ORIGINAL ARTICLE

Modeling assessment of seepage and slope stability of dam under static and dynamic conditions of Grindeho Dam in Ethiopia

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Abstract

This research work was carried out using Geo-Slope software programmes, i.e., to compute the infiltration and slope stability analysis of the Grindeho dam using SEEP/W and SLOPE/W. Embankment dam failure may occur due to different reasons, such as structural instability, hydraulic conditions, seepage through the dam body and foundation. The determination of the factor of safety for the dam slope stability and quantify the amount of seepage through the dam, under different cases of operations, is vital to ascertain the dam overall safety. In this research, Finite Element modelling is used through Geo-Studio software to simulate slope stability and seepage analysis of the embankment dam. Three distinct operational cases are considered for the dam analysis: end of construction before filling the reservoir, after/full reservoir condition, and rapid reservoir condition drawdown. Four separate methods of analysis were used to verify the stability of the slope embankment: Morgenstern-Price, Bishop, Janbu, and Spencer. The requirements of the Benchmark Safety Legislation (US Army of Corps Engineers and British Dam Society) are observed. The simulation results of the upstream and downstream side of the dam section have a direct effect on the factor of safety, the outcome of the stability analysis performed showed that all sections of the dam are safe within the specified range of factors of safety for the potential all loading and operation cases. But all the slip surfaces move through the section of the dam shell, which shows that this zone is the weaker zone and requires spatial attention. The simulation results obtained from the SEEP/W program revealed that 15,291.5 m^3/year and 22,818.56 m^3/year amount of seepage loss is present in the Grindeho dam during the drawdown case and full reservoir case, respectively.

Keywords Finite element modeling · Geo-studio · Seepage · Stability of slope

Introduction

Initially, for water supply and irrigation, only small dams were built. Today, however, many countries in the world have high priorities for dam building for various purposes (irrigation, hydropower, navigation, fisheries, etc.). About 1 billion people depend on food produced by reservoir related irrigation (FAO 2017). There is no alternative to how this food could have been produced by other means. Many countries in the world are impacted by water shortage. Thousands of dams have yet to be constructed to store water and make it available worldwide during the first half of this century (شجاعی، رویا 1393), especially in developing countries.

As 80% and above of the people in the country rely on agriculture, Ethiopia also gives high priority to the construction of the embankment dam. (FAO 2017). And most of the agricultural practices depend on natural rainfall, and the actual avoidance of the country's famine and drought is the beginning of numerous water supply projects, i.e., if no rain, the continuity life in the country will enter under notation (Bewket 2008). Various water resource projects, such as dams and irrigation projects, which support the supply of water from natural rainfall and ensure the sustainability of life, should therefore be built in different areas (feasible areas) of the country to avoid this risk. Among them, the Grindeho dam is built to help the struggle against drought, but due to the presence of a high amount of seepage on the *d/s* face of the dam, the life of this dam is at risk. In addition to the objective of economic benefits, most of the dam projects often discuss the overall socio-economic growth of the people in the region (Head n.d.). One of the key benefits of irrigation schemes is to discourage rural people from

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commuting to the cities, while at the same time providing them with a higher standard of life in their native areas. Seepage under an embankment is much more dangerous than that for a concrete dam (Htwe and Naing 2017), since embankments are usually built on soft material which is liable to be scoured out. Whereas a concrete dam is usually built on rock which is not worn away so rapidly by the scouring action of water, and even then a defective dam will not necessarily be endangered by passage of water through it or even under it (Johansson 1997).

Overtopping and internal erosion through the dam or the foundation is the most frequent reason for embankment dam failures (Schmertmann 2004).

Recent research shows that embankment dam failure caused by internal erosion can occur very suddenly, and it may be just a few hours from an early warning of a concentrated leak at the downstream toe to a complete dam failure at the crest (Schmertmann 2004).

It is vital for the growing future safety of the dam to minimise the amount of water seeping through the dam body and foundation to determine good building quality in dams, particularly embankment dams. But, this is difficult to detect by conventional methods. So, it needs to develop a new method. Geo-studio computer program is one of basic methods to accomplish this task.

The analysis is conducted using the state-of-the-art finite element method-based computer program—Seep/W from Geo-studio international, Unsaturated and saturated flow within the slopes was modelled with a finite element seepage analysis using SEEP/W (Geo-studio 2012) software.

