# HYDRAULIC FAILURE OF MICRO EMBANKMENT DAMS AND REMEDIAL MEASURES

## (CASE STUDY: ZANA MED, AMHARA REGION)

**By**

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## ABSTRACT

The main intention of this study is identifying the causes of hydraulic failure of Zana Micro-Embankment dam with emphasize on seepage. The selected area is found in Amhara National regional state, North Gonder zone, East Belesa woreda. The dam is located on Zana River, tributary of the Tekeze River.

Even though the study area has been selected based on the available data as compared with the other problem area, to attain the primary objective of the research the available data is so limited. The work has delt with a unidirectional investigation. Seepage analysis and filter media design of the dam which has been stated in the design document were thoroughly investigated.

Darcy's law-phreatic line, flow Net and SEEP/W software model are used to analyze the quantity of seepage through homogeneous and zoned dam, without the provision of filter material. The flow net diagram is drawn with help of AutoCAD soft ware aided by free hand sketching for both cases.

The expected quantity of seepage estimated with these different methods relatively resembles each other. The maximum seepage through the dam as per the SEEP/W software model analysis that includes foundation seepage is $7.06*10^{-3}$ $cm^3$/sec. This value is compared with the quantity of seepage estimated at the designed document that is $7.31*10^{-2} cm^3$/sec. Therefore, the design document has no problem of quantifying the expected quantity of seepage. However, the drainage system is not properly designed at the design document. To this end, failurity of seepage at the d/s face of the dam which are threatening the dam stability are expected to result from improper filter media design. Even though, the dam has a problem data on construction history, this study analyze with the help of field investigation, the cause of seepage failurity at side of spillway due to poor construction quality.

To alleviate the problem grouting, impervious blanketing and d/s berming are the proposed remedial measures for seepage and leakage failures.

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# Introduction

## *Section .01 General Description of Hydraulic Failure Problem*

Throughout record history, there is an evidence that mankind has feared and respected the destructive power of water, in the form of tides and floods. It is one of the most powerful forces of nature. Hidden in rock crevices and soil pores, it exerts unbelievable forces that tear down mountainsides and destroy engineering works. When seepage is uncontrolled, it can cause serious economic losses and take many human lives [P.Novak 2001].

Dams are valuable assets; problems can worsen however, and can become more expensive to repair if they are not solved promptly. A minor problem can turn into a major reconstruction project or even result in a complete dam failure. Most dams have seepage through or around the embankment because of water moving through the soil structure. The rate at which water moves through the embankment depends on the characteristics of soil in the embankment, how well it is compacted, the foundation and abutment preparation, and the number and size of cracks and voids within the embankment. Many seepage problems and failures of earth dams have occurred because of inadequate seepage control measures or poor/incomplete cleanup and preparation of the foundations and abutments. Seepage can lead to piping and embankment sloughing or sliding, both of which can lead to dam failure. If seepage occurs without dislodging and removing soil particles, no structural damage will result. However, if soil particles are washed away in seepage, severe problems may develop [www.waterpowermagazine.com].

Many embankment dams are constructed in Ethiopia most of which are used for irrigation purpose. However, their capacity reduces frequently before their design life time due to a number of reasons. The main causes of capacity reduction are Hydrological, Structural and Hydraulic failure of which hydraulic failures contributes 58% in Amhara region [Tefra B. 2006].

This thesis work is intended to identify the hydraulic failures mainly seepage. Most of the dams in this country lack instrumentation, recorded construction history and laboratory results. The available design documents are not properly handled and do not include all relevant documents. The above problems are expected to be the challenges of this thesis. This thesis work has considered the Zana micro embankment dams for a case study.

## *Section .02 Description of the study area*

### (a) Location, Topography, Climate, Geology

**Location**

Zana micro-embankment dam, the selected study area, is found in Amhara National Regional state, North Gonder zone, East Belesa worda. Zana MED is located on Zana River which is tributary of the Tekeze River. The geographical coordinate of the area is $12^o19'$ to $12^o16'$ North in latitude and $37^o55'$ to $37^o85'$ East in longitude with an average altitude of 2000 masl. It can be accessed by all weather road through the regional town Bahir Dar to Gohala which is small town near the study area at a distance of 164Km,and 15km in dry weather road from Gohala .

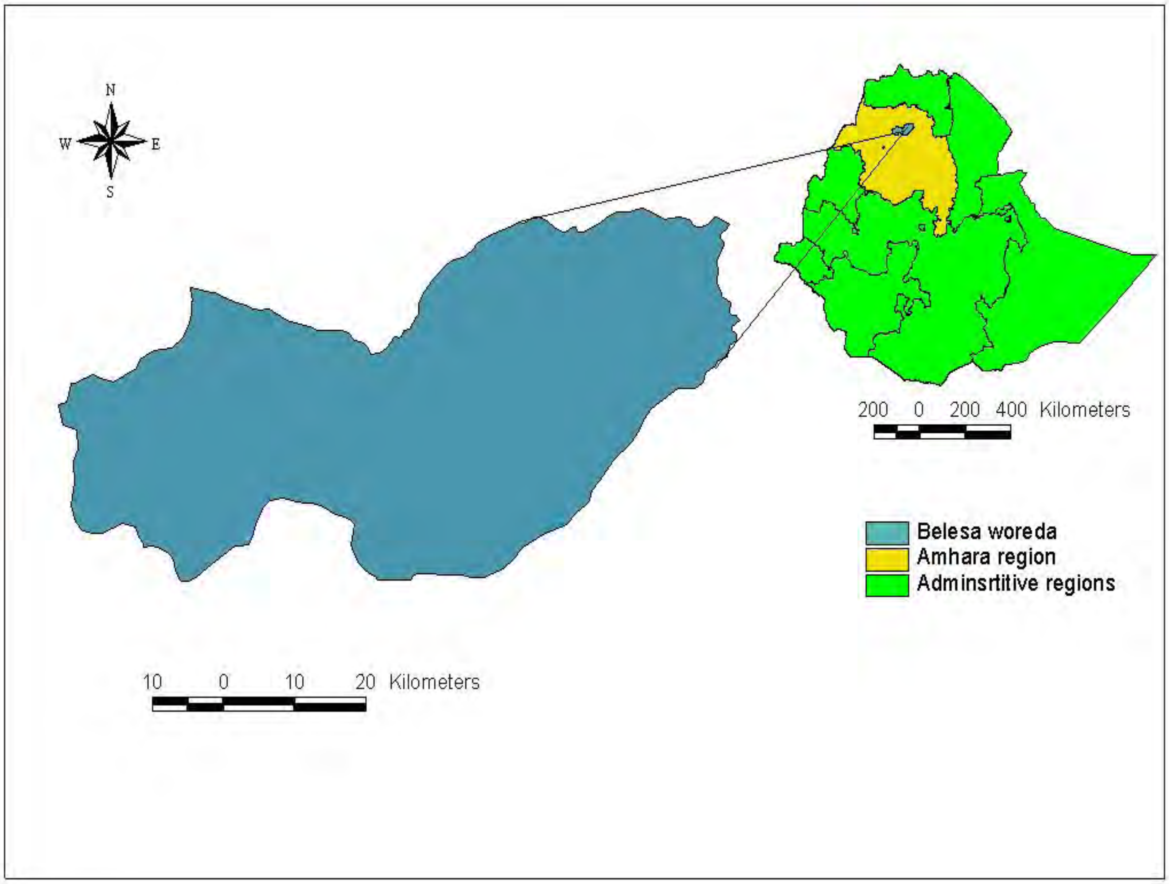


Fig1.1: Location Map of the study area

**Topography**

Zana micro embankment dams lay on the high land part of Ethiopia. The topography showed that, the right abutment is flattered compared with the left and do no have saddle for spillway. Due to this an earthen dam type with appetence structure of over flow ogee type spillway was selected. The dam axis lay on across the Zana River. The topography of the study area has good land grading for surface irrigation and greeded Mountain catchments.


Fig1.2: Topography of the study Area

**Climate**

Climate condition within the project area is classified as continental, with hot winter and relatively short cold summers. The main dry season extends from October to May, being longer and drier in the project area. There is a pronounced bi-modal rainfall distribution, with the first and generally smaller rains (belg) peaking in April, and the second in September. Rainfall variability is expected, particularly in the lower rainfall areas of the northeast highlands. Average annual precipitation is about 957mm.

**Geology**

According to the geological map of Ethiopia (scale 1:2,000,000) the area around the dam site is dominant by Alkali-olvin basalt, Tuff and rare Rhyolite. However, based on geological and subsurface investigations the rock at the dam sites is dominated by basalt; and the reservoir area is covered by soils of different grain size. The area is dissected with differently sized gullies. In some places alluvial deposits are observed and others are covered with silty clay soils.

The subsurface investigation showed that, Zana MED lay on the foundation of base rock at a depth of four meters and this might increase to some seven meter at the river bed. During that sex boreholes were dug to carry out the feasibility study along the dam axis. The result showed that, all five pits end up with highly compacted hard rock and one of them (pit no-2) end on pervious formation that has got a depth of 3.5m from the surface and water is stricken at that point. The pit no-3 has been lied on pervious formation that extended up to 4.5m depth and highly compacted at after a depth 4.5.The two abutments are found on firm with good water tight condition. With the above reason proposed four meter width with side slopes of 1:1 cut off trench at the bottom the dam is proposed to reduce the foundation seepage. The laboratory permeability testing has been carried out on the shell and core materials as shown in the table below

Table 1.1: Laboratory Results of Proposed Construction Materials

| Material Type | Proctor Test | | Permeability (cm/Sec) | Specific Gravity |
|---|---|---|---|---|
| | OMC (%) | MDD | | |
| Highly Plastic clay(Core material) | 31 | 1.36 | $11.2*10^{-9}$ | 2.78 |
| Light clay (Shell material) | 29 | 1.46 | $2.34*10^{-6}$ | 2.76 |

### (b) Purpose of Project

Several severe droughts have occurred in Ethiopia particularly in Amhara region in the last three decades that have caused considerable damage the rainfed agriculture. Consequently, sever famines occurred which have greatly affected the way of life of several people and also hampered the country's socioeconomic development in Ethiopia, Amhara region.

Commission for Sustainable Agricultural and Environmental Rehabilitation in Amhara Region (Co-SAERAR) is established at October 1995. It has started its work with definite targets and objective to alleviate the food shortage problems of the drought affected areas of the Amhara region through the use small scale irrigation project, to promote and encourage sustainable agricultural crop production. The commission strongly believes that this measure is to be the best and the most effective mitigation measure which illuminates the misery life and food insufficiency of the people by increasing the output per unit area of land leading to improve the livelihood of farmers .

This project was designed in 1996 G.C., and constructed from 1997 to 1998 G.C. The dam was intended to serve for irrigation purpose for the commanding area of about 85 ha. From the commissioned of the dam till the 2004 G.C the dam has been served for the targeted beneficiaries with out significant amount of seepage through its embankment.

### (c) Water Resource Potential / Assessment

The study area is located on the borders of Amhara and Tigray regions, which is the remote area within the region. It has no meteorological station with in the catchment area. Zana MED is proposed to utilize the surface water potential of the study area for irrigating gross area of about 85ha by submerging about 24ha of cultivated land .The hydrology data from Ribb gauging station and the annual rain fall data from the Adiss

Zemen meteorological station is used to simulate the rainfall run off relationship. The total catchments areas of the project is approximately 2500ha with estimated weighted run off coefficient approximately 0.35.The average annual runoff volume for catchments area is $8.38*10^6$ $m^3$ with average annual rainfall 0f 957.53mm. Zana River is not intermittent river and has an average base flow of 30 l/sec. The live storage of the dam is 795600 $m^3$ [CO-SAERER, 1996].


