# Failure Analysis of Homogeneous Earthen Dam

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**Abstract.** Earthen dams are the most widely used water retaining structures. Homogeneous dams are best suited for moderate heights and relatively flat side slopes. Seepage through these dams may lead to piping and sloughing. Therefore, filters, which prevent the loss of fines and keep the phreatic line away from the downstream face, are essential for the safety of such dams. This study presents a failure analysis of a homogeneous dam made up of fine sand. The dam is lined with geomembrane on the upstream face with brick tiling over it. After first filling of the reservoir, the major breach occurred in the dam. Limit Equilibrium and Finite element analyses are carried out to simulate and study probable causes and mechanisms of failure using GeoStudio and Plaxis 3D respectively. The probable causes of failure are found as a) excavation on a downstream slope and quality control at site b) seepage on the downstream side and inadequate filter. The possible remedial measures for rehabilitation of the dam against such failures are evaluated by providing a) vertical chimney filter b) horizontal drain and c) rock-toe. The existing section of the dam without any filter is to be reinforced by providing an external filter on the downstream slope with berms.

**Keywords:** Homogeneous, Earth dams, Filters, Remedial measures, Seepage

## 1 Introduction

Earthen dams are constructed using naturally available material with minimum processing. Depending upon the type of material used for construction, these dams are classified as homogeneous earthen dam, zoned earthen dam and diaphragm earth dam. These dams are not perfectly impervious as a result water seeps through these dams. Seepage water affect the stability of the earthen dam as pore pressure increases inside the dam body. Thus, seepage and slope stability analysis are important to determine the stability of earthen dam. Failure of these dams results in huge destruction all around. Different modes of failure are hydraulic failure, seepage failure and structural failure. Hydraulic failure includes failure due to overtopping, erosion of upstream face by wave action, gully formation on the downstream slope due to running water. According to the international committee on large dams (ICOLD, 1995), and Foster et al. (2000), one –third or more of the total identified failures was caused by dam overtopping. Internal erosion and piping through dam and its foundation possess serious problem to the stability of earthen dam. Internal erosion and piping can be divided into four phases: initiation and continuation of erosion, progression to form a pipe and formation of a breach (Fell et al., 2003). It is generally found that approximately half of the piping failure are associated with the presence of conduit through the embankment. The different modes of piping associated with conduits are piping into the conduit, along and above the conduit or out of the conduit (Fell et al., 2005). Leakage from the conduit does not have to be underestimated. It is important to carefully detect the leakage and take remedial measures before the failure occurs. Structural failure occurs when there is sliding of soil mass which may occur due to various reasons such as steep slope, rapid drawdown of reservoir water, external loading, rainfall, steady seepage.

Limit equilibrium method is most common approach for slope stability analysis. The most common limit equilibrium techniques are methods of slices, such as the ordinary method of slices (Fellenius) and the Bishop simplified, Spencer, and Morgenstern-Price methods. The Finite element method represents a powerful alternative approach for slope stability analysis which is accurate, versatile and requires fewer a priori assumptions, especially, regarding the failure mechanism (Griffiths et al.1999).

## 2 Project Description

A homogeneous earthen dam located in northern India is constructed to supply drinking water to nearby villages. The dam is made up of fine sand with both the upstream and downstream slope as 1:3. It is lined with the geomembrane and has brick tiling over it. During the first filling of reservoir, the part of the dam section breached and resulted in inundation of nearby villages. At the time of failure, the dam is almost full to its capacity.

## 3 Numerical Modelling

The numerical modelling of the present study is done using GeoStudio and PLAXIS 3D. In GeoStudio, seepage and slope stability analysis are carried out using SEEP/W and SLOPE/W. Seepage analysis is carried out using saturated/unsaturated material model for dam body. This model requires saturated water content ($\theta_s$) and residual water content ($\theta_r$). These values are taken from the literature as these values has little influence on factor of safety (Bhowmik et al. 2018). Zero pressure boundary condition is applied at toe of the dam and new boundary condition is created with constant head at full reservoir level. Limit equilibrium analysis is carried out using Slope/W with Mohr Coulomb as material model. Grid and radius method is used to find the critical slip surface.

Three-dimensional (3D) finite element (FE) modelling is carried out using Plaxis 3D. Soil is modelled using 10-noded tetrahedral soil elements with Mohr Coulomb material model. Mesh optimization is carried out to obtain factor of safety with minimal error and within reasonable computation time. Factor of safety is calculated by varying element distribution type from very coarse to very fine. Fine element distribution type is used in this study. Phreatic line is obtained using steady state groundwater flow as pore pressure calculation type. Sides of the model are kept normally fixed and base is fully fixed. Factor of safety is calculated using safety calculation. The material properties used for the analysis are presented in Table 1.