Study area

General description of study area

The Grindeho dam is located in the eastern zone of Tigray regional state. The existing rain-fed agricultural practice in the area has been seriously affected by recurrent drought. To alleviate this problem, the solution sought is to support and shift the existing rain-fed agricultural practice to modern irrigation with sustainable use of both surface and groundwater resources.

The Grindeho dam site is found in the Tekeze basin having a good potential of surface water that can irrigate more than 100 ha during the dry season.

Also, as a consequence of this project, water for livestock and other developmental packages will not be a problem after the implementation. In other words, apart from the irrigation practice, other development opportunities, such as road, job, ecological changes, and fish, will be some of the benefits from the project.

Input data

The necessary input data (i.e., Dam design cross-sectional, geological report data, reservoir Water level from the dam site recorded data, detail dam design report and laboratory test result, material properties of dam) required for the Geo-studio computer program are collected from Tigray Water Works Design and Supervision Enterprise (TWWDSE) and Water Works Construction Enterprise as well as from Grindeho dam site.

Location of the project area

Grindeho dam site, reservoir and its command area are located in the Northern part of Ethiopia, Tigray region. The geographic location of the dam site is 571,209 mE and 1,508,393 mN (UTM zone-37).

Specifically, it is located in the eastern zone of Tigray Regional State, Woreda—KeletAwlaelo and Tabia Hadent. The site is located 44 km northeast of Mekelle and it has the total catchment area of 78.03 km^2.

The location of the Tigray Regional Government, KeletAwlaelo woreda and the project area are shown in the figure below.

Grindeho dam site is located on the southeastern side of Agulae village/town at about 27 km (Fig. 1).

Input data

The necessary input data (i.e., Dam design cross-sectional, geological report data, reservoir Water level from the dam site recorded data, detail dam design report and laboratory test result, material properties of dam) required for the Geo-studio computer program are collected from Tigray Water Works Design and Supervision Enterprise (TWWDSE) and Water Works Construction Enterprise as well as from Grindeho dam site.

Geotechnical parameters for analysis and design

To determine the engineering properties of the fill materials, representative soil samples were collected from the proposed dam site and laboratory test has been done in the Tigray Water Resources Bureau-Geotechnics and Laboratory center (Tables 1, 2).

Methods of analysis

Quality assessment of dam activities using geo-studio software has not been a standard technique in the past, but it will be one of the best alternative methods for
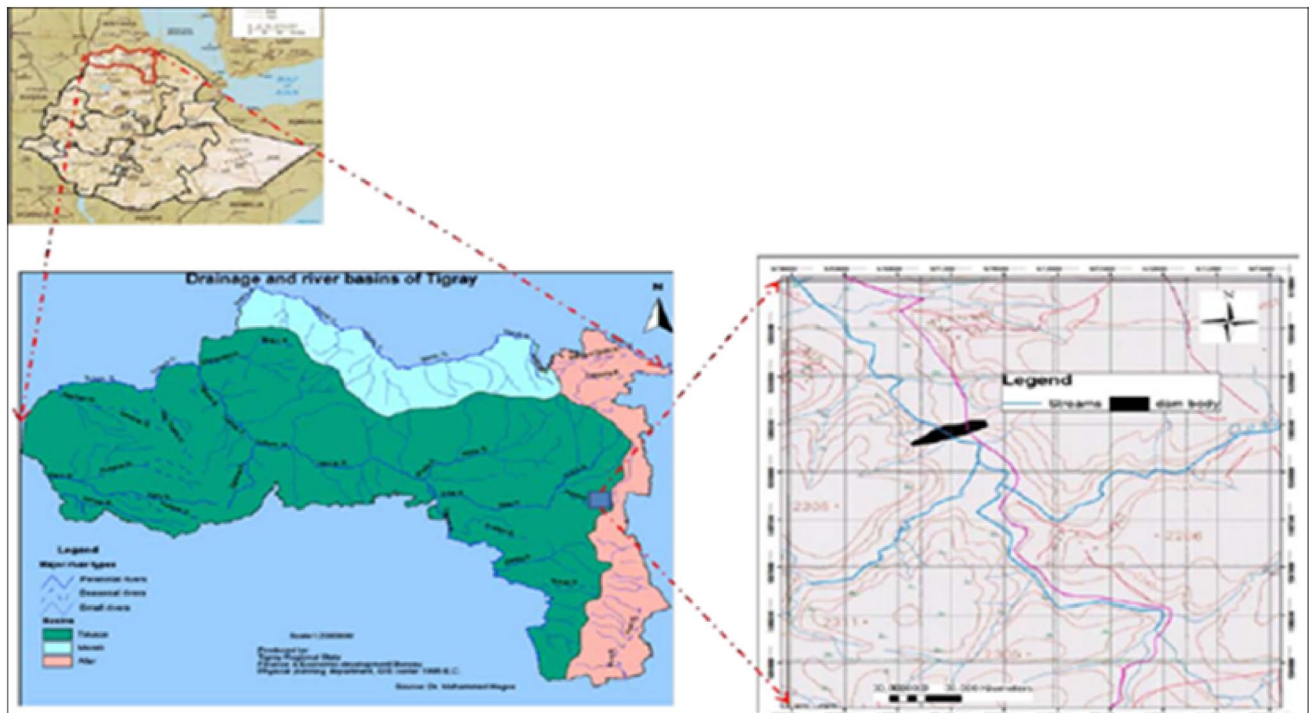
Fig. 1 Location map of the study area