Fig1.3 Excess Water Flow over the Spillway during July, 2007

## Section .03 Objectives of the study

### (a) General Objective

The general objective of the thesis work is to identify the causes of hydraulic failure of Zana MED, giving emphasis to seepage. Lastly the paper is coming up with the possible remedial measures.

### (b) Specific Objective

- Investigate the current conditions of structure at Zana MED
- Investigate the causes of hydraulic failures
- Recommend appropriate remedial measures

# Literature Review

## *Section .04 Seepage in Embankment Dams*

Major features of the design of Embankment dam are required foundation treatment, abutment stability, seepage conditions, stability of slopes adjacent to control structure approach channels and stilling basins, stability of reservoir slopes, and ability of the reservoir to retain the water stored. These features should be studied with reference to field conditions and to various alternatives before initiating detailed stability or seepage analyses. Which makes the design of an embankment dam is complex because of the unknown materials property of foundation.

Earth dams should be designed to utilize available material to the best advantage and to conform to actual conditions at site. Sherard et al. (1963 a) say,"…the characteristics of the particular site have a great influence on the design of an earth dam than they do on many other engineering structure". Detail design sometimes will be influenced heavily by the strengths of foundation and construction materials, but the basic features are usually ditched by seepage considerations [P.Novak, 2001].

Seepage through the embankment, foundation and abutments must be collected and controlled to prevent excessive uplift pressures, piping, sloughing, and removal of material by solution, formation of cracks, joints and cavities. The design should consider seepage control measures such as foundation cutoffs, adequate and non brittle impervious zones, transition zones, drainage blankets, upstream impervious blankets and relief wells
Criteria for safe design have to be so specified that they cover all possible cause of failure. The following criteria are commonly accepted for safe design of embankment dams.

1) There should be no risk of overtopping of the dam section. The most important aspect of this criterion is estimation of the design flood and provisions of adequate spillway capacity to pass that flood with require net freeboard to protect the dam crest against wave splash.

2) The seepage line should be well within the downstream face of the dam section. If the dam section is homogeneous and no drainage arrangements are made, any seepage is going to emerge on the downstream face. This results in 'sloughing ' or softening of the d/s face and may lead to local toe failure, which may progressively develop upwards. This can be safeguarded against by providing a free drainage zone on the d/s face or by intercepting the seepage inside the dam section by internal drainage.

3) There should be no possibility of 'piping' through the embankment or the foundations. In the dam section the main protection against piping is provided by filters or transition zones which prevent migration of soil particles with seepage water.

4) There should be no opportunity for free flow of water from the u/s and d/s face. Free flow implies flow of water under pressure through a continuous crack or passage and not seepage flow through soil pores. Once a concentrated leak starts, it rapidly enlarges and is almost impossible to stop. Hence it is essential that every precaution be taken against leakage to ensure the safety of the dam.
5) The u/s and d/s slopes of the dam should be stable and safe against sliding under the most critical conditions to which they might be subjected. At the end of construction, there may be high residual pore pressures in the impervious zone of the dam, a condition which may be critical for both faces, especially for dams with thick cores rapidly constructed.

6) The u/s face will be subject to wave action from the reservoir. It has to be protected by some kind of protective layer, the preferred choice being dumped rock riprap or stone pitching .The d/s face, if of erodible material, needs protection against rainfall.
7) The embankment, foundation, and abutments must be stable under all conditions of construction and reservoir operation including seismic.
8) Freeboard must be sufficient to prevent overtopping by waves and include an allowance settlement of the foundation and embankment as well as for seismic effects where applicable [U.S Army Corps of Engineeers,1993].

## *Section .05 Estimation of seepage*

### (a) Flow Net Analysis

***I) Isotropic soils***

The analysis of seepage by flow nets contributes to the proper design and construction of many dams. The analysis of seepage using flow net starting with drawing a flow net diagram with subjective division of equipotential line and flow line. If the number of division point increases the result become more accurate, but the line makes an orthogonal line with each other

If the soil is an isotropic soil; its permissibility is constant in all direction, horizontal permissible is equal to the vertical permissible i.e. $K_h$ = $K_v$. The amount of seepage through it can also be computed from the flow net analysis. The flow net is drawn by free hand sketching and making suitable adjustment and corrections until to draw the flow line and equipotent line intersect at right angle.

The seepage rate (q) can be computed from the flow net, using Darcy's law. Applying the principle of continuity between each pair of flow lines, it is evident that the velocity must vary inversely with the spacing and flow through the field or through the flow channel containing this square.

Using Darcy's law.

$$\Delta q = k.iA$$
$$= K\left[\frac{\Delta H}{\Delta x}\right](\Delta y x 1)$$

Where $\Delta H$ is the energy drop between the two equipotential lines

$\Delta x$ is horizontal distance between the flow line

$\Delta y$ is Vertical distance between the equipotential lines

k= hydraulic conductivity

$$\Delta H = \frac{\text{Total drop (H), i.e. total head causing flow}}{\text{Number of increments into which the total drop is equally divided } (N_d)}$$

$$\Delta q = K\frac{H}{N_d}\left(\frac{\Delta y}{\Delta x}\right)$$
$$= \frac{K.H}{N_d} \quad , \quad \text{Since } \Delta y = \Delta x$$

The total flow through all the channels, i.e. the total flow through the unit width of the dam

$$\Rightarrow q = \sum \Delta q$$
$$= \left(\frac{K.H}{N_d}\right) \text{x number of flow channels, } N_f$$

$$q = \frac{K_s H}{N_d} N_f \text{ ……………………………………………….. [Eq-1]}$$

***ii) Non- isotropic soils***

If the permeability of the soil is different in the horizontal direction than that in the vertical direction, the soil type is non-isotropic soil and the seepage quantity is estimated using the effective permeability ($\overline{K}$). The flow net is drawn in the same manner as was explained earlier for isotropic soils, with the only difference the dam section shall be drawn to the same vertical scale but to a transformed horizontal scale. All horizontal dimensions shall be reduced by multiplying them by a factor equal to

$$\bar{K} = \sqrt{K_h K_v}$$

$$\Rightarrow q = \sqrt{K_h K_v} H \frac{N_f}{N_d} \text{ ........................................... [Eq-2]}$$

## (b) Darcy's Law - Phreatic Line Analysis

The location of the seepage line in earth dam is required for the following purposes:

- To mark the top flow lines so that the flow net can be draw to determine the quantity of seepage and the pore water pressure.
- To ensure that the seepage line does not intersect the d/s face and cause it is softening or sloughing and consequent failure of the d/s slope.
- To mark the diving line between dry (or moist) soil above the seepage line and the saturated soil below it so that the corresponding unit weights can be determined for the stability analysis [Arora, K.R.1996].

Phreatic line analyses vary with the type of dam, its drainage system within it and angle on inclination on the downstream face of the dam. Therefore, the analysis for a homogeneous dam without any drainage system and its angle of inclination less than $30^0$ is, Casadragde has show that the Phreatic line coincides with the base parabola, provided the slope of the of the d/s face is flat. Schaffernake and Van Iterson gave an approximate analytical solution for determination of the distance a, the phreatic line cuts the d/s face from the toe, for the slope angle $\alpha < 30^0$

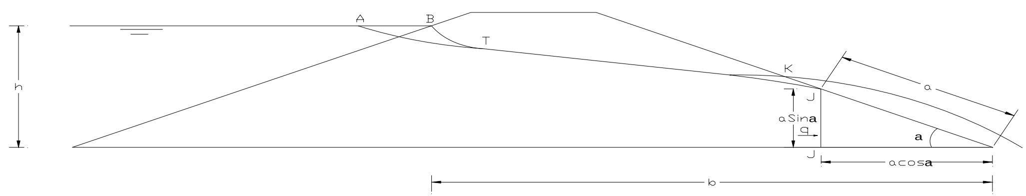

Fig 2.1: Homogenous dam without drainage

Using Darcy's Law

$$q = k\ i\ A \qquad \text{[Eq-3]}$$

$$i = \frac{dy}{dx} = \tan\alpha \qquad \text{[Eq-4]}$$

Where i= assumed hydraulic gradient

α = angle of inclination at the d/s face

k= hydraulic conductivity

Y, unit area =a sin $\alpha$

From equation 3 & 4

$$\Rightarrow \quad q = k\ a \tan\alpha \sin\alpha \qquad \text{[Eq-5]}$$

To find the value of a, from equation 3 & 5

$$a \tan \alpha \sin \alpha \, dx = dy \, Y$$

Integrating equation 4 between the limits x= a cos α, and y= a sin α to x=b and y=h

$$\mathbf{a} = \frac{b}{\cos\alpha} - \sqrt{\frac{b^2}{\cos_{\alpha}^{2}} - \frac{h^2}{\sin_{\alpha}^{2}}} \quad \text{…………………. [Eq-6]}$$

For slope angle $30^{0} < \alpha < 60^{0}$

$$a = \sqrt{b^2 + h^2} - \sqrt{b^2 - h^2 \cot^2 \alpha} \quad \text{…………………. [Eq-7]}$$

## (c) SEEP/W Software Model

SEEP/W is a finite element software product which is a part of GEO-SLOPE international model that is leading of geotechnical modeling software products. It helps to analyzing groundwater seepage and excess pore-water pressure problems within porous materials such as soil and rock. The model comprehensive formulation allows the analyses ranging from simple, saturated steady-state problems to sophisticated, saturated-unsaturated time-dependent problems. SEEP/W can be used to analysis and design geotechnical and civil problems.

The unique CAD-like technology in SEEP/W allows generating finite element mesh by drawing regions on the screen and interactively applying boundary conditions and specify material properties and estimate the material property functions from easily measured parameters like grain-size, saturated conductivity and saturated water content.

Once we have solved the seepage problem, SEEP/W offers many tools for viewing results. Generate contours or x-y plots of any computed parameter, such as head, pressure, gradient, velocity, and conductivity. Velocity vectors show flow direction and rate. Interactively query computed values by clicking on any node or flux section. Then export results into other applications, such as Microsoft Excel or Word, for further analysis or to prepare presentations.

An analysis of the expected quantity of seepage through the embankment and dam foundation using SEEP/W software model requires the sets of parameters like; model section of the dam, permeability coefficient of material, the piezometer reading and boundary conditions [www.geo-slope.com].

### *Modes of Seepage/Leakage Failure of Embankment Dams*

### (d) General

Failure of earth dams can be caused by seepage piping, foundation instability, deformation and deterioration, and earthquakes. However, most of the recorded failures around the world are related to seepage problems. To avoid failure of earth dams due to seepage, settlement, and piping, observations before and after construction are essential. During construction of earth dams, continuous field observations of deformation and pore water pressures have to be made while field observations after construction normally include seepage and the piezometric head. Without the observations, the dam may suddenly fail, and the losses of life and property damage will be great because of sudden release of a large volume of water, often with little or no advance warning. There are many causes of failure of an earth dam. From many statistics, the failure of earth dams were mainly due to seepage or piping and it is widely recommended that the monitoring of seepage through an earth dam will control the safety of the dam [Bharat S. & R.S Vershney, 1995].

At most dams, some water will seep from the reservoir through the foundation .where it is not intercepted by subsurface drain, the seepage will emerge downstream from or at the toe of embankment .If the seepage forces are large enough, soil will be eroded from the foundation and be deposited in the shape of a cone around the outlet. A continues or sudden drop in the normal pool level may be an indication that seepage is occurring [www.eige.com].

