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Adequacy of Seepage Analysis in Core Section of the Earthen Dam with Different Mix Proportions

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Abstract

Earthen dams are built since early days of civilization. These dams constitute to be the most common type, because it is generally built of locally available materials which derive strength from their position, friction and cohesion. Many earth fill dams are vulnerable to failures due to seepage problems that take place in the core since all soils are pervious to a smaller or larger extent. One of the ways to control seepage problem in earthen dam is by using proper materials for core section since the core section of earthen dam provides impermeable barrier within the body of the dam. Thus, this paper analyses the usage of various materials with different combinations to zone type earthen dams with central impervious vertical core and to study the behavior of phreatic line at downstream phase by varying effective length of horizontal drainage filter. The results obtained from laboratory, proposed geometry of dam and corresponding stability analysis made for various materials showed that materials with impervious nature only provides safety to core part of the earthen dam

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Keywords: Dams; Core; Horizontal filters; Hydraulic gradient; Mix proportion; Phreatic line; Seepage; Stability; Zone type earthen dam

1. Introduction

Dams are the massive artificial barrier generally used to store water. It is typically created by the emplacement and compaction of a various compositions of soil, sand, clay and/or rock. Soil compaction can lead to modification

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of soil structure and thus reduce permeability. Principal purposes of compaction in earthen dam is to increase stiffness to minimize settlements during and after construction, to increase strength to prevent sliding shear failure of dam and to make water tight to obtain required imperviousness of the core zone. The earth fill dam continues to be the most common type of dam, principally because its construction involves utilization of materials in their natural state with a minimum processing. The rapid advancement of the science of soil mechanics have made to use different materials, to adopt various skills and techniques which create confidence to build earth dams with improved designs. The interest of present study is focused towards zone type earth dams with central impervious core. Because, the pervious outer zones enclose, support and protect the impervious core and also its advantages will lead to economics in cost of construction. The purpose of core section of the earthen dam is to arrest the seepage of water from upstream side to downstream side. Hence, selection of core material for proper functioning of dam is a great challenge. The study will concentrate on seepage as earthen dam always impound water in it. Thus, one of the ways to control seepage problem in embankment is by using proper materials for core section. Many studies have been documented in the literature on core materials, effect of zoning, failures in dam and drainage pattern of earthen dam, the following points are summarized.

The core materials of glacial origin have more piping accidents than that of core materials of alluvial origin (Mark Foster et. al, 2000). The use of combination of 60% clay and 40 % sandy gravel as the core material solved the potential problems of post construction settlement in one of the most seismotectonic active zone in Iran at Karkheh dam (S.R Tafti et.al, 2008) and Impervious soils are generally suitable for the core (IS: 1498-1970). If the cross section consists of a fine grained core supported by stiffer shells, the interaction between different materials could cause a load transfer, whose intensity depends on dam geometry as well as on difference in stiffness (Luca Pagano et. al, 1998). Higher the global or average hydraulic gradient more likely piping will occur and also the narrow width of the core have a contributing factor in the development of cracks through the core (John H. Schmertmann, 2008). The use of horizontal drainage filter will recedes the phreatic line from the downstream toe (R Ziaie Moayed et.al) and also the application of a horizontal drain in an embankment dam is a prevalent method to lower the phreatic line (Amir Malekpour et.al, 2012).

Based on literature review, it is observed that limited studies regarding core section of earthen dam using design mix in its construction were done. In view of this observation, an experimental work was undertaken and the present paper is the outcome of such a work. The objective of this paper is to study the influence of different materials and their combinations in the core section to compute seepage and slope stability and to evaluate how the length of horizontal filter affects the seepage discharges through the core section of the dam.

2. Experimental program

Four field soils of different localities of Mysore designated as S-1, S-2, S-3 and S-4, three locally available soils namely Silty sand, Clayey sand and Black Clayey soil and their combinations as design mix and layer system were subjected to experimental investigation, which was carried out in two stages.

2.1. Field soil samples

Four types of field soils were collected by measuring field density using core cutter method. According to the BIS methods for the representative soil samples collected from the field, the physical properties, index properties, swelling properties, compaction and permeability characteristics and shear parameters were computed.