Table 1 Summary of laboratory results

Material type	Depth (m)	Atterberg limits			Grain size			
		LL (%)	PL (%)	PI (%)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
Core	2.0	64	28.6	35.4	0.0	2.9	55.4	41.7
Shell	1.8	42	21.03	20.97	0.0	13.8	65.8	20.4

Table 2 Average engineering parameter for the fill materials

Material type	Cohesion, C' (Kg/cm^2)	Friction angle'(0)	Optimum moisture content OMC (%)	Maximum dry density, MDD (g/cm^3)	Permeability, K (cm/s)
Core	0.5160	20.96	31.5	1.47	$2.57e^{-7}$
Shell	0.5963	33.33	18.8	1.7	$8.10e^{-5}$

assessing dam protection in the future. Seep/W from Geo-studio International, Unsaturated and saturated flow inside the slopes was modelled with a finite element seepage analysis using SEEP/W (Geo-studio 2012) software. The analysis is performed using the state-of-the-art Finite Element method-based computer program (Fig. 2).

Field and lab tests

Lab result output

Proctor test

Proctor test (optimum moisture content and maximum dry density determination) is decided graphically as shown below on the graph which is drawn dry density versus moisture contents (Fig. 3).

From the above graph, M.D.D is 1.4704 g/cm^3 and O.M.C is 29.6%. Finally, this result is sent to field for compaction test.

Atterberg limit test (LL, PL and PI)

The result of moisture content versus number of blows, the resulting graph is shown below (Fig. 4).
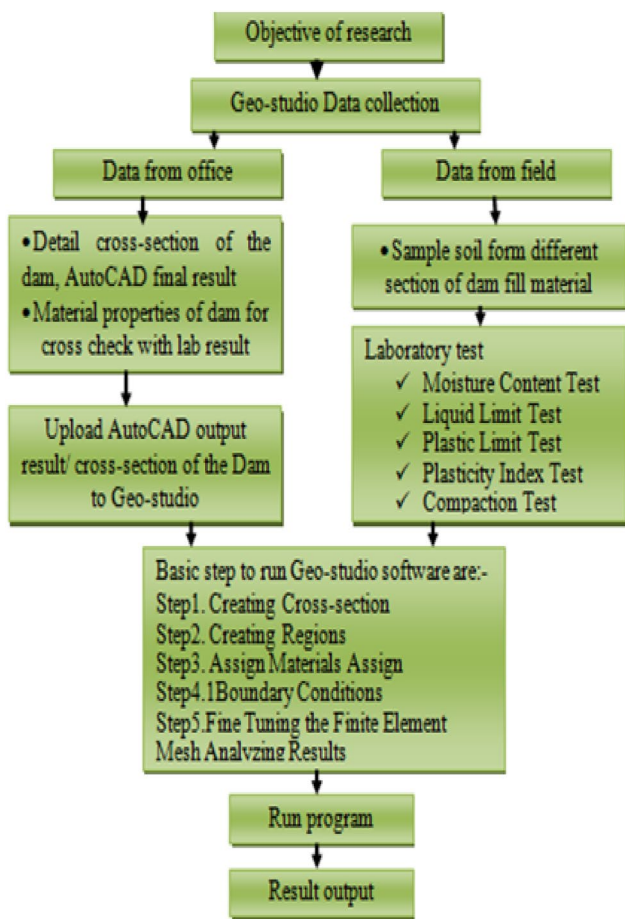
Fig. 2 Flow chart of Geo-studio step

Fig. 3 Dry-density versus moisture content

Fig. 4 Moisture content versus number of blows

Finally, we can read the liquid limit from the resulted graph and plastic limit by taking the average of the two trial values. The plasticity index is then, the difference of liquid limit and plasticity index.