**Table 1**. Material properties used for analysis

| Properties | Embankment | Base | Rock toe | Filter |
|---|---|---|---|---|
| Elastic modulus, $E$ (kN/m$^2$) | $75 \times 10^3$ | $150 \times 10^3$ | $350 \times 10^3$ | $90 \times 10^3$ |
| Friction angle, $\phi$ (Degree) | 27 | 29 | 42 | 38 |
| Cohesion, $c$ (kPa) | 0 | 0 | 0 | 0 |
| Poisson's ratio, $\nu$ | 0.35 | 0.35 | 0.35 | 0.35 |
| Unit weight, $\gamma$ (kN/m$^3$) | 18 | 18 | 20 | 18 |
| Permeability, $K$ (m/s) | $10^{-5}$ | $10^{-5}$ | $10^{-2}$ | $10^{-3}$ |

# 4 Failure Analysis of Dam

Before the failure of dam, leakage was observed on the downstream side and to detect the leakage, excavation was done. Failure analysis has been carried out by studying the probable causes of leakage and effect of excavation on the stability of dam to know the cause of failure.

## 4.1 Probable causes of leakage

Leakage is one of the important factors which affects the stability of an earthen dam. The various possible causes of leakage are studied by analyzing the design of the failed section as shown in figure 2. The probable causes of leakage are: -

***4.1.1 Leakage through joints*:** Section on which leakage was observed had a pipeline through it. It is observed that there was a bend in the pipe near the downstream side. There may be the possibility of leakage through the joints of pipe.

***4.1.2 Improper compaction around the pipe*:** Pipes represent discontinuities through the embankment and foundation. Whenever pipe or conduit is laid through the embankment, proper compaction around the pipe is difficult. Improper compaction can cause cracking of earth fill and develop preferential flow path through which water can flow and erode the soil. This uncontrolled flow of water leads to internal erosion and piping.

***4.1.3 Puncture in the membrane:*** The dam is lined with the membrane on the upstream side. Since the leakage was detected during the first filling of reservoir, there may be the possibility that there was a puncture in the membrane during construction.

## 4.2 Effect of excavation on stability

Although the dam is lined with the membrane on the upstream face, the steady state seepage analysis has been carried out by assuming no membrane to check whether the failure is due to leakage alone. Factor of Safety for the failed section under steady state seepage is found to be 1.36 by limit equilibrium method as shown in Figure 1 and 1.40 by finite element method. It shows that the leakage alone is not the cause of breach in the dam. The effect of excavation on stability is studied by modelling it in Plaxis 3D. In Plaxis 3D, the part of the volume is deactivated in plastic phase and safety analysis is carried out for each plastic phase to know the variation in factor of safety with excavation depth.

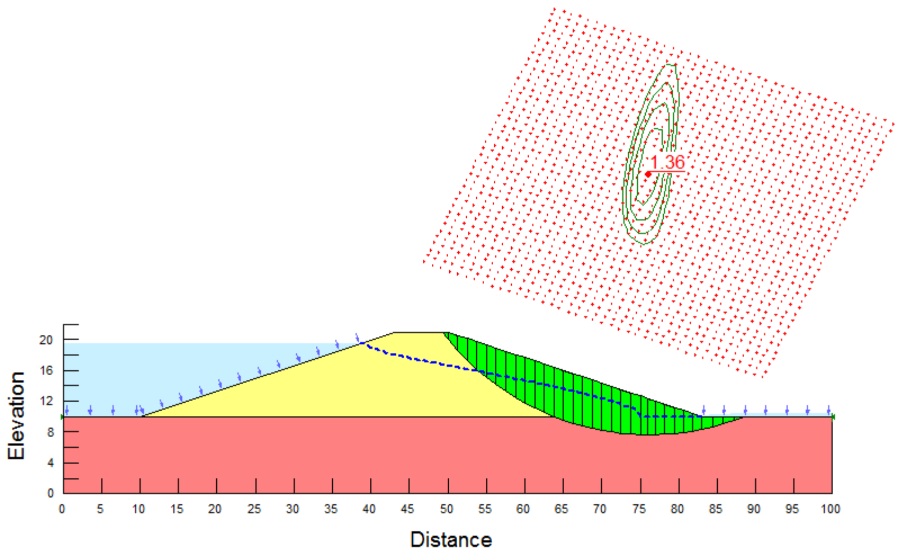



**Fig. 1.** Slope stability analysis of failed section under steady state seepage using GeoStudio

Figure 2 shows that factor of safety decreases with excavation depth. After 4m of excavation, factor of safety decreases from 1.4 to 1. Therefore, excavation at downstream side is critical in filled reservoir.