Table 1. Physical properties of field soils under study

Soil Designation	Specific Gravity G	Free Swell Ratio	Free Swell Index (%)	Grain size distribution (%)				Index Properties (%)				Classification
				Gravel	Sand	Silt	Clay	Liquid Limit W_L	Plastic Limit W_P	Plasticity Index I_P	Shrinkage Limit W_S	
S-1	2.65	1.29	29	14	50	25	11	25	19	6	22	SM-SC
S-2	2.69	1.02	2	14	64	15	7	24	16	8	15	SM-SC
S-3	2.66	1.15	15	9	46	29	16	29	21	8	19	SM-SC
S-4	2.64	1.22	22	5	59	23	13	29	18	11	18	SC

Table 2. Values of compaction characteristics, permeability and shear parameters of field soils under study

Soil designation	Maximum dry density γ_{dmax} (kN/m^3)	Optimum moisture content (%)	Permeability K (cm/sec)	Ultimate compressive strength q_u (kN/m^2)	Angle of failure α (Degrees)	Undrained cohesion C_u (kN/m^2)	Angle Φ_u (Degrees)
S-1	19.55	11.7	6.9×10^{-6}	122	61	34	32
S-2	20.43	9.7	6.4×10^{-4}	98	62	26	34
S-3	19.90	11.6	4.3×10^{-5}	197	59	59	28
S-4	20.18	11.8	8.3×10^{-6}	218	57	71	24

2.2. Design mix and layer system

Mix proportions were prepared by selecting locally available materials such as silty sand, clayey sand and Black Clayey soil with several advantages in terms of sustainability i.e. reduction of material cost along with reduction in energy costs related to transportation. Among four field soil samples, S-2 was taken for design mixes because of its inherent properties which differs this soil from others and are as follows.

- The soil acquires low OMC and high dry density value after compaction
- The soil has very low value of FSI (1.85%), it means it is purely non-swelling kind of material
- The soil has higher value of relative density (89%)

Although S-2 have inherent properties as listed above, it showed low value of undrained cohesion 'C_u' and relatively high value of angle of internal friction 'Φ_u' compared to other soil samples. Hence, S-2 is chosen for mix proportion.

Table 3. Designation of various mixes under study

Samples taken in the ratio 25:25:50 as a whole	Designation
Silty sand+Clayey sand+S-2	MP-1
Silty sand+Black Clayey soil+S-2	MP-2
Clayey sand+Black Clayey soil+S-2	MP-3
Samples taken in the ratio 33.3:33.3:33.3 each as a separate	**Designation**
Silty sand+Clayey sand+S-2	LS-1
Silty sand+Black Clayey soil+S-2	LS-2
Clayey sand+Black Clayey soil+S-2	LS-3

During laboratory testing of mix proportion, the ratio of 25:25:50 was chosen arbitrarily and three types of design mix were prepared. For one mix two locally available selected materials were taken 25% each, which was mixed with 50% of S-2 and make the whole to 100% and the physical properties, shrinkage properties, compaction and permeability characteristics and shear parameters were computed. To check the state of compactness, relative density value was computed for all the prepared deign mix. Also an attempt is made during laboratory testing to use materials in certain different way i.e. by adopting layer system. Any two collected local materials and S-2 were taken in equal quantity and placed in layer wise. Similarly as mix proportion three types of layers were prepared and permeability range and value of 'C_u' and 'Φ_u' were computed.

Table 4. Values of specific gravity, void ratio, shrinkage limit, dry density, relative density and compaction characteristics of prepared mixes under study

Soil Designation	Specific Gravity G	Void Ratio e	Shrinkage Limit W_S	Dry Density γ_d	Maximum dry density γ_{dmax}	Optimum moisture content	Relative density I_d
			%	kN/m^3	kN/m^3	%	%
MP-1	2.68	0.47	23	17.93	20.1	10.6	76.69
MP-2	2.65	0.54	24	16.84	19.95	10.5	67.43
MP-3	2.66	0.62	18	16.09	19.2	12.1	64.11

Table 5. Co-efficient of permeability and shear parameters of prepared mix and layered system