Some seepage is inevitable through all earth dams. If the seepage is suitably controlled, it doesn’t cause any harm other than loss of some water. However, if the seepage is uncontrolled and concentrated, it may lead to piping and the subsequent failure of the earth dam [Arora, K.R. 1996]. There are a number of common failure modes to which embankment dams may be vulnerable each failure mode may result in partial or complete embankment failure. Most dams in active use today exhibit seepage of one form or another. The location, rate of flow, and turbidity (clear or murky) are the critical factors when evaluating the seriousness of seepage from a dam [www.michigan.gov].

### *2.3.2 Piping*

Piping refers to subsurface erosion along a seepage pathway within or beneath an embankment which results in the formation of a low pressure conduit allowing concentrated flow. The resulting void space promotes progressive erosion extending u/s towards the source of the seepage. In the worst case, the seepage may result in the creation of a direct channel from pond to the dam face. Excessive piping may result in local or general failure of the piping may result in local or general failure of the embankment foundation [www.des.nh.gov].

#### *(i) Dam Body*

Piping is the progressive backward erosion staring from the exit point and subsequent removal of the soil from within the body of the dam, occurs when the seepage force is very large and concentrated flows take place, and form pipe-like conduit inside the dam and the hydraulic gradient further increase. The process continues and ultimately a pipe-like conduit is formed and rush of water and soil occurs leading to piping [Arora, K.R 1996].

***(ii) Dam Foundation***

Foundation failures are not uncommon among earth fill structures, where a weak layer of soil or rock exists at shallow depth in the foundation below the structure, movement along the a failure plane will occur if the earth fill loading produces stresses in excess of the shear strength of the soil in the weak layer[www.des.nh.gov]. Piping in the foundation occurs when the rate of pressure drop (i.e. hydraulic gradient) resulting from seepage through the soil particle exceeds the resistance of the soil particle, and also occur when there are pockets of loose soil in the foundation failure [Arora ,K.R 1996].

## Leakage

Breaks, separation of joints, or loss of conduit material within the dam structure itself could lead to leakage of water under pressure into the interior of the dam. This action could cause the washing out of material within the dam embankment, creating the possibility of failure on the structure. Probably the most potentially serious situation is when a rupture occurs in the conduit on the upstream side of the gate, because high water pressures are maintained on the upstream side of the control mechanism, a leak which develops can cause greater internal erosion at a faster rate. The simple fact that high pressures exist in the conduit makes the development of leaks and seepage more likely. For this reason, new dams are constructed with their low-level outlet controls located at the upstream side of the dam [www.michigan.gov]. Conduit Cracks may develop due to foundations settlements or due to the deterioration of the conduit itself; leakage occurs through these cracks, may lead to the failure of the dam .Seepage along the conduit walls occurs if there is a zone of poorly compacted soil around the conduit or if there is a gap between the conduit and surrounding soil [Arora, K.R.1996].

### 2.3.4 Sloughing of Downstream Toe

The sloughing of the d/s toe of the dam occurs under the reservoir full condition when the d/s portion of the dam becomes saturated and continuously remains in the same state, causing the softening and weakening of soil mass .This usually occurs when the phreatic lines cuts the downstream face. The soil particles are subjected to a drag force in the direction of flow .The horizontal component of this drag force will tend to dislodge the soil particles if it exceeds the resistance offered by the soil [Bharat S. & R.S Vershney, 1995].

## *Seepage Control in Earth Dams*

### *General*

The primary object of any dam is to impound water behind it and will change the natural balance of conditions at its site, as water is brought into storage ,a new seepage pattern will develop in the barrier that confine the reservoir. This water if seeps through the embankment, abutment or through the dam foundation in excessive quantity may damage the dam partially or fully. Therefore, it is very important to control the seepage through embankment dam.

Seepage control is necessary to prevent excessive uplift pressures, instability of the d/s slope, piping through the embankment and /or foundation, and erosion of material by migration into open joints in the foundation and abutments [www.epa.gov].The need for seepage control will depend on the quantity, content, and/ or location of the seepage.

Controlling the quantity of seepage that occurs after construction is difficult and quite expensive .It is not usually attempted unless drawdown of the pool level has occurred or the seepage is endangering the embankment or appurtenant structures. The control of seepage through and under the embankment must be as complete as possible to ensure stability and resistance to piping [P. Novak, 2001].

To ensure safety of dam, it is very important to handle the seepage water in the dam so as to maintain the original practices of soils in their place. As with other engineering works, earth dams and their foundation can be protected from seepage by two fundamental processes:-

Those which keep the water out or reduce the seepage quantities,

- Cutoff trenches
- Grout curtains
- Sheet-pile walls and other thin cutoffs
- Impermeable upstream

Those which use drainage methods to control that enters

- Embankment zoning
- Longitudinal drain and blankets
- Chimney drains extending upward into embankments
- Partially penetrating toe drains
- Relief well

### *Seepage Control through Dam Embankment*

The three methods for seepage control in embankment are

**(i)** **Use of filters**: - Every seepage discharge face, both internal and external, that could be susceptible to piping and heave, must be covered with filters that permit the water to escape freely but hold the particles in place. The filters have two main functions:

- To prevents internal erosion by blocking migration of soil particles from the base soil
- To facilitate internal drainage of seepage flows without built-up of excessive seepage forces and hydrostatic pressures in filters or drains.

These two requirements are satisfied by Terzaghi's filter criteria defined by the following equations:

$$\frac{D_{15} \text{ of filter}}{D_{85} \text{ of Protected layer}} < 4 \text{ to } 5$$

$$\frac{D_{15} \text{ of filter}}{D_{15} \text{ of protected layer}} > 4 \text{ to } 5$$

**(ii) Use of impervious Core**

Seepage reduction in embankment dams is done by providing an impervious core at the middle of the section. Most of the energy due to the stored water is consumed by seepage through the core, which is subject to excessive seepage forces in the process. The core is, therefore, used in combination with filter and drainage; the filter protects the core against piping resulting from excessive seepage forces, and the drainage prevents the seepage from entering the downstream shell. The overall effect, in addition to reduced quantity of seepage through the core, is reduction or elimination of water pressure and seepage forces in the downstream shell and in critical exit regions. The main requirements of core material are to provide the necessary degree of imperviousness, deformable in order to withstand differential settlements without cracking, and non-erodible in the event of cracking.

The design of filters d/s of the sloping core is more critical than that for the central core since the seepage through the sloping core will be more in a d/s direction .For the same quantity of core material, the sloping core would have the same horizontal width as the central core but the thickness measured normal to the plane of the sloping core would be less. [www.waterpowermagazine.com].

A core material of very low permeability may be required when the reservoir is used for long-term storage. A core material of medium permeability may be utilized when the reservoir is used for flood control. The top of the core should be above the maximum reservoir elevation but below the bottom of the frost zone, a vertical core located near the center of the dam is performed over an inclined u/s core because the former provides higher contact pressure between the core and foundation to prevent leakage, greater stability under earthquakes, loading, and better access for remedial seepage control [www.epa.gov].

For reducing seepage through the body of the dam, a core of impervious material, such as silty clay or clayey silt, is generally provided. However, sometimes core walls of concrete or masonry are also provide .The impervious core forms a barrier within the body of the dam against the seepage water. The type of core is selected depending on the availability of material, topography of the site, foundation conditions. Its purpose is to minimize seepage losses through the embankment.  As general rule, sufficient impervious material is available to result in small seepage losses through the embankment .Therefore, the quantity of seepage passing through the foundation and abutment may be more significant than the quantity passing through the core [www.waterpowermagazine.com].

**(iii) Use of Drains**

- **Pervious D/s shells**: - in general, earth dams are not isotopic, the horizontal permeability ($K_h$) being generally higher than the vertical permeability ($K_v$) due to compaction in thin layers and non-uniformity of borrow material .An assumption is usually made for design purpose that adequate seepage control will be obtained if the permeability of the shell material is about 20 times the permeability of the core material (i.e. Ks/Kc =20). Based on the flow net study made by Casagrande have show that: It is thus obvious that zoning alone may not ensure control over seepage if the permeability of the d/s zone is less than 100 to 500 times that of the u/s impervious core or if there is a high degree of stratification in the core. Thus, although it may sometimes be possible to achieve a satisfactory degree of seepage control by zoning alone, the uncertainty associated with permeability of the material placed in each zone as well as the degree of anisotropy, make it almost always desirable to provide internal drains in all important earth dams.

- **Chimney drains**: - the most effective seepage control measure in earth dams, extending along the d/s face of the impervious core in a zoned dam section, or placed in the heart of a homogeneous dam section, and connected to the d/s drainage blanket for drainage, the chimney drain intercepts the entire seepage from the u/s irrespective of the degree of anisotropy of the fill material and accommodates any abnormal flows through cracks that might occur in core or the u/s portion of the dam section. Properly designed and built chimney drains with adequate outlets frequently save many times their cost through lowered permeability requirements for large volumes of shell material. When chimney drains are provided, the d/s shells of dams can be constructed of any material of adequate strength with no restriction on permeability and often at a substantial reduction in cost. In a homogeneous dam section the provision of a chimney drain eliminates steady seepage pore pressures in the portion d/s of the drain and the d/s slope can be made steeper.

- **Rock toe**: - The d/s toe of a homogeneous dam is the most critical region in respect of seepage instability as the entire seepage tends to concentrated here. The soil mass in this region is subjected to excessive seepage forces which may cause heaving and sloughing of the toe if not duly protected. Rock toes and drainage blankets or filters drains are therefore provided on the d/s of homogeneous dams mainly to;
    - Provide a controlled outlet to seepage
    - Lower the seepage line and keep it well within the slope
    - Prevent piping and heaven at the d/s toe and thus improve stability of the dam against seepage

The high of the rock toe is generally kept equal to about one-third the reservoir head, which is about the height at which the seepage line emerges at the d/s face of the dam.

Usually two layers of graded filter, suitably designed to serve as a transition zone between the embankment material and the rock fill, are provide at the u/s contact face of the rock toe.

The required thickness of the drain from the following equation based on Darcy's law

$$q = K\frac{h^2}{2L} \text{ ……………………………… [Eq-8]}$$

Where, q = seepage flow per unit width of the filter drain

K= permeability of the filter material of the drain

h= thickness of the filter drain

L= length of the drain up to its point of outfall into the toe drain.

Quite often the thickness of the filter drain is decided on the basis of practical Consideration of placement and compaction .A minimum thickness of about 15 to 30cm is usually provided on small dams. Toe drains located at the toe of the dam, are usually provided in conjunction with horizontal filter drains to collect seepage and lead it to the outfall drain through suitable spaced cross-drains [www.waterpowermagazine.com].

### *Seepage Control through Dam Foundation*

The foundation and abutment of dams ,which are usually stable under the influence of natural ground -water flow , may develop a tendency to internal erosion and piping due to the change ground-water regime on reservoir impoundment.

The measure for under-seepage control through the foundation include a positive cutoff formed in an excavation up to an impervious stratum and backfilled with compacted impervious material ,concrete cutoffs walls ,grout curtain ,slurry trench cutoff (earth backfilled) ,sheet piles ,u/s impervious blanket ,vertical drains, relief wells and filter trenches. The effective control of seepage requires that the earth embankment, its foundation, and the adjoining structure should behave as one unit

If the foundation of an earth dam consists of an impervious stratum, generally, no specific measures are required to reduce the seepage. However, in rock foundations, grouting and some surface treatment may be required.

On the other hand, methods are commonly used to control seepage through pervious,

- Seepage reducing methods comprise trench cut-offs, u/s impervious blankets, concert diaphragms, slurry trench cut-offs, and grout curtains. These devices consume energy at locations within the foundation where large water pressures and seepage forces have no detrimental effects .The net result of these methods in that these forces are reduced in critical exit regions. In view of the various uncertainties due to geological features methods are generally used in combination with properly designed filters and drainage features to ensure safely of the dam and the water- retention capacity of the reservoir.