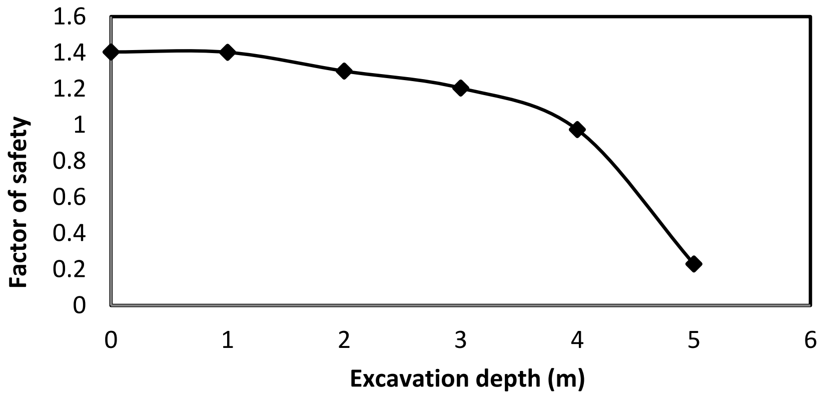



**Fig. 2.** Variation of factor of safety with excavation depth

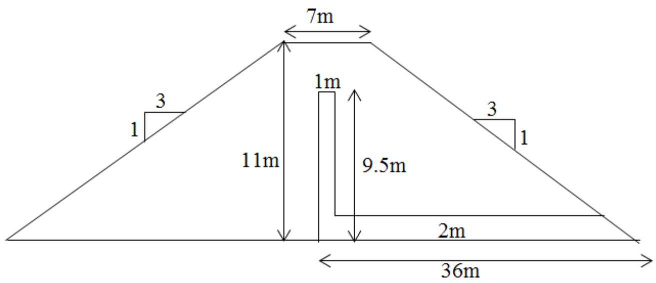
## 5 Remedial Measures

### 5.1 Measures for stability of failed section

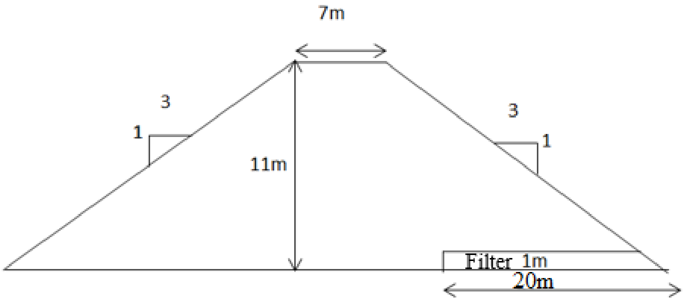
Factor of safety of the failed section under the steady state seepage was found to be 1.36 which is less than the desired factor of safety for long term stability. A parametric study has been carried out with different possible methods to achieve the desired factor of safety. Seepage in homogeneous earthen dam is controlled by vertical filter, horizontal filter and rock toe. Analysis has been done with all three filters to obtain the factor of safety of 1.5 under steady state seepage. Figure 3 shows the remediated section using different filters.

### 5.2 Measures for stability of existing section

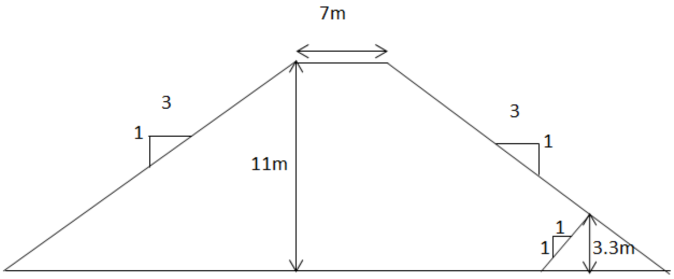
Discontinuous rock toe is provided in the dam, so there are some sections where there is no filter protection. Although the dam is lined with the membrane on the upstream face but there may be the possibility of leakage in future. So, the analysis has been carried out for steady state seepage without membrane. It is found that factor of safety under steady state seepage without filter has value less than 1. Thus, if there is any leakage in future then it may lead to the failure of dam. To stabilize the existing section, the analysis is carried out using external filter with berms on downstream side. Width of the berm is taken as 4m and slope 1:3. A parametric study has been carried out to optimize the height of the berm. Figure 4 shows the variation of factor of safety with height of the berm.




a)




b)




c)