Soil Designation	Permeability K	Ultimate compressive strength q_u	Angle of failure α	Undrained cohesion C_u	Angle Φ_u
	cm/sec	kN/m^2	Degrees	kN/m^2	Degrees
MP-1	1.3×10^{-5}	173	59	52	28
MP-2	3.6×10^{-5}	202	57	66	24
MP-3	9.2×10^{-6}	323	55	113	20
LS-1	5.0×10^{-5}	21	64	5	38
LS-2	1.2×10^{-7}	46	63	12	36
LS-3	1.1×10^{-7}	137	60	40	30

3. Seepage Analysis

To find seepage discharge through the body of the dam, the section of zoned type earthen dam is proposed for 9 m and 18 m height of the dam and certain components are incorporated. A crest width of 4 m is provided in proposed design to insure adequate room for compaction by tamping rollers and to provide roadway across the dam with suitable parking areas for the convenience of visitors. A freeboard of 2 m and 2.5 m is provided for dam of height 9 m and 18 m respectively in proposed design. In present design approach, homogeneous well graded material is assumed as casing material with provision of upstream slope 3:1 and downstream slope $2\frac{1}{2}$:1. A core width of 4 m same as that of crest width at the level of reservoir is provided in the present design. A vertical core is provided with the critical slope of 1:1 for both upstream and downstream slope in the proposed design. The seepage control measures are necessitated to prevent adverse effects of water percolating through dam and its foundation. Horizontal drainage filter is incorporated in the dam section as a seepage control measure in the present study because horizontal filter keep the phreatic line well within the embankment, enhances leakage because of shorter seepage path, provides drainage for foundation and accelerates consolidation.

By incorporating above mentioned details in the design, seepage analysis is carried out for different core materials in a zoned type earthen dam for two heights 9 m and 18 m by keeping critical upstream and downstream slope of 1:1 as constant to all core materials. The variable parameter in the design is horizontal drainage filter length. The horizontal filter of 25%, 50% and 75% of the distance from the downstream toe to the centre line of the dam are provided. The nature of variation in phreatic line pattern is analyzed for all drainage conditions both for 9 m and 18 m height of dam. The quantity of seepage discharge at the downstream phase is calculated for different core materials for all the conditions of drainage.

In the present study, the quantity of seepage discharge is calculated from two methods i.e. by considering average slope of phreatic line i in Darcy formula and by considering geometry of seepage by taking values of number of flow channels N_f and number of potential drops N_d after constructing flow net to proposed dam section for 9 m and 18 m height of the earthen dam.

The quantity of discharge calculated from both the methods i.e. by considering average slope of phreatic line and by considering the values of N_f and N_d of the flow net will give identical results for 9 m and 18 m height of the dam respectively. It is observed that for both 9 m and 18 m height of the dam as the length of horizontal drainage filter increases, the discharge through the core of the earthen dam also increases accordingly. This clearly shows that the provision of length of horizontal filter is directly proportional to the quantity of discharge through the dam.

Following figure presents phreatic line drawn to zoned type earthen dam section with horizontal filter of width 25%, 50% and 75% from downstream toe to axis of the dam of height 9 m respectively. Similar figures are proposed for the dam height of 18 m for seepage analysis.