LL = 63 %
PL = (22.95 + 22.22)/2 = 22.59%
PI = LL − PL = 63 − 22.59 = 40.41%.

Field test

Compaction test for clay

For field compaction studies, we use input data from laboratory findings that we saw earlier in the proctor test. These data are O.M.C and M.D.D which have a calculated result of 29.6% and 1.4704 g/cm^3, respectively.

Bulk Density = ((Wt of wet soil from hole)/
(wt of sand in hole))
× 1.35(unit weight of fine sand)
= 12000 g/8724 g × 1.35g/cm^3 = 1.85g/cm^3.
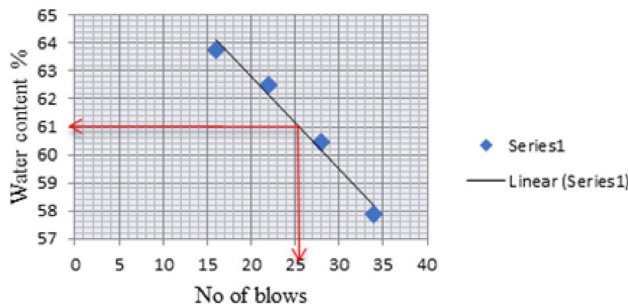
M.C (%) = (Wt of water)/(Wt of dry sample)
× 100 = 37.4g/130.8g × 100 = 28.6%.

Dry Density = (Bulk Density)/
(moisture content + 100)
× 100 = 1.43g/cm^3.

Degree of compaction = (Dry Density)/
(M.D.D) × 100 = 1.43/1.4704 × 100 = 97.25%.

Seepage and slope stability

Seep/w is the software used in this study for simulating the water seepage from a reservoir through an earth dam, and slope/w is the software utilized for computing the factor of safety against slope failure using different methods and under different soil conditions (Mishal and Khayyun 2018). The general governing differential equation for two-dimensional seepage is expressed as:

$$\partial/\partial x(kx \times \partial H/\partial x) + \partial/\partial y(ky \times \partial H/\partial y) + Q = \partial\theta/\partial t,$$
(1)

where H is the total head; kx and k_y are the hydraulic conductivity in the x and y directions, respectively; Q is the flow rate

and ⊖ is the volume water content. This equation expresses that the difference between the input and output flow rates is equivalent to the change in storage of the soil systems. SLOPE/W solves two factors of safety equations (force and momentum). All the used methods of slices can be visualized as special cases of the General Limit Equilibrium solution. A factor of safety is characterized as that variable by which the soil shear strength must be reduced so that the mass of soil will bring into a condition of constraining balance along a chose slip surface (Mishal and Khayyun 2018).

The shear strength for an effective stress analysis is defined as:

$$S = c' + (\sigma n - u)\tan\emptyset', \tag{2}$$

where S is the shear strength; C' is the cohesion of the soil; $\emptyset'$ is the angle of friction; σn is t*he* total normal stress and u is the pore-water pressure. The slip surface may be circular, linear or comprises any shape characterized by a progression of straight lines. The factor of safety in horizontal force equilibrium is:

$$\begin{aligned}Ff = \ &\Sigma(c'\beta\cos\alpha + (N - u\beta)\tan\phi'\cos\alpha)/\\&(\Sigma N\sin\alpha + \Sigma kW - \Sigma D\cos\omega \pm \Sigma A)\end{aligned} \tag{3}$$

And the factor of safety in moment of equilibrium is:

$$\begin{aligned}Fm = \ &\Sigma(c'\ \beta R + (N - u\beta)R\tan\phi')/\\&(\Sigma Wx - \Sigma Nf + \Sigma kWe \pm \Sigma Dd \pm \Sigma Aa)\end{aligned} \tag{4}$$

where W is the slice weight; N is the normal force on the base of the slice; D is an external load; kW is the horizontal seismic load; R is the radius for a circular slip surface; x and e are the horizontal and vertical distances from the centerline of each slice to the center of rotation, respectively; d is the vertical distance from a point load to the center of rotation; a is the vertical distance from the resultant external water force to the center of rotation; A is the resultant external water forces and ω, α, β are the angle of the load from the horizontal, the angle between the tangent to the center of the base of each slice, and the horizontal.