- Drainage in conjunction with filters; foundation drainage is commonly accomplished by provision of horizontal drainage blankets, relief wells and drainage trenches. Drainage trenches are toe drains installed in a pervious foundation overlain by an impervious layer if it is not too thick to be penetrated by an open trench. The drainage trench is effective in relieving uplift pressures in pervious layers of shallow thickness which it can penetrate substantially. A drainage trench is usually not effective if the underlying pervious foundation is stratified, as it will relieve uplift pressures only in the uppermost stratum. The existence of moderately impervious stratum or even stratified fine sands between the bottom of the drainage trench and the underlying pervious layer will render ineffective or decrease the efficiency of the trench [www.waterpowermagazine.com].

## Physical Properties of Embankment Dam Material

### 2.5.1 General

Selecting the appropriate material for each zone and ensuring proper construction will provide control of normal seepage as well as leakage arising from distortion of the fill or from foundation displacement. The character of the materials comprising the foundation and the embankment of earth dam has a very important influence on seepage and its effect [Bharat S. & R.S Vershney, 1995].

Availability of usable material near the site influences the choice of this type of dam. The selected type of dam must be sufficiently impermeable to retain the reservoir and must be stable enough to withstand the forces to which it will be subjected; should be capable of resisting internal erosion or piping. The different materials near a particular site are likely to possess characteristics that satisfy these requirements to different degrees. The important soil properties to be considered are; permeability, compacted density, shears strength, compressibility, flexibility and erosion resistance.

Cracking occurs when the tensile strain induced in the embankment due to crest elongation zones or differential settlement exceeds the tensile strain capacity of the soil. Yet no clear–cut correlation has been established between soil type and its cracking potential in dams even though different soils should have different capacities to withstand tensile stresses depending on their deformability characteristics. Experience indicates that cracking has occurred in dams constructed with all types of soils.

### Properties of Impermeable Strata

The first essential requirement for the core (impermeable strata) material is the availability of suitable material at an economic distance from the dam site. The borrow areas for the impervious zone have to be located near the dam site. Later it has to be investigated for available quantity and relevant soil properties.

Two desirable properties to be looked for core material are the flexibility and erosion resistance. Flexibility means ability to deform without cracking. Non cohesive granular material cannot retain open cracks but such materials are very pervious therefore they cannot be used in core. Flexibility increases with an increase in Plasticity Index. However, very high values of Plasticity Index may be associated with high compressibility. Erosive resistance is mainly derived from two sources cohesion of the fines and the resistive action of coarse particles to the flowing water and their tendency to wedge up in the leakage channel. This effect is best obtained in a well graded sand gravel mixture with enough finer particles to provide imperviousness. In such a material the coarser particles within the crack obstruct the flow and prevent development of high velocities. In tough plastic clay the resistance to erosion is provided by the strong inter particle adhesion.

The minimum core thickness is governed by the safety against piping or leakage. The minimum thickness for tolerable seepage looses and for proper compaction, the core thickness should thus depend on the type of material available and the design of transition or filter zones. If the available materials have high erosion resistance as well as good flexibility, smaller thickness of the core can be used.

### *Properties of Drains*

The filter design for the drainage layers and internal zoning of a dam is a critical part of the embankment dam design. It is essential that the individual particles in the foundation and embankment are held in place and do not move as a result of seepage forces. This is accomplished by ensuring that the zones of material meet “filter criteria” with respect to adjacent materials.

In a zoned embankment dam the coherence between the fine and coarse zones for an intermediate or transition section is required. Drainage layers should also meet these criteria to ensure free passage of water. All drainage or pervious zones should be well compacted and where a large carrying capacity is required, a multilayer drain should be provided [www.waterpowermagazine.com].

## *Remedial measures of Seepage*

### 2.6.1 General

Seepage control measure may form a complicated structure through which seepage occurs at the embankment and its foundation. This can make precise detection and remedial control difficult. Remedial action may range from continued or additional monitoring to rebuilding or abandonment of the dam. Choice of remedial methods will depend on several factors, which include;

- Geotechnical environment
- Risk
- Degree of correction required
- Cost

Several factors, including consequences of continued detrimental seepage, the geotechnical environment (embankment, foundation, abutment), seepage, will determine the type and degree of remedial seepage control. Some of the more critical consequences include:

a. Breaching of the embankment or loss of support to structural members due to piping
b. Breaching of the embankment from slope instability induced by loss of material and/or strength due to seepage.
c. Loss of significant amounts of reservoir water
d. Maintenance problems or loss of useful areas due to seepage on the downstream slope or areas d/s of the embankment.

The remedial designer must also consider the interplay of the remedial measure with other dam elements .For example;

- Effect of excavation for drains, cutoff trenches, slurry trenches… etc, on embankment stability.
- Difficulty of tying remedial measure to existing seepage control elements.
- Possibility of hydraulic fracturing when grouting.

The efficient use of remedial measures is very dependent upon geotechnical characteristics of the particular sites as built configuration, reservoir uses, and pool history.

## Storage Restriction

The most direct method to alleviate a seepage problem is to lower the reservoir and restrict pool levels in order to stop or reduce seepage and its effects. If piezometer and seepage quantity measurement devices are in place at this time, the effect of this remedy will be experimentally determined. Normally, lowering and restriction of the reservoir pool is not an acceptable long-term solution, but this depends on restriction levels and purpose of the reservoir. Care must be taken in lowering the reservoir since rapid drawdown can lead to instability of the upstream slope. Of course, risk of upstream slope failure would normally be a preferred alternative to breaching of the dam and release of a full reservoir.

## Grouting

This is a common, long-used remedy for seepage. Its effectiveness is dependent upon being able to rather specifically locate the leaking area and fill the culprit openings without damage to the embankment. Possible damage includes cracking of impermeable cores or other impermeable areas of the embankment, foundation, or abutments, and clogging of drains. If grouting results in sealing of the foundation just downstream of or beneath the downstream portion of the dam, uplift pressures may increase beneath the embankment or seepage may be forced up into the downstream portion of the embankment. Pore pressure instrumentation should be in place to monitor such changes before grouting begins. This must be considered in design of remedial controls. Because of the many variables in grouting, it is highly desirable to have an experienced contractor and field engineer. In many cases, post grout drilling may be warranted to determine if the grout has thoroughly penetrated the desired area.

### Upstream Impervious Blanket

If it is determined that sealing of the reservoir bottom and sides immediately upstream of the embankment will be useful in reducing undesirable seepage quantities and pressures beneath the embankment, an upstream impervious blanket may be employed. If successful and economically feasible, this is one of the most efficient measures since the source of water is controlled upstream of the embankment and its foundation. Fine-grained materials placed on the upstream embankment slope may be removed during drawdown because of low saturated strength and high saturated weight. If seepage can also go through the upstream portion of the embankment and then into the foundation an upstream blanket will be less effective and another remedy may be necessary.

### Downstream Berm

Berm control seepage by increasing the weight of the top stratum so that the weight of the berm plus top stratum is sufficient to resist uplift pressure. If the materials have low permeability, they will reduce seepage, but increase uplift pressures beneath the downstream toe of the dam since they force seepage to exit further downstream of the dam. If pervious, they must be designed as a filter or with an underlying filter to prevent upward migration of line particles from the foundation materials beneath them. Again, a seepage analysis must be made to determine the resisting load required of the berm. Downstream slope stability of the embankment will normally increase because of the resistance to sliding provided by the berm.

## Slurry Trench Cutoff

It has two major technical considerations in the use of slurry trenches as remedial seepage control measures are

- The effect on stability of the embankment due to excavation of the trench and the presence of a vertical plane of relatively weak soil.
- Tying the slurry trench to other existing or proposed seepage control measures. If a competent upstream blanket exists, the trench may be placed upstream of the embankment and tied to the blanket or may be placed through the dam and any pervious substratum if stability requirements are met.

## Relief Wells

It can relieve excessive uplift and potential piping when pervious layers are overlain by relatively impervious strata by providing controlled release of relatively large volumes of water. Relief wells, as compared with cutoffs, allow loss of reservoir water and require proper handling of discharge flows and periodic maintenance.

Flooding and erosion from well discharges must be prevented. Wells may be installed quickly with a minimum of downstream right of way and, in many cases, without reducing reservoir levels. If high uplift is present, installation may be boring and difficult, and requiring extra measures to keep the hole open and stable until the screen and filter are installed.

## Drainage of Downstream Slope

Seepage emerging on or at the toe of the downstream slope will normally be controlled by one of the methods previously mentioned; Expedient installation of filter materials and a toe drain can help prevent piping of embankment and foundation materials and may increase embankment stability, but will not normally reduce seepage quantities. If seepage is confined to a small area or areas, horizontally drilled drains may help control the problem. Horizontal drains of slotted pipe normally do not have a filter envelope and would generally be used for seepage or as an expedient measure until a more permanent solution could be installed [www. U.S Army Crops of Engineers, 1993].

## *World Experience on Seepage Failure and Remedial Measures*

Loss of life and damage to structures, utilities and crops may result from a dam failure. Dam failures and incidents involve unintended releases or surges of impounded water. These may come from poor initial design or construction, lack of maintenance and repair, or the gradual weakening of the dam through the normal aging processes [www.leg.wa.gov/rcw/index.cfm].

There are a lot of dams exposed for seepage failures in this real world. As an example, these dams are listed below:

### ❖ Boldwin Hill dam

The Boldwin Hill dam in Los Angeles, Califorina, was constructed on April 18, 1951. The dam was designed as a homogeneous earth fill dam and it was 71m high and 195m long. The design was considered under drain systems and a reservoir lining. The reservoir was in service continuously from July 1951 until failure on December 14, 1963 except for a short time in 1957 when it was drained.

**Failure Sequence**

On December 14, 1963, at about 11:15 A.M an unprecedented flow of water was heard in the spillway pipe at the dam. The water came from drains under the reservoir lining. At approximately 1:00P.M, muddy leakage was discovered d/s from east abutment of the dam. At 2:20 P.M., lowering of the reservoir water level revealed a 3ft wide break in the reservoir’s inner lining. Futile attempt was made to plug the hole with sandbags and water broke violently through the d/s face of the dam. By 5:00P.M. The reservoir had emptied, revealing a crack in the lining extending across the reservoir bottom in line with the breach in the dam.

In general, analysis and post failure measurements showed the fault plans being separated in the order of 6 to13mm. In some places, the opening had been enlarge by erosion, which could be attributed to rainwater infiltration in years prior to construction, reservoir seepage in the period 1951-63, or out rush of water during the failure.

## ❖ Teton Dam

The U.S. Bureau of Reclamation designed Teton Dam. It was a compacted, central core, Zoned, Earth and gravel fill embankment. Its gross height was 126m and it was 950m long at the crest. Its total volume was about 7.65million cubic meter. The dam construction was completed on November 26, 1975.

Teton Dam failed during the morning of June 5, 1976. Faiulre occurred during first filling of the reservoir storage having begun on October 3, 1975. At the time of failure, water depth above the original streambed was about 84m, which was within 7m of max normal reservoir level. There was no obvious evidence of impending failure ten hours before commencement of its final stage. Between 7:00A.M. on June 5, when initial damaging leaks were first seen in the right groin of the dam, and noon of that day, total breaching and failure occurred, beginning with the appearance of muddy springs in the right groin, followed quickly by piping through the embankment and ending with collapse of the crest into the rapidly enlarged “pipe”.

### Failure Sequence

On June 4, 1976, there was no evidence of appreciable leakage as late as 9:00 P.M. On June 5, shortly after 7:00A.M., several individuals viewed from across the gap the appearance of small seepage emerging at the downstream toe and about one-third the way up the right groin of the dam. By 7:30A.M., the outflows were reported to appear muddy.