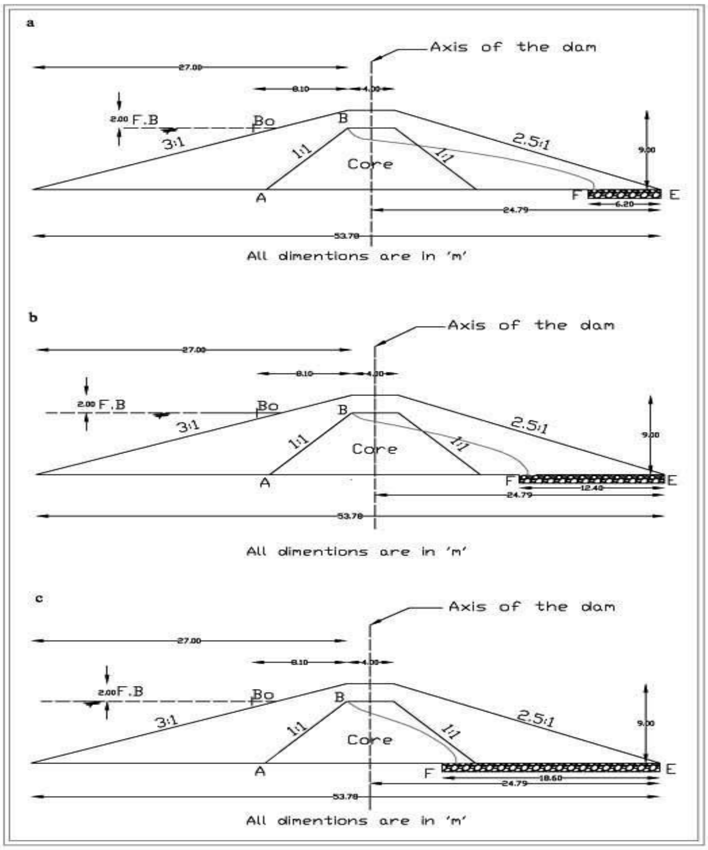

Fig. 1. (a) Phreatic line drawn with horizontal filter of width 25% from downstream toe to dam axis; (b) Phreatic line drawn with horizontal filter of width 50% from downstream toe to dam axis; (c) Phreatic line drawn with horizontal filter of width 75% from downstream toe dam axis.

4. Stability Analysis

The method which is adopted for examining the stability of slopes of an earthen embankment is the Swedish Slip Circle Method or Slices Method because it is a general method of slope stability analysis and can be used for non-homogeneous soil masses, stratified deposits, fully submerged or partly submerged conditions.

A continuous surface of potential shear failure passing through the dam is assumed. The shape and location of the surface are chosen arbitrarily on the basis of judgment as being a possible failure surface.

In the present study, the stability is checked by computing factor of safety for different core materials both for reservoir full condition and sudden draw down condition without considering pore water pressure. For reservoir full condition, submerged unit weight (γ') of soil is taken for calculation of both resisting forces ($\sum N'$) and driving forces ($\sum T'$). For sudden draw down condition, submerged unit weight (γ') of soil is taken for resisting forces ($\sum N'$) and saturated unit weight (γ_{sat}) of soil is taken for driving forces ($\sum T'$). The equation used for computation of factor of safety is as follows:

$$F.S = \frac{[C_u \times L_a + tan\ \Phi_u \times \Sigma(N')]}{\Sigma T'} \quad (1)$$

Where, 75% dependable value of undrained cohesion 'C_u' and corresponding value of angle of internal friction 'Φ_u' and dry density are considered for core material of embankment for analysis and 'L_a' is the measured length of cylindrical failure surface.

Table 6. Shows results of stability analysis of different core materials for two sample heights 9m and 18mrespectively

Soil Designation	Factor of Safety (F.S)			
	H=9 m		H=18 m	
	Full reservoir condition	Sudden draw down condition	Full reservoir condition	Sudden draw down condition
S-1	1.75	0.98	1.33	0.75
S-3	2.16	1.23	1.47	0.83
S-4	2.33	1.32	1.48	0.84
MP-1	1.92	1.12	1.35	0.79
MP-2	2.05	1.21	1.34	0.8
MP-3	2.96	1.73	1.73	1.02
LS-3	1.73	1.01	1.29	0.75

5. Result and Discussion

Three different property locally available soils i.e. silty sand, clayey sand and Black Clayey soil are used in preparing design mix because the focus of the present study is on the combination of materials, how they behave as a whole when they subjected to experimental investigation. The prepared design mix showed greater resistance to shrinkage which is essential property for core material as they always in contact with water.

5.1. Standard Proctor test

Among four field soil samples tested, S-2 have high dry density value and low optimum moisture content value although all soils nearly belong to same IS classification. This clearly indicates that the physical structure and texture of the soil is a key characteristic affecting water flow which depends upon the void ratio of soil samples. Later the results of compaction for soils of design mix proportion showed lower value of dry density compared to field soil samples because of heterogeneousness attained by mixing three kinds of materials.

5.2. Permeability test

Among four field's soil samples, S-2 is the permeable material compared to rest three soil samples. So, this sample is not recommended to use as a core material in the present study. When this soil sample is stabilized with other local materials in the form of mix proportion and layer system, decrease in value of permeability is observed. This reduction in value is due to addition of local materials to S-2 which reduces passage of voids to permit fluids to pass through. Among mix proportion and layer system, layer system proves to have low value of permeability as mentioned in Table 5. It is because of heterogeneousness in the form layers of different kind of material. This pattern will hinder the flow of water from one layer to the next results in small discharge.