Stability analysis using the limit equilibrium methods (LEM)

Limit equilibrium methods assume that when a slope fails, a rigid soil mass is sliding on a potential failure surface (Liu and Zhao 2013). At failure, soil strength is fully mobilized along the failure surface and the sliding mass is in static equilibrium. Slope stability is usually expressed in terms of a factor of safety that is usually defined as:

Factor of safety = Available sheer strength/

　sheer stress required to maintain equilibrium.
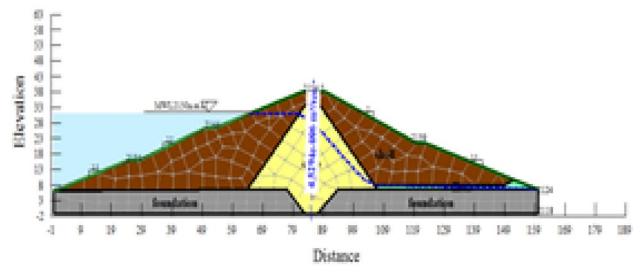

Fig. 5 Seepage during full of reservoir

Thus, the factor of safety is a ratio of the shear strength capacity of the soil to the shear stress induced on the potential failure surface (US Army Corps 2003).

Embankment dam failures

A review of the data from the 1975 and 1988 (Safety 2012), studies indicate that about 40 percent of failures and accidents to embankment dams are the result of leakage and piping through the dam, foundation, and/or the abutments.

Output results of Geo-Studio software

Seepage in the dam

As the result shown below, 4.5294e−0.06 m³/s water seepage is through the core of the dam to the downstream (Fig. 5).

Seepage losses

The annual amount of water loss through the dam body and foundation is:

$$Q = q \times B, \tag{5}$$

where q = seepage loss rate (m³/year/m) and B = total width of dam, (width of seepage path, B = 159.75 m), $q = 4.5294 \times 10^{-6}$ m³/s/m or 142.84 m³/year/m.

$Q = q \times B \ (\text{Mm}^3) = 142.84$ m³/year/m $\times$ 159.75 m = 22, 818.56 m³/year.

For 50-year design period, 1140928 m³ water loss is by seepage though embankment and foundation (Fig. 6).

Seepage losses

The annual amount of water loss through the dam body and foundation is determined by ($Q = q \times B$) formula,
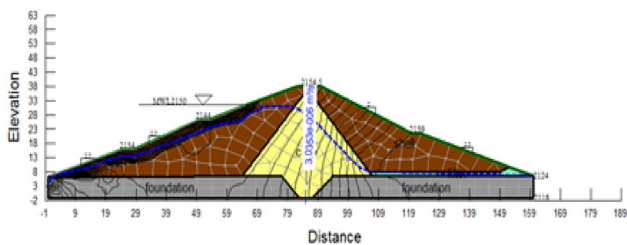
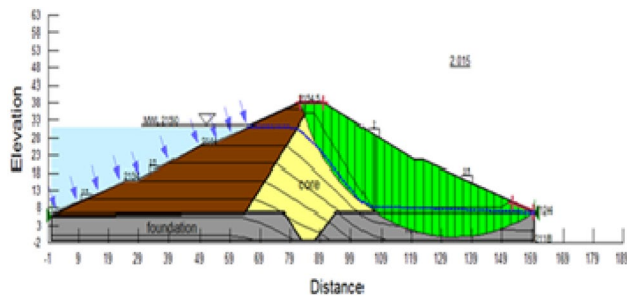**Fig. 6** Seepage during reservoir drawdown condition