**Fig. 3.** Remediated section using a) Vertical filter b) Horizontal filter c) Rock toe

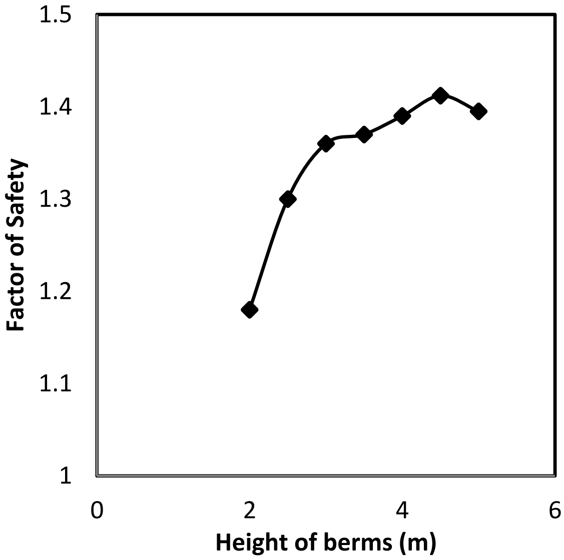



**Fig. 4.** Variation of factor of safety with height of berms

It is observed that there is not much difference in factor of safety for a berm height of 4m and 4.5m. Figure 5 shows the stability analysis of existing section with berm height 4m.

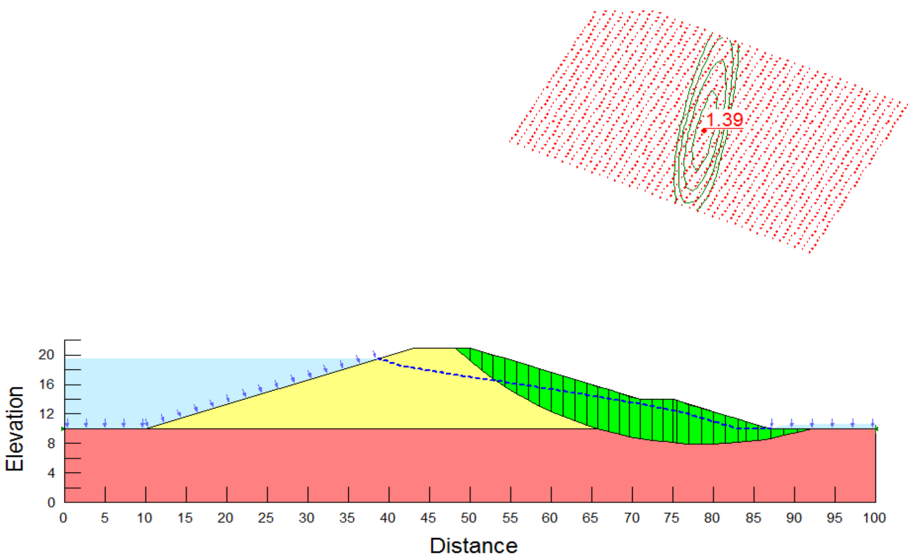



**Fig. 5.** Stability analysis of existing section with berm height 4m

But there is a decrease in factor of safety for a berm height of 5m due to failure in berms. It is not possible to obtain the desired factor of safety in this case. However, factor of safety of 1.4 can be used as the dam is already lined with the membrane. Figure 6 shows the remediated section for existing portion of dam.

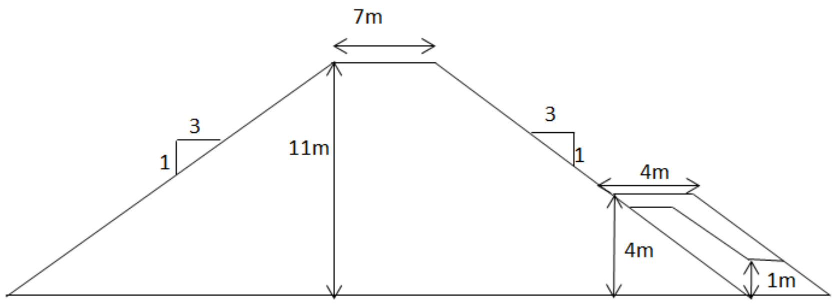



**Fig. 6.** Remediated section for existing portion of dam

### 5.3 Measures for reducing leakage

The stability of dam can be improved further by reducing leakage through the dam. This can be done by providing adequate filter which prevent the loss of fines and improves the stability. The leakage through the pipe can be avoided by blocking and grouting the pipe drains. To avoid the puncture of membrane, quality measures should be adopted at site while laying membrane. It is also beneficial to install field monitoring system to check the pore pressure variation.

## 6 Conclusions

Failure analysis of homogeneous earthen dam is presented in this paper. From the study, it is concluded that

- Pipes through the embankment should be avoided as it leads to different failure modes of earthen dam. However, in case the pipe is provided in the dam then it should be provided with horizontal filter or vertical filter diaphragm to avoid the washing of fines in case of leakage.
- Quality control at site is necessary whenever a membrane is used as a barrier to minimize the frequency of holes.
- External filter with berms can be used in existing dams which are not provided with internal filters.
- Plaxis 3D finite element method gives higher factor of safety than limit equilibrium method (GeoStudio)

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