5.3. Density Index

From the laboratory test results of relative density it is observed that, nearly dense state of relative density (65% to 85%) is achieved for design mix and this dense soil mass can become good core material when it is compacted by suitable standard vibratory rollers in the field.

5.4. Unconfined Compression test (UCC test)

The experimental results of this test are necessary for the determination of the bearing capacity of foundations, dams, etc. and mainly to calculate factor of safety during stability analysis. Among four field soil samples tested, S-2 will have low value of undrained cohesion 'C_u' and high value of angle of internal friction 'Φ_u'. Later these tests were conducted for prepared three design mixes and the results shows all the three mix have considerably good values of undrained cohesion 'C_u' and angle of internal friction 'Φ_u'. MP-3 will have very high value of undrained cohesion 'C_u' and low value of angle of internal friction 'Φ_u' which proves to be the best among all the material. While in the layer system, only LS-3 exhibits good value of cohesion. LS-1 and LS -2 lack good value cohesion because of improper bondage between the layers at the interface due to the presence of silty sand. So, use of these two materials is not recommended in core section of earthen dam because it may cause sliding failure within the core zone of the dam.

5.5. Seepage and Stability Analysis

The critical state of steady seepage occurs when seepage flow intersects the downstream slope and the piping takes place. By provision of horizontal filter, the phreatic line recedes from the d/s slope. So, the application of horizontal drain in an embankment dam is a best method to lower the phreatic line and to dissipate the excessive pore water pressure. Thickness of horizontal filter usually provided in embankment dam is based on gradation of materials used in filter and experience of the design engineer. But, the increased thickness will reduce piping problems. In the present design approach, it is observed that for 25% of filter provided from d/s toe to axis of the dam, the phreatic line is flat and nearer to d/s side. As the percentage length increases say 50% of horizontal filter from d/s toe to dam axis, phreatic line lies away from d/s side by acquiring intermediate position. Further increase in percentage length say 75% of horizontal filter from d/s toe to dam axis, phreatic line lies within the core section of the dam, which is not recommended because it erodes the material of the core and creates large piping paths.

The results of stability analysis showed that the materials used in the core gives safety for 9 m height earthen dam than 18 m height earthen dam. It is observed that the materials used in present experimental investigation are suitable for small or medium height dam.

6. Conclusions

Based on the results obtained from laboratory experiments, proposed geometry of cross section of zoned dam and their corresponding seepage discharges and stability analysis made for various materials, the following conclusions are drawn.

An attempt of mixing three different materials in the design mix proves to be good agreement after arriving at the test results. Increase in value of undrained cohesion and decreased value of angle of internal friction is observed from field soils to design mixes. Usage of 25% Black Clayey soil in the design mix enhances certain properties such as Cohesion, reduces the permeability value which is an essential property for a core material. The use of materials in the layer form is complex and requires more skill in the field but by attaining the same ratio of layers in the field as that of laboratory experiments, the layer system works to be effective.

In the present proposed section of vertical core zoning, the core height is limited till the freeboard and is considered sufficient. This idea saves the material used for core and leads to economy in construction. The quantity of discharge calculated by considering average slope of phreatic line and by considering the values of N_f and N_d of the flow net will give identical results. So, any one method can be adopted for practical case.

The provision of length of horizontal filter is directly dependent on the quantity of discharge through the dam because as the length of horizontal drainage filter increases, the discharge through the core of the earthen dam also increases accordingly. For the present proposed zoned section and the kind of material used for core, provision upto about 50%-60% distance of horizontal filter from the d/s toe to the dam axis is sufficient to discharge water from u/s to d/s portion of the earthen dam. The provision of horizontal filter distance 75% and above from the d/s toe to the dam axis is avoided as far as possible because phreatic line falls entirely within the body of the core, which erodes the material causing failure. It is understood that quantity of seepage is not dependent on the thickness of the horizontal filter provided. But, the increased thickness prevents the occurrence of piping and assures the stability of the slope.

From the results of stability analysis, the kind of materials used in the core gives safety for small or medium height earthen dam. By providing sufficient dimensioned berms, stable slopes both in u/s and d/s side, this materials are used for high earthen dams as the earthen dam derives strength from their position due to self consolidation process after certain elapse of time.

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