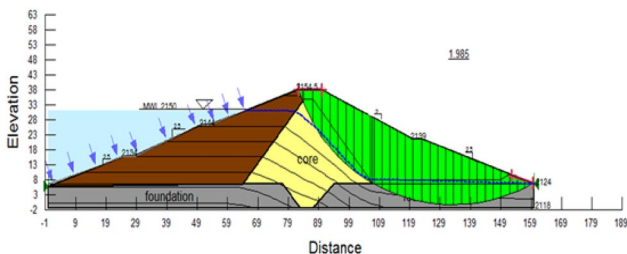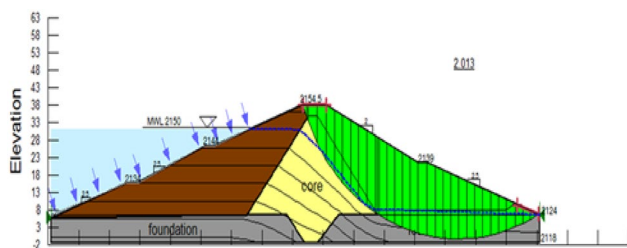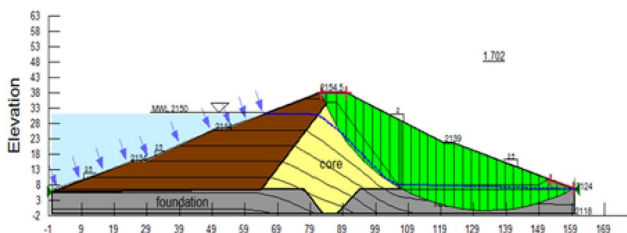**Fig. 7** F.S determaine by Bishop's method

Fig. 8 F.S determaine by Janbu's method

where q = seepage loss rate (m³/year/m) and B = total width of dam, (width of seepage path, B = 159.75 m), q = 3.0353 × 10⁻⁶ m³/s/m or 95.72 m³/year/m.

$$Q = q \times B \left(Mm^3\right) = 95.72 \text{ m}^3/\text{year/m} \times 159.75$$

m = 15291.5 m³/year.

For 50-year design period, 764573 m³ water loss is by seepage though embankment and foundation.

Slope stability analysis of dam

For slope analysis of the dam, three different cases of operation are considered: end of construction before filling the reservoir, after/full reservoir condition and rapid drawdown of the reservoir. Four major analytical methods are used to assess the stability of the dam: Morgenstern-Price, Bishop, Janbu, and Spencer. Benchmarks for the safety regulation criteria are United States army of Corps Engineers and British dam society.

Fig. 9 F.S determaine by Morgenstern-price method

Fig. 10 F.S determaine by Bishop's method

Reservoir full condition

A. Downsteam of the dam for full reservoir case

The factor of safety determination of the dam under different methods of analysis is listed below (Figs. 7, 8, 9, 10).

B. Upstream of the dam for full reservoir case (Figs. 11, 12, 13, 14).

Reservoir empty condition

A. Downsteam of the dam for empty reservoir case (Figs. 15, 16, 17, 18).

B. Upstream of the dam for empty reservoir case (Figs. 19, 20, 21, 22).

Drawdown of the reservoir condition

A. Upsteam of the dam for Drawdown reservoir case (Figs. 23, 24, 25, 26).

Summary of the result in Table 3.