By 8:30A.M., the muddy flows had increased reportedly from 0.57 to 0.85m3/sec, coming from the right abutment dam contact. By 10:30 A.M., the point of emergence of muddy leakage had progressed up the right groin to a level about two-thirds the height of the dam. By 11:20A.M., a large hole had been washed out of the face of the dam at the groin. In the next 30minuts, as a result of violent discharge and caving fill, the hole or "tunnel" enlarged and progressed head ward to the crest. Five minutes later, the crest collapsed and breaching was complete. By 6:00P.M., the reservoir was virtually empty, with an estimated peak outflow rate in excess of 28300 $m^3$/sec.

Two principal engineering investigations of the failure were undertaken. Their considerations, in varying degree, focused chiefly on the following potential causes:

1. Erosion of the underside of the core zone (zone 1) of brittle, erodible, compacted silt (loess) by excessive leakage through or just over the grout curtain in the intensely jointed rhyolite, into which the right abutment cutoff trench had been excavated.
2. Erosion of Zone 1 via transverse cracking of Zone 1 within the cutoff trench due to differential settlement along the steep right abutment.
3. Erosion of zone 1 via hydraulic fracturing of zone 1 due to arching of zone 1 across the deep, steeply sided, right abutment cutoff trench, such fracturing promoted by full reservoir pressure against the u/s face of the cutoff-fill-to-jointed-rhyolite contact.

## ❖ Lower Baker Dam

Lower Baker Dam is a thick arch dam of 87m height. Shortly after its completion in 1924, seepage through the abutments was noticed. This increased in time, and the abutments were grouted using asphalt in 1934. By 1960 seepage flow had again increased to undesirable amounts about 1.7 $m^3$/sec. Asphalt grouting followed by portland cement grouting in 1960 reduced leakage to 0.11 $m^3$/sec. Studies were made before grouting on possible means of reducing flow, such as blanketing or blocking entries with gravel. These studies were inconclusive. Leakage again increased with time, and by 1982 was about 3.4 $m^3$/sec. The abutments were again grouted in late 1982 and early 1983. The work was competed using asphalt, reducing total leakage to about 0.28 to 0.34 $m^3$/sec, a 90% reduction [Advanced Dam Engineering, 1988].

## Methodology of the study

Zana micro embankment dam which has suffered from hydraulic failure is considered to analysis cause of failurity. The method followed to analysis this problem is data collection at primary and secondary level. In addition to that, the analysis of the problem is supported with literature review.

## *Section .06 Data collection*

### (a) Primary data

- With visual inspection, assess the failure of the dam.
- Interview of the kebele representative of Development Agent (DA) and the beneficiaries within the command area.
- Identify the problem including the location of seepage failure at the dam body and appurtenance structures.
- Collect pictures that show the location of seepage failures at the dam body and its appurtenant structures with digital camera.

### (b) Secondary data

- Dam and its appurtenances design ,Geological report and irrigation infrastructure design document are data collected from the Water Resource Development Bureau of Amhara Region
- Digitized map of the region
- Guideline, Manuals and Standard Design of small &Medium scale irrigation projects have collected from the Ministry of Water Resources

## *Section .07 Analysis of Data*

Analysis of seepage through dam has an advantage to maintain the safety of the dam and minimizing loss of water. It will also help to consider the value of the water and relative cost of various seepage reduction measures. The analysis through embankment dams has to be made using different methods .In the study area the expected quantity of seepage through the embankment and dam foundation is carried out using Darcy's-phereatic line , Flow Net and SEEP/W soft ware model with help of the hydraulic design parameters of the dam adopted from the design report.

## Assessment and Evaluation of the Case Study Area

### *Section .08 General Description and the Major Findings*

Previously described that the reasons for reduction of retaining capacity of the dam with in Amhara region are hydrological, Structural and hydraulic failures of which hydraulic failure has proportion of 58% [Tefera B2006]. This study is mainly focused on identification of the causes of hydraulic failure of the case study area. Based on the above reason and the available data at the Regional Water Resource Development Bureau, Zana MED is selected for this case study.

Zana micro embankment dam is zoned type dam with an appurtenance structure of ogee type spillway at the right side of it. It was designed and constructed by Commission for Sustainable Agricultural and Environmental Rehabilitation in Amhara Region (Co-SAERAR) in 1996 and 1998 G.C respectively. The dam is constructed for irrigation purpose. It has impounding capacity of about $8.38*10^6m^3$ at normal pool level. The contributing watershed area is about 2500ha with a base flow of about 30 l/sec.

The salient features of the dam and its appurtenant structures are described below.

(I) Dam body

- Embankment level =2003masl
- Max water level =2002masl
- Normal water level =2000.50masl
- Minimum river bed level =1983masl
- Top width =4m
- Crest length =348m

- Upstream
  - Slope =1:2.5above the berm
  - Slope 1:3 below the berm
  - Berm length=3m
  - Berm level =1996 masl
- Downstream
  - Slope =1;2.5
  - Berm length =3.0m

- Berm level =1996 masl

(II) Spillway

- Ogee type spillway
- Design discharge ,q =130m3/sec
- Design head =1.5m
- Spillway crest length 32m
- Spillway crest level =2000.5m

Based on investigation held on the study area, problem of seepage has been physically observed at the berm of downstream face of the dam. Moreover, leakage at the junction of the embankment and left side of the spillway exist. These are shown in fig 4.1 and 4.2 below. Compared with seepage at the berm, the amount of leakage is significant and it has formed conduit which indicates that the structure really need attention. The dam is vulnerable to these problems for the last four years. However, the dam has no measured data for the amount of seepage or leakage quantity. Leakages through the side of spillway are significant. Unless some mitigation measures are taken these conditions may bring damage or catastrophic failure on the structure after some years. In addition to this, the loss of water on the reservoir have an impact on the daily life of the beneficiary's whose life depend on the designed command area. Since the time of field visit was rainy season, we couldn't measure the amount of seepage and leakage quantity.

The major task of this study is analyzing the main cause of seepage and leakage failures on the structure. Even though the project area is selected based on the above two big reasons, the available data at the Region Water Resource Development Bureau for this research area is so limited that the research work on the dam was highly dependent on the design document. The study area has no construction history, operation & maintenance manual and measured seepage quantity. Therefore, analysis of this paper mainly focused on the design document which was supplemented by field investigation. The analysis includes checking the designed quantity of seepage and seepage control and drainage system of the structure with different condition and methods. The overall findings ended with proposing appropriate remedial measures to shield the structure from catastrophic failure.

**Fig 4.1: Location of Leakage Area at the side of Spillway Footing**


**Fig 4.2 Seepage areas at the Berm of d/s Dam**

## *Section .09 Analysis and Presentation of Findings*

Analysis has been carried out to realize the cause of hydraulic failure with emphasize on seepage problem of the dam. As explained above consulting the design document seepage with different cases and methods have been analyzed and presented below. The methods used to quantify the expected amount of seepage through the embankment are Flow net, Darcy's Law -phreatic line and SEEP/W model software.

### 4.2.1 Darcy's Law-Phreatic line

Even though Zana MED is zoned type dam; the analysis of seepage at the design document is only for homogeneous dam without filter drain. In our case this technique has been used to estimate the expected quantity of seepage for two cases i.e. homogeneous and zoned dam without drainage system. The detail analysis has been show below.

The data adopted from the design document are:-

- River bed level = 1983masl
- Normal pool level = 2002 masl
- Embankment level = 2003masl
- Depth of water (H) =19 m
- Dam height =20 m
- Permeability coefficient for
  - Shell material, $k_s = 2.34*10^{-6}$ cm/sec
  - Core material, $k_c = 1.12*10^{-8}$cm/sec

## (I) Homogeneous Dam

Homogeneous dam analysis has been carried without provision of drainage system. The permeability of the shell material that is light clay (gravely clay) has permeability of $2.34*10^{-6}$ cm/sec. In this case the seepage line cuts the d/s faces and is going to emerge on the downstream face. The point J is the point where the seepage line cut d/s faces of the dam at a distance of 'a' meter from the toe. This results in 'sloughing ' or softening of the d/s face and may lead to local toe failure .Therefore this point needs an exit correction. Based on the method of Schaffernak and Van Iterson the analytical solution for an angle < $30^0$ is expressed as it is shown below.

$$q = K (\tan\alpha) (a*\sin\alpha) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{[Eq-5]}$$

For $\alpha = 21.8^{0} < 30^0$ the value a

$$a = \frac{b}{\cos\alpha} - \sqrt{\frac{b^2}{\cos\alpha^2} - \frac{h^2}{\sin\alpha^2}}$$ ………………………….. [Eq- 6]

Where b= B - 0.7M

=116.5 – 0.7 *57

b = 76.6m

$$= \frac{76.6}{\cos 21.8} - \sqrt{\frac{76.6^2}{\cos 21.8^2} - \frac{19^2}{\sin 21.8^2}}$$

a = 17.21m

The amount of seepage per unit length, q

$q = K_s (\tan\alpha) (a*\sin\alpha)$

$=2.34*10^{-6}(\tan 21.8) (17.21\sin 21.8)$

= $5.98*10^{-6}$ cm3/sec/m

The total seepage over the full length of 348m is estimated to be $2.08*10^{-3}$ $cm^3/sec$

To draw phreatic line

$$Yo = \sqrt{b^2 + h^2} - b$$

$$= \sqrt{76.6^2 + 19^2} - 76.6$$

$\Rightarrow$ Yo= 2.32m

The coordinate points on the phereatic line

$$Y = \sqrt{2xy_0 + y_0^{\ 2}}$$
$$= \sqrt{4.64x + 5.38}$$

Table 4.1: Coordinates Points of phreatic Lines

| X(m) | 21.5 | 26.5 | 31.5 | 36.5 | 41.5 | 46.5 | 51.5 | 56.5 | 61.5 | 66.5 | 71.5 | 76.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Y(m) | 10.25 | 11.33 | 11.55 | 13.22 | 14.07 | 14.87 | 15.63 | 16.35 | 17.05 | 17.72 | 18.36 | 18.98 |

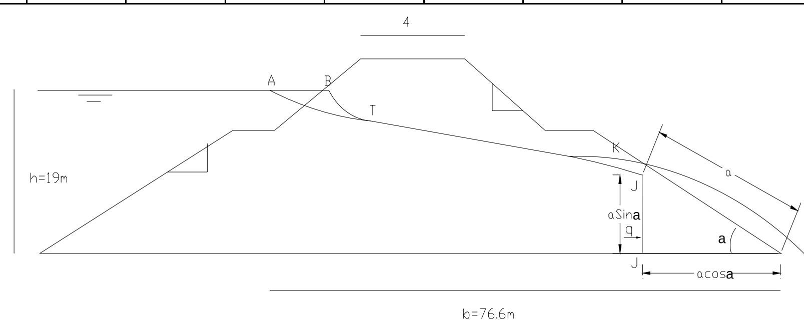


**Fig 4.3: Phreatic Line at the Homogeneous Dam**

## (II) Zoned Dam

In case of zoned dam analysis, the impact of permeability of shell material with the core material should be checked first. And if the ratio of permeability of shell material with core material (Ks/Kc) is greater than 20, the effect of shell material on core is negligible

$$\frac{K_s}{K_c} = \frac{2.34*10^{-6}}{11.2*10^{-9}}$$
$$=208.93>>>20$$

For this case the analysis is made as if the dam is homogeneous. The core material is highly plastic clay with permeability of $1.12*10^{-8}$cm/sec.

