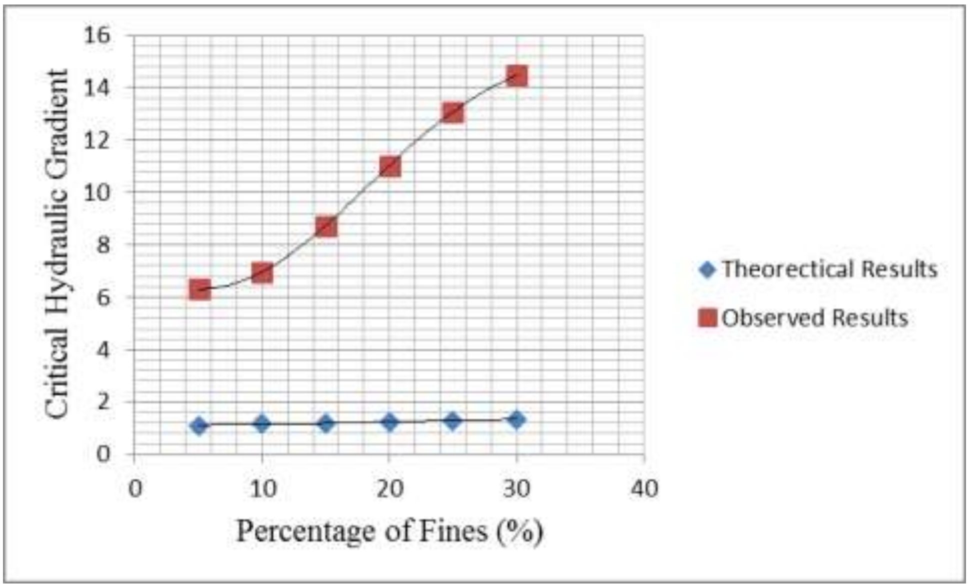

Figure 11: Comparison between Experimental and Theoretical results

DISCUSSION OF RESULTS

Table 6: Ratio between Experimental and theoretical values

Percentage of Fines (%)	Optimum Moisture Content (%)	Maximum dry density (kgm^{-3})
5	13.5	1804.0
10	15.0	1850.0
15	15.0	1884.0
20	16.5	1888.5
25	16.5	1897.0
30	15.0	1935.0

Figure 11 and Table 5 shows the comparison between theoretical and experimental results for Critical hydraulic gradient. Theoretical values were calculated according to the Terzaghi's equation with only considering the unit weight of soil sample.

The experimental values are always higher than the theoretical value. The reason for the difference is due to the bond generated between the particles. Percentage of fine particles were increased from zero percent to thirty percent and the experiment was performed at the optimum moisture content in this research. Due to the increase of fine particles there were two effects in the hydraulic gradient at piping. One is fine particles are filling the voids and reducing the permeability and it increases the plastic behaviour of soil sample. At optimum moisture content, bond between soils are very song because it is the well packed stage of soil sample. So there are no path for water to penetrate and strong bond between soil is capable of withstanding higher hydraulic gradient. Due to this reason the theoretical value is always greater than the Experimental value.

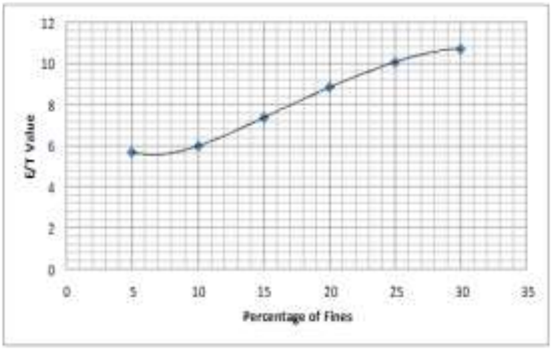

Figure 12: E/T Value vs. Percentage of Fines

CONCLUSION

Piping failure of earth dams and embankments is quite important for the safety of settlements downstream as well as for protection of property.

Theoretically the critical hydraulic gradient is given as a function of soil unit weight only. It does not relate the characteristics of soil such as fines content, compatibility and plasticity. But in this experiment, when fines content increases, at the optimum moisture content plasticity of sample increases and creates a bond between particles. For the piping of soil, the water pressure applied needs to overcome these bonds. Therefore, with the increase of Fines critical hydraulics gradient increases and the value is much higher than the Theoretical value.

Normally for checking the earth structure theoretical method was adopted to check the factor of safety against the piping. In our research the values obtained by experiments are very much greater than (5.7 times greater than theoretical value at 5 percentage of fines) the theoretical value. Soil is an anisotropic material. Therefore it is very difficult to predict the variation of properties. But when theoretical values are used the design should always be in safer side.

RECOMMENDATION FOR FUTURE WORK

In the current world, increase in the needs of population such as irrigation and hydro power and unpredictable whether have become major problems. To overcome this, water management should be done carefully. For the storage the larger reservoirs should be constructed. According to this research if the dam is constructed with 30 per cent of fines at the optimum moisture content degree of compactness is very high and critical hydraulic gradient is also higher than the theoretical value (10 times greater than the theoretical value).If theoretical values are adopted to design then the structure should be very much safe and will have higher resistance to piping phenomena. But the piping failure is not only depended on effects of fines thus requiring to consider other parameters in the design. Nowadays embankments are constructed with importance given to the safety, durability of structure and safety of humans.

During the excavation piping situation can be avoided if the soil parameters are known and (Kevin S. Richards,Krishna R. Reddy)precautions can be used to ensure safety of labourers and machineries in construction activities of foundation such as dewatering.

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