Conclusion

The purpose of this paper is to calculate the amount of seepage through the dam and assess the slope stability of the embankment dam using the state-of-the-art machine
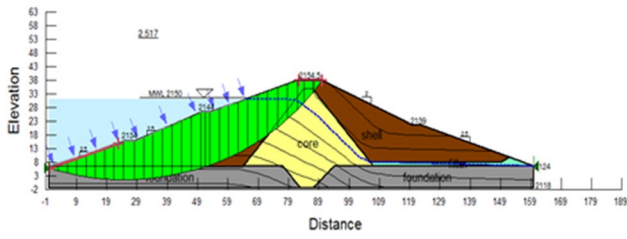
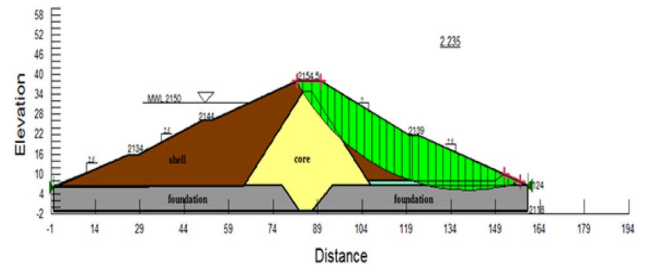**Fig. 11** F.S determaine by Bishop's method
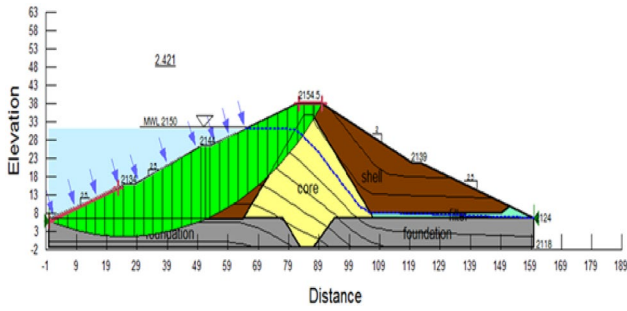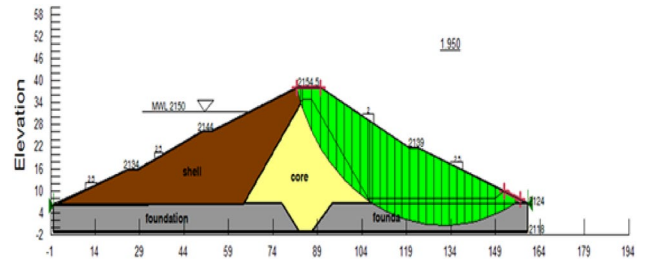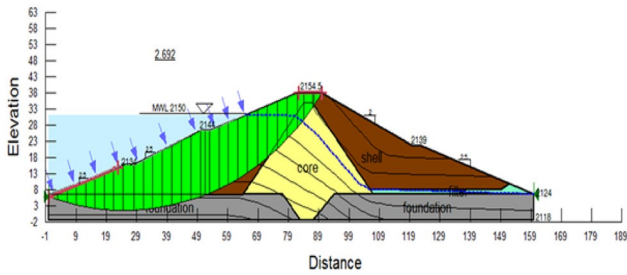

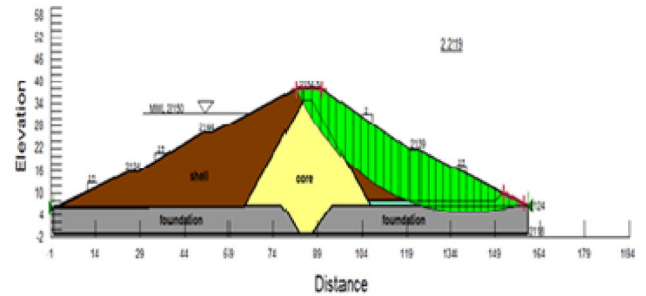**Fig. 12** F.S determaine by Janbu's method

Fig. 13 F.S determaine by Morgenstern-price method
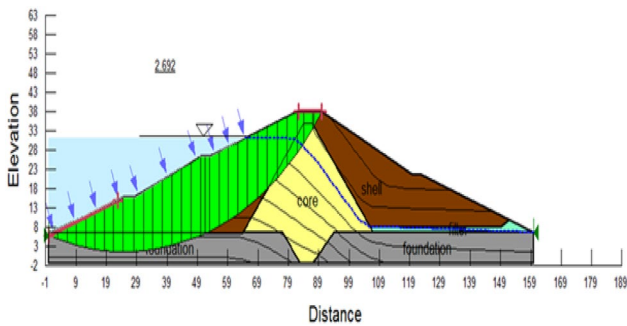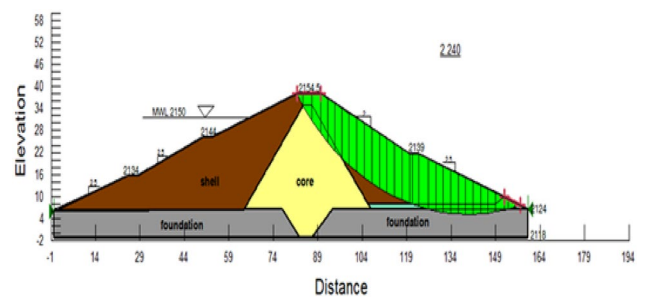