$q = K (\tan\alpha) (a*\sin\alpha)$ ………………………….. [Eq-5]

For an angle of inclination $\alpha$ $=40.18^0$ that is $30^0 < \alpha < 60^0$

$a = \sqrt{b^2 + h^2} - \sqrt{b^2 - h^2 \cot^2 \alpha}$ …………………… [Eq-7]

b= B-0.7M

= 48 - 0.7*22.5

=32.25m

$= \sqrt{32.25^2 + 19^2} - \sqrt{32.25^2 - 19^2 \cot^2 40.18}$

a =<u>14.34m</u>

$q = 11.2*10^{-9}(\tan 40.18) (14.34 \sin 40.18)$

$=8.75*10^{-8}cm^3/sec/m$

Therefore the total seepage over the full length of 48m is estimated to be $4.2*10^{-6}cm^3/sec$

To draw phreatic line

$Yo = \sqrt{b^2 + h^2} - b$

$= \sqrt{32.25^2 + 19^2} - 32.25$

Yo= 5.18m

The coordinate points on the phereatic line

$$Y = \sqrt{2xy_0 + y_0{}^2}$$

$$= \sqrt{10.36x + 26.83}$$

Table 4.2: Coordinates Points of Phreatic Lines

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| X(m) | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 32.25 |
| Y(m) | 5.18 | 8.85 | 11.42 | 13.50 | 15.30 | 16.9 | 18.37 | 19 |

**Fig4.4: Phreatic Line at the Zoned Dam**

## 4.2.2 Flow Net

At the original design document the flow net is constructed manually. It was not attached to the design document because of scale reason. In the document only stated the number of flow lines and equipotential lines are mentioned. In this case flow net diagram was made using Auto CAD software and free hand sketch. The point used to draw the flow net for homogeneous and zoned have attached at annex-1 and 2 respectively. Flow net diagram for homogeneous dam is shown in Fig-9 and have 19 flow lines ($N_f$) and 74 Equipotential lines ($N_d$). The expected amount of seepage through Homogeneous dam is estimated using Eq-1

$$q = \frac{K_s H}{N_d} N_f \text{ ……………………………………………….. [Eq-1]}$$

$$= \frac{2.34*10^{-6}*19}{74}*19$$

$=1.14*10^{-5}$ cm$^3$/sec/m

The total seepage over the full length of 348m is estimated to be $3.97*10^{-3}$cm3/se
Flow net diagram for homogeneous dam

In case of zoned dam, as it has been mentioned earlier, the shell material has no impact on the core material, the analysis considered only the core of the dam that has permeability coefficient of $11.2*10^{-9}$cm$^3$/sec.

Flow net diagram for Zoned dam is shown in fig-10 and have 19 flow lines ($N_f$) and 31 Equipotential lines ($N_d$)

$$q = \frac{K_c H}{N_d} N_f$$

$$= \frac{11.2*10^{-7}*19}{31}*19$$

q $=1.3*10^{-7}$cm$^3$/sec/m

The total seepage over the full length of 48m is estimated to be $6.24*10^{-5}$cm$^3$/sec

Flow net diagram for Zoned dam

### 4.2.3 SEEP/W Software Models

SEEP/W software model, property of Water Works Design and Supervision Enterprise, is 2004 version .The procedure we follow to analyze the problem using this model is

- Model the cross sectional area of the dam
- Insert hydraulic conductivity of the material .In our case such a data is not incorporated in design document. This parameter is imported from the existing data based on the hydraulic permeability of material and editing with the available data. In case of foundation permeability assumed the saturated permeability because the geological report stated the base rock is found at depth of 7m and that has been fill with boulders and gravels.
- Insert boundary condition that influence the seepage, head of water above it, and the location of seepage exit where pressure head will be zero
- Locate the fluxes section where the result will be labeled
- Verify/optimize the data given
- If the data have no error, solve the problem
- Label the phreatic line and contour line with in it

In view of the various uncertainties due to geological features, the analyses have been made for three different cases homogeneous, zoned and zoned with foundation consideration.

The result of the analysis using SEEP/W software model for the case of homogeneous dam is presented below. The analysis considered the dam without filter drainage system and neglected the impact of foundation seepage. The adopted parameters of the dam are 116.5m of bottom width, 4m top width and dam height of 20m .Its permeability coefficient has a value of $2.34*10^{-6}$ cm/sec. As shown from the figure the estimated quantity of seepage at the center the dam and near the toe of the dam are $1.72*10^{-8}m^3$/sec/m and $1.457*10^{-8}m^3$/sec/m respectively.

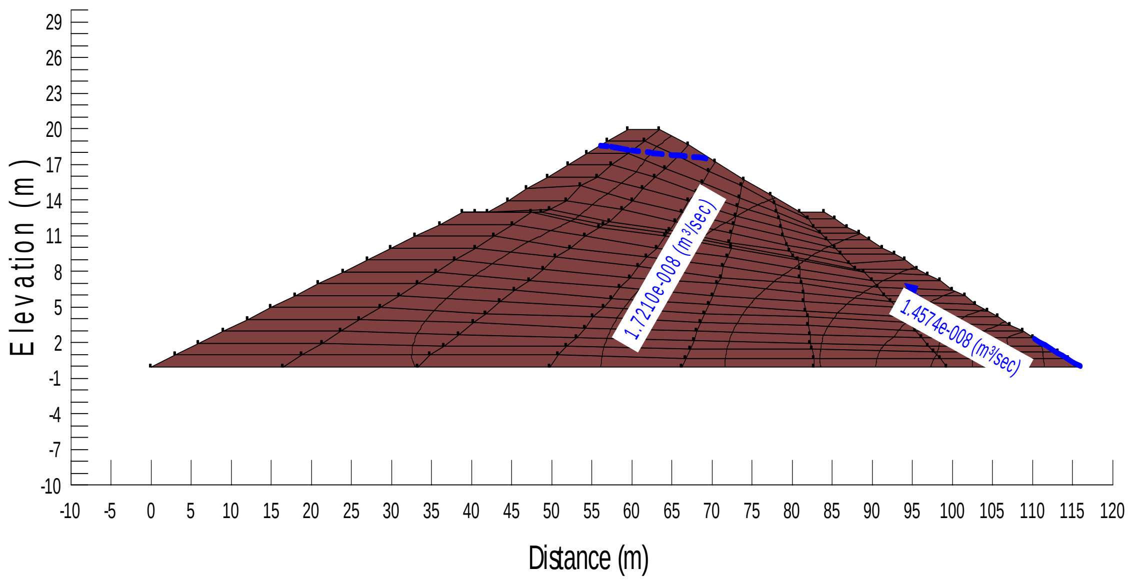


Fig 4.5: Seepage Analysis through Homogeneous Dam

The analysis of zoned dam using SEEP/W soft ware model is differ with the other two method used above. In this case the dam is analyzed without filter drainage system and foundation seepage .However, the analysis is considered the impact of shell material with the core. The adopted parameters of the dam are 116.5m of bottom width, 4m top width and a dam height of 20m. The permeability coefficient of shell and core material has

$2.34*10^{-6}$ &$11.2*10^{-9}$ cm/sec respectively. As shown from the figure the estimated quantity of seepage at center of the dam is $3.183*10^{-10}$ $m^3$/sec/m.

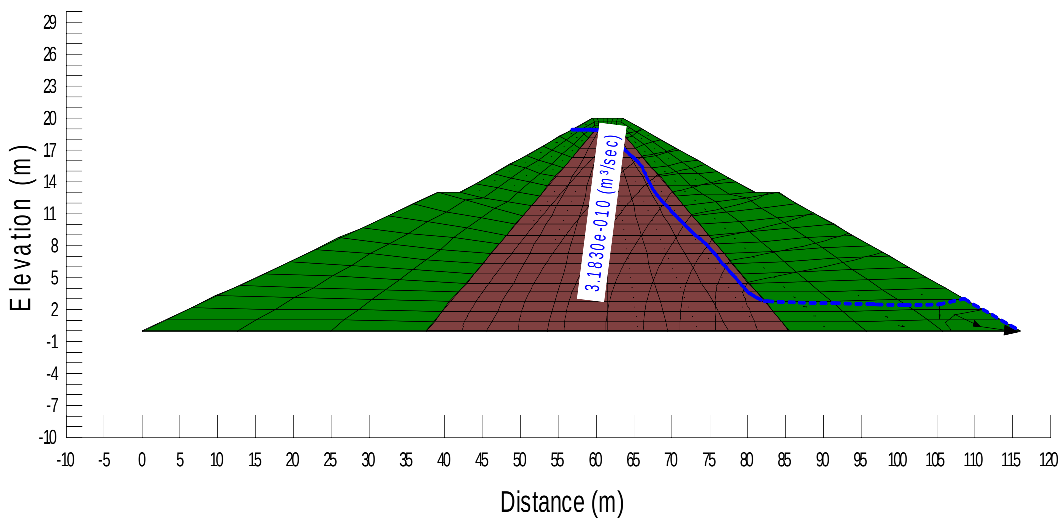


Fig 4.6: Seepage Analysis through Zoned dam

For the case of zoned dam with consideration of foundation seepage using this model is shown below. The analysis considered the dam without filter drainage system. The required data are adopted from the dam design and geology report. The parameters of the dam are 116.5m of bottom width, 4m top width and dam height of 20m.In addition to this the permeability coefficient of shell and core material are $2.34*10^{-6}$ &$11.2*10^{-9}$ cm/sec respectively. From the geology report the base rock is found at a depth of 7m and considers total longitudinal length of 130m. The coefficient of Permeability at the foundation is assumed saturated permeability. The estimated quantities of seepage at center of foundation and at the toe of the dam are $2.03*10^{-8} m^3$/sec/m and $1.457*10^{-8} m^3$/sec/m respectively.

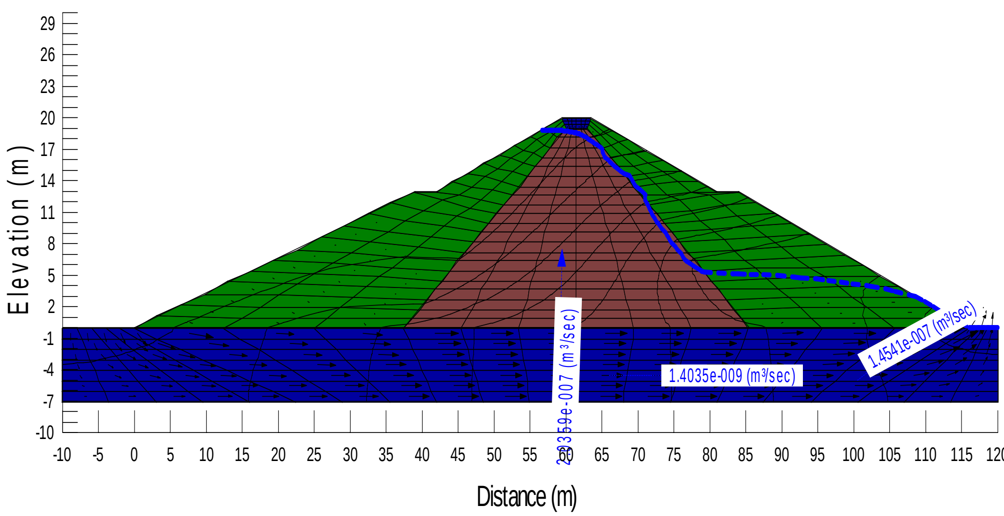


Fig 4.7: Seepage analysis through Zoned dam with foundation

## Results and Discussion

As explained in the previous explanation the analysis paid attention to different cases with three methods to quantify the expected amount of seepage. The result showed that the expected quantity of seepage have considerable magnitude with SEEP/W model for zoned dam case that considers foundation seepage. However, the model is analyzing the case without detail investigation of foundation material property with an assumption on saturated hydraulic permeability material. This value may have some degree of improvement if the detail investigation was made on the foundation material. The results of each method have attached on the table below.

**Table5.1: Results of Expected Quantity of Seepage with Different Method and Cases**

| Methods | Homogeneous dam ($cm^3$/sec) | Zoned Dam ($cm^3$/sec) | Zoned Dam with foundation ($cm^3$/sec) |
|---|---|---|---|
| Phreatic line | $2.08*10^{-3}$ | $4.2*10^{-6}$ | |
| Flow net | $3.97*10^{-3}$ | $6.24*10^{-6}$ | |
| SEEP/W | $5.98*10^{-4}$ | $1.17*10^{-5}$ | $7.06*10^{-3}$ |

As shown from the above table, the expected quantity of seepage estimated with these different methods relatively resembles each other in quantity. In this study, the maximum seepage through the dam as per the SEEP/W software model that includes foundation seepage is $7.06*10^{-3}$ $cm^3$/sec. This value is compared with the quantity seepage estimated at the designed document that is $7.31*10^{-2} cm^3$/sec .This value is estimated that the foundation seepage twice that of embankment. Therefore, the design document has no problem of quantifying the expected quantity of seepage.

However, as it has been explained earlier the dam has been exposed for seepage/leakage failure .In view of this fact, the intention of the paper is to identify the main cause of failure and propose remedial measure for it. Further exploration on the design document was needed giving emphasize to the design of filter/ drainage system.

The filter design for the drainage layers of a dam is a critical part of the embankment design. Particularly the design of filters d/s of the sloping core is more critical than that for the central core since the seepage through the sloping core will be more in a this direction. The soil mass in this region is subjected to excessive seepage forces which may cause heaving and sloughing if not designed properly. To ensure safety of dam, it is very important to handle the seepage water in the dam so as to maintain the original practices of soils in their place.

At the design document transition filter media hadn't been designed properly. There is no gradation curve both for filter and drainage material. The document stated that, if the permeability of the shell material is 25 times that of the core material, it is up to the designer to use available filter material at the project area by increasing the thickness of the inclined and horizontal filter to 1.5m.

Through investigation of the filter media and drainage system of design reveals that:-

- There are no clearly described parameters of the filter media or properly written document for the construction engineer. No one knows how the filter and drainage system is there put. Hence if no filter media is provided as required to that matter not properly constructed this gives way for failure in seepage.
- Probably the designer has given poorly designed filter media for construction and again this can be a cause for this failure.

## Seepage/Leakage Mitigation Measure of the Case Study

Seepage and leakage have been identified as problem for zana MED for the last four years. At the beginning minor seepage occurred at the d/s berm of the dam. Subsequently leakage at the right side of spillway junction with the embankment was observed. Farmers, who use the dam, said that the capacity of the dam retaining water has reduced with time. The amount of seeping water quantity markedly increased in its spatial occurrence and volume after seven years of normal operation. This confirm that the dam have faced problem of retaining the designed quantity of water.

Pervious study was conducted on the general performance of dam within the region. The case study area has some short comings to fulfill its intended purpose. The study pointed out that, the performance of the dam has reduced to retain water as it is stipulated in the design document. The failurity in its general form was stated to be hydraulic.

During field visit we observed water at the berm of d/s face of the dam. In addition to the water at rock toe of the dam, relatively a lot of amount water flows through the junction of spillway and embankment body. The water that flow at right side of the spillway is relatively clear with some silty clay. It has formed conduit like structure as show in the figure 4.1. At the d/s berm water form marsh area and it flows with very low velocity which may expose the dam for problem of sloughing in the long run. The field visit was conducted during rainy season to conform wheather the water at the berm is from seepage or not. We asked Farmers and Development Agents (DA) of the area about the general situation of the dam. They said that, the water at the berm is not only rain water and further explained the problem occurred at dry season even when the water level reached at the normal pool level of the reservoir. The water leaks at the junction of spillway has considerable amount throughout the year that has an impact on their life. Therefore, it has fundamental importance to limit these problems related with seepage/leakage through it. It is not only matter of keeping water loss within in limit, but also to control the safety of the dam.

To set out remedial measures to the problem of the dam the impact of this action with the other dam elements should be considered and analyzed. The possibilities of choosing and installing a remedial measure will be depend on geotechnical environment, risk, degree of correction required and cost. This will be determined with detail investigations on multi disciplinary team. Unless the concerned organization could make detail study on this problem, the structure hereafter is at risk and may bring big loss in many aspects. The failure may be

- Breaching of the spillway part that adjoins the dam embankment
- Breaching of the d/s of embankment body due to slope instability induced by loss of material strength due to seepage
- Loss of significant amounts of reservoir water which have direct impact on the user

If the embankment and environment allow, remedial actions are proposed for the downstream face of the embankment and junction of spillway to the embankment.

1. Grouting is an effective and common method that is being applied for this type of problem. The objective of grouting is to fill the opening, usually joins of the rock, with cement or other material. For larger openings, for the case of Zana MED, a solution material such as fly ash and sand may be mixed with the cement for economy. Portland cement grout is essentially a mixture of cement and water. Water-cement ratios for grouting have been and still are controversial. Many organizations start, and sometimes continue, with very thin grouts with ratios of 5:1 by volume have been commonly used and sometimes even 10:1 by volume has been injected. In using such materials, one should recognize that the finest cracks or openings that can be grouted will have minimum widths of about three to five times the diameter of the coarsest particles of the grout mixture. Usually, splitting techniques are desirable. First, the large openings are grouted with sand grout and then holes located between the first holes are grouted with neat cement grout to fill the smaller openings. The usual specification for portland cement fineness for grouting is at least 3500 $cm^2/gm$ in the Blaine test in order to avoid the more coarsely ground materials.

However, there are many variables in grouting; it is highly desirable to have an experienced professional with detail investigation. Post grout drilling may be warranted to determine if the grout has thoroughly penetrated the desired area. This method reduces the quantity of leakage significantly; particularly when tight or fine-grained materials are used.

2. At the upstream part of the dam an impervious blanketing is one of the most efficient measures since the source of water is controlled upstream of the embankment and its foundation. It is clear that sealing of the u/s reservoir bottom and sides immediately u/s of the embankment will be useful in reducing undesirable seepage quantities and pressures beneath the embankment. The required thickness for blanketing is decided after detail investigation of seepage quantity and general condition of the dam is made.
3. Reasonable thickness of impervious blanket of appropriate length is placed over the soft seepage areas at the downstream face of the dam as one of the remedial measures. This adds weight and provides a working platform for installation of relief wells at points of excessive seepage.
4. Berm control seepage is made by increasing the weight of the top stratum so that the weight of the berm plus top stratum is sufficient to resist uplift pressure and the water will not rise to the berm . Again, a seepage analysis must be made to determine the resisting load required of the berm. Downstream slope stability of the embankment will normally increase because of the resistance to sliding provided by the berm.

# Conclusion and Recommendation

## *Section .10 Conclusion*

Attempt has been made to identify the main causes of hydraulic failure of the Zana dam giving emphasis to seepage. The design document is investigated exhaustively on the quantification of the expected quantity of seepage through the embankment with different methods and cases. The methods used to estimate the quantity of seepage are Darcy's-phreatic line, Flow Net and SEEP/W software model. The biggest value of all these three methods, compared with the original estimated quantity of seepage is a little bit less. Hence there is no major problem in quantification of seepage.

Besides the efforts were made on the counter checking of seepage estimation at the design document, the design of filter media is also investigated. However, the document has no detail design of filter media to dispose the seeping water. The document has no laboratory analysis on the proposed filter material. The designer stated that the parameter filter media are set out based on his practical experience. This study identified that the problem of seepage at the d/s berm is due to luck of practical experience of the designer or improper design of the filter media.

As explained earlier the dam has been exposed for leakage problem. However, there is a problem of mandatory data to analyze the cause of leakage at the side of spillway. The above reasons make the conclusion difficult. So in general we may say the cause of leakage failure at the side of spillway with the help of field investigation on the problem area is due to improper compaction or any others reason during construction period.

Finally, though the proposed remedial measures are mainly based on the finding from the existing document, author’s professional judgment and reflection from world experience. This study is recommends the remedial measures to solve the problem. These are grouting at the leakage point, impervious blanket and d/s berm

## *Section .11 Recommendation*

Since the study of this paper work is not supported by the overall required documents, identifying the main cause of failure is so stiff. Therefore, further study focusing on the following points are recommended

- ❖ Identification on the source hydraulic failure needs an extensive back analysis with help of frequent field visit.
- ❖ The study area has exposed for such failure, therefore, for further detail investigation the amount of seepage should be measured.
- ❖ The recommended remedial measures to address the problem are based on literature review, before the implantation it needs detail analysis with the experienced professionals.

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# APPENDICES

Annex -1 Point Used to Draw the flow Net for Homogeneous Dam

| Head (h) | Bed width (b) | Yo $=\sqrt{b^2+h^2}-b$ |
|---|---|---|
| 19 | 76.6 | 2.32 |
| 18 | 78.35 | 2.04 |
| 17 | 80.1 | 1.78 |
| 16 | 81.85 | 1.55 |
| 15 | 83.6 | 1.34 |
| 14 | 85.35 | 1.14 |
| 13 | 89.2 | 0.94 |
| 12 | 91.3 | 0.79 |
| 11 | 93.4 | 0.65 |
| 10 | 95.5 | 0.52 |
| 9 | 97.6 | 0.41 |
| 8 | 99.7 | 0.32 |
| 7 | 101.8 | 0.24 |
| 6 | 103.9 | 0.17 |
| 5 | 106 | 0.12 |
| 4 | 108.1 | 0.07 |
| 3 | 110.2 | 0.04 |
| 2 | 112.3 | 0.02 |
| 1 | 114.4 | 0.00 |
| 0 | 116.5 | 0.00 |

| H | 19 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| b | $Y_o$=2.32 | 2.04 | 1.78 | 1.55 | 1.34 | 1.14 | 0.94 | 0.79 | 0.65 | 0.52 | 0.41 | 0.32 | 0.24 | 0.17 | 0.12 | 0.07 | 0.04 | 0.02 |
| 1.5 | 3.51 | 3.21 | 2.92 | 2.66 | 2.41 | 2.17 | 1.92 | 1.73 | 1.54 | 1.35 | 1.18 | 1.03 | 0.88 | 0.73 | 0.61 | 0.46 | 0.35 | 0.25 |
| 6.5 | 5.96 | 5.54 | 5.13 | 4.75 | 4.38 | 4.01 | 3.62 | 3.30 | 2.98 | 2.65 | 2.35 | 2.06 | 1.78 | 1.50 | 1.25 | 0.96 | 0.72 | 0.51 |
| 11.5 | 7.66 | 7.15 | 6.64 | 6.17 | 5.71 | 5.25 | 4.74 | 4.34 | 3.92 | 3.50 | 3.10 | 2.73 | 2.36 | 1.98 | 1.67 | 1.27 | 0.96 | 0.68 |
| 16.5 | 9.05 | 8.45 | 7.87 | 7.32 | 6.78 | 6.24 | 5.65 | 5.17 | 4.68 | 4.17 | 3.70 | 3.27 | 2.82 | 2.37 | 1.99 | 1.52 | 1.15 | 0.81 |
| 21.5 | 10.25 | 9.59 | 8.93 | 8.31 | 7.71 | 7.09 | 6.43 | 5.88 | 5.33 | 4.76 | 4.22 | 3.72 | 3.22 | 2.71 | 2.27 | 1.74 | 1.31 | 0.93 |
| 26.5 | 11.33 | 10.60 | 9.87 | 9.20 | 8.53 | 7.86 | 7.12 | 6.52 | 5.91 | 5.28 | 4.68 | 4.13 | 3.57 | 3.01 | 2.52 | 1.93 | 1.46 | 1.03 |
| 31.5 | 12.31 | 11.52 | 10.74 | 10.00 | 9.29 | 8.55 | 7.75 | 7.10 | 6.43 | 5.75 | 5.10 | 4.50 | 3.90 | 3.28 | 2.75 | 2.10 | 1.59 | 1.12 |
| 36.5 | 13.22 | 12.37 | 11.54 | 10.75 | 9.98 | 9.19 | 8.34 | 7.64 | 6.92 | 6.18 | 5.49 | 4.84 | 4.19 | 3.53 | 2.96 | 2.26 | 1.71 | 1.21 |
| 41.5 | 14.07 | 13.17 | 12.28 | 11.45 | 10.63 | 9.79 | 8.88 | 8.14 | 7.37 | 6.59 | 5.85 | 5.16 | 4.47 | 3.76 | 3.16 | 2.41 | 1.82 | 1.29 |
| 46.5 | 14.87 | 13.92 | 12.99 | 12.11 | 11.24 | 10.36 | 9.40 | 8.61 | 7.80 | 6.97 | 6.19 | 5.46 | 4.73 | 3.98 | 3.34 | 2.55 | 1.93 | 1.36 |
| 51.5 | 15.63 | 14.64 | 13.66 | 12.73 | 11.82 | 10.90 | 9.88 | 9.06 | 8.21 | 7.34 | 6.51 | 5.75 | 4.98 | 4.19 | 3.52 | 2.69 | 2.03 | 1.44 |
| 56.5 | 16.36 | 15.32 | 14.29 | 13.32 | 12.38 | 11.41 | 10.35 | 9.48 | 8.59 | 7.68 | 6.82 | 6.02 | 5.21 | 4.39 | 3.68 | 2.81 | 2.13 | 1.50 |
| 61.5 | 17.05 | 15.97 | 14.90 | 13.89 | 12.91 | 11.90 | 10.79 | 9.89 | 8.97 | 8.01 | 7.11 | 6.28 | 5.44 | 4.58 | 3.84 | 2.94 | 2.22 | 1.57 |
| 66.5 | 17.72 | 16.60 | 15.49 | 14.44 | 13.42 | 12.37 | 11.22 | 10.28 | 9.32 | 8.33 | 7.40 | 6.53 | 5.65 | 4.76 | 4.00 | 3.05 | 2.31 | 1.63 |
| 71.5 | 18.36 | 17.20 | 16.05 | 14.97 | 13.91 | 12.82 | 11.63 | 10.66 | 9.66 | 8.64 | 7.67 | 6.77 | 5.86 | 4.93 | 4.14 | 3.16 | 2.39 | 1.69 |
| 76.5 | 18.98 | 17.78 | 16.60 | 15.48 | 14.38 | 13.26 | 12.03 | 11.02 | 9.99 | 8.93 | 7.93 | 7.00 | 6.06 | 5.10 | 4.29 | 3.27 | 2.47 | 1.75 |
| 81.5 |  | 18.35 | 17.13 | 15.97 | 14.84 | 13.68 | 12.41 | 11.38 | 10.31 | 9.22 | 8.19 | 7.23 | 6.26 | 5.27 | 4.42 | 3.38 | 2.55 | 1.81 |
| 86.5 |  | 18.90 | 17.64 | 16.45 | 15.28 | 14.09 | 12.79 | 11.72 | 10.62 | 9.50 | 8.43 | 7.45 | 6.45 | 5.43 | 4.56 | 3.48 | 2.63 | 1.86 |
| 88.7 |  |  | 17.86 | 16.65 | 15.48 | 14.27 | 12.95 | 11.86 | 10.76 | 9.62 | 8.54 | 7.54 | 6.53 | 5.49 | 4.62 | 3.52 | 2.66 | 1.88 |
| 90.8 |  |  | 18.07 | 16.85 | 15.66 | 14.43 | 13.10 | 12.00 | 10.88 | 9.73 | 8.64 | 7.63 | 6.61 | 5.56 | 4.67 | 3.57 | 2.70 | 1.91 |
| 92.9 |  |  | 18.27 | 17.04 | 15.84 | 14.60 | 13.25 | 12.14 | 11.01 | 9.84 | 8.74 | 7.72 | 6.68 | 5.62 | 4.72 | 3.61 | 2.73 | 1.93 |
| 95 |  |  | 18.48 | 17.23 | 16.01 | 14.76 | 13.40 | 12.28 | 11.13 | 9.95 | 8.84 | 7.80 | 6.76 | 5.69 | 4.78 | 3.65 | 2.76 | 1.95 |
| 97.1 |  |  | 18.68 | 17.42 | 16.19 | 14.92 | 13.54 | 12.41 | 11.25 | 10.06 | 8.93 | 7.89 | 6.83 | 5.75 | 4.83 | 3.69 | 2.79 | 1.97 |
| 99.2 |  |  |  | 17.60 | 16.36 | 15.08 | 13.69 | 12.54 | 11.37 | 10.17 | 9.03 | 7.97 | 6.90 | 5.81 | 4.88 | 3.73 | 2.82 | 1.99 |
| 101.3 |  |  |  | 17.79 | 16.53 | 15.24 | 13.83 | 12.68 | 11.49 | 10.28 | 9.12 | 8.06 | 6.98 | 5.87 | 4.93 | 3.77 | 2.85 | 2.01 |
| 103.4 |  |  |  | 17.97 | 16.70 | 15.40 | 13.97 | 12.81 | 11.61 | 10.38 | 9.22 | 8.14 | 7.05 | 5.93 | 4.98 | 3.81 | 2.88 | 2.03 |
| 105.5 |  |  |  | 18.15 | 16.87 | 15.55 | 14.11 | 12.93 | 11.73 | 10.49 | 9.31 | 8.22 | 7.12 | 5.99 | 5.03 | 3.84 | 2.91 | 2.05 |
| 107.6 |  |  |  | 18.33 | 17.03 | 15.70 | 14.25 | 13.06 | 11.84 | 10.59 | 9.40 | 8.30 | 7.19 | 6.05 | 5.08 | 3.88 | 2.93 | 2.07 |
| 109.7 |  |  |  | 18.51 | 17.20 | 15.86 | 14.39 | 13.19 | 11.96 | 10.69 | 9.49 | 8.39 | 7.26 | 6.11 | 5.13 | 3.92 | 2.96 | 2.09 |
| 111.8 |  |  |  | 18.68 | 17.36 | 16.01 | 14.53 | 13.31 | 12.07 | 10.80 | 9.58 | 8.46 | 7.33 | 6.17 | 5.18 | 3.96 | 2.99 | 2.11 |
| 113.9 |  |  |  | 18.85 | 17.52 | 16.16 | 14.66 | 13.44 | 12.19 | 10.90 | 9.67 | 8.54 | 7.40 | 6.23 | 5.23 | 3.99 | 3.02 | 2.13 |
| 116.5 |  |  |  |  | 17.72 | 16.34 | 14.83 | 13.59 | 12.32 | 11.02 | 9.78 | 8.64 | 7.48 | 6.30 | 5.29 | 4.04 | 3.05 | 2.16 |

Annex -2 Point used to draw the flow net for Homogeneous dam

| Head (h) | Bed width(b) | $Yo = \sqrt{b^2 + h^2} - b$ |
|---|---|---|
| 19 | 32.3 | 5.17 |
| 18 | 33.1 | 4.57 |
| 17 | 34 | 4.02 |
| 16 | 34.8 | 3.50 |
| 15 | 35.6 | 3.03 |
| 14 | 36.4 | 2.60 |
| 13 | 37.3 | 2.20 |
| 12 | 38.1 | 1.85 |
| 11 | 38.9 | 1.52 |
| 10 | 39.7 | 1.24 |
| 9 | 40.6 | 0.99 |
| 8 | 41.4 | 0.77 |
| 7 | 42.2 | 0.58 |
| 6 | 43 | 0.42 |
| 5 | 43.9 | 0.28 |
| 4 | 44.7 | 0.18 |
| 3 | 45.5 | 0.10 |
| 2 | 46.3 | 0.04 |
| 1 | 47.2 | 0.01 |
| 0 | 48 | 0.00 |

| H | 19 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| b | $Y_o$=5.17 | 4.57 | 4.02 | 3.5 | 3.03 | 2.6 | 2.2 | 1.85 | 1.52 | 0.99 | 0.77 | 0.58 | 0.42 | 0.28 | 0.18 | 0.1 | 0.04 | 0.01 |
| 1.5 | 6.50 | 5.88 | 5.31 | 4.77 | 4.27 | 3.82 | 3.38 | 3.00 | 2.62 | 1.99 | 1.70 | 1.44 | 1.15 | 0.96 | 0.76 | 0.56 | 0.35 | 0.17 |
| 6.5 | 9.69 | 8.96 | 8.27 | 7.60 | 6.97 | 6.37 | 5.78 | 5.24 | 4.70 | 3.72 | 3.26 | 2.81 | 2.35 | 1.93 | 1.54 | 1.14 | 0.72 | 0.36 |
| 11.5 | 12.07 | 11.22 | 10.42 | 9.63 | 8.88 | 8.16 | 7.45 | 6.78 | 6.10 | 4.87 | 4.28 | 3.70 | 3.12 | 2.55 | 2.04 | 1.52 | 0.96 | 0.48 |
| 16.5 | 14.05 | 13.10 | 12.20 | 11.30 | 10.45 | 9.62 | 8.80 | 8.03 | 7.24 | 5.80 | 5.10 | 4.41 | 3.73 | 3.05 | 2.44 | 1.82 | 1.15 | 0.57 |
| 21.5 | 15.78 | 14.74 | 13.75 | 12.76 | 11.81 | 10.89 | 9.97 | 9.11 | 8.23 | 6.60 | 5.81 | 5.03 | 4.26 | 3.48 | 2.79 | 2.08 | 1.31 | 0.66 |
| 26.5 | 17.34 | 16.22 | 15.14 | 14.06 | 13.03 | 12.02 | 11.02 | 10.07 | 9.10 | 7.31 | 6.43 | 5.57 | 4.72 | 3.86 | 3.09 | 2.30 | 1.46 | 0.73 |
| 31.5 | 18.77 | 17.57 | 16.41 | 15.26 | 14.14 | 13.06 | 11.98 | 10.95 | 9.90 | 7.96 | 7.01 | 6.07 | 5.15 | 4.21 | 3.37 | 2.51 | 1.59 | 0.79 |
| 36.5 | | 18.83 | 17.60 | 16.36 | 15.18 | 14.02 | 12.86 | 11.77 | 10.64 | 8.56 | 7.54 | 6.53 | 5.54 | 4.53 | 3.63 | 2.70 | 1.71 | 0.85 |
| 41.5 | | | 18.70 | 17.40 | 16.15 | 14.92 | 13.69 | 12.53 | 11.33 | 9.12 | 8.03 | 6.96 | 5.91 | 4.83 | 3.87 | 2.88 | 1.82 | 0.91 |
| 46.5 | | | | 18.38 | 17.06 | 15.77 | 14.47 | 13.25 | 11.99 | 9.65 | 8.50 | 7.37 | 6.25 | 5.11 | 4.10 | 3.05 | 1.93 | 0.96 |
| 48 | | | | 18.66 | 17.32 | 16.01 | 14.70 | 13.45 | 12.17 | 9.80 | 8.63 | 7.48 | 6.35 | 5.19 | 4.16 | 3.10 | 1.96 | 0.98 |