Fig. 14 F.S determaine by Spencer method

Fig. 15 F.S determaine by Bishop's method
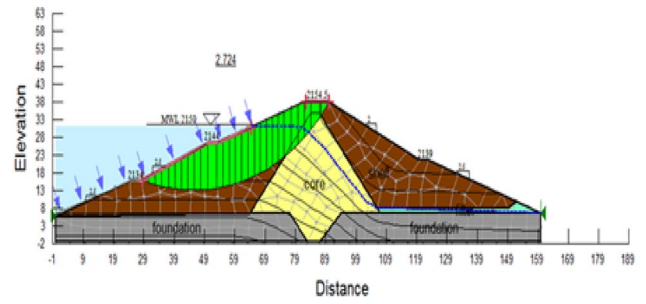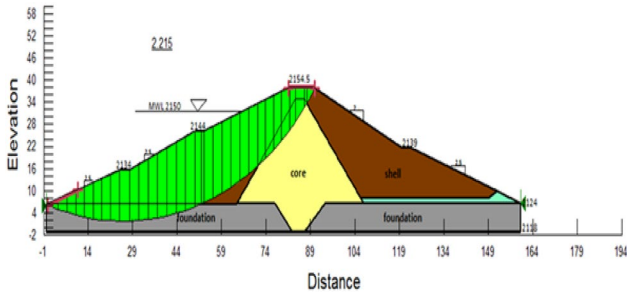

Fig. 16 F.S determaine by Janbu's method

Fig. 17 F.S determaine by Morgenstern-price method

Fig. 18 F.S determaine by Spencer method
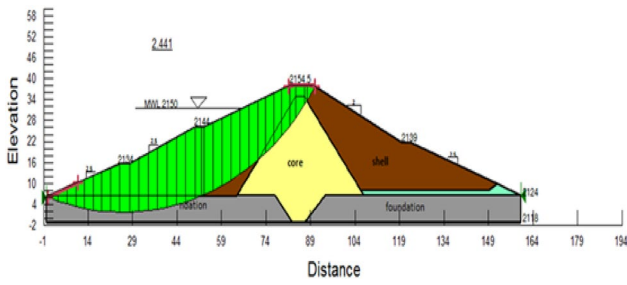
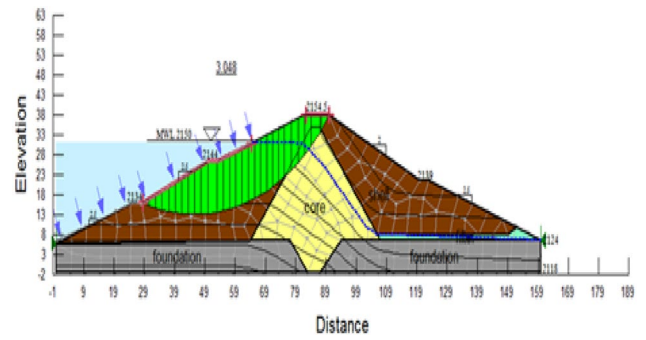**Fig. 19** F.S determaine by Bishop's method

Fig. 20 F.S determaine by Janbu's method
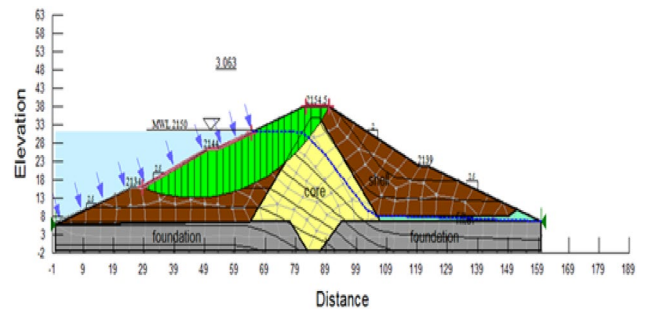
Fig. 21 F.S determaine by Morgenstern-price method

Fig. 22 F.S determaine by Spencer method

Fig. 23 F.S determaine by Bishop's method
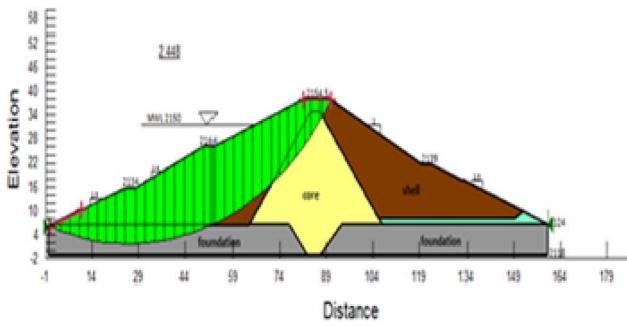

Fig. 24 F.S determaine by Janbu's method

Fig. 25 F.S determaine by Morgenstern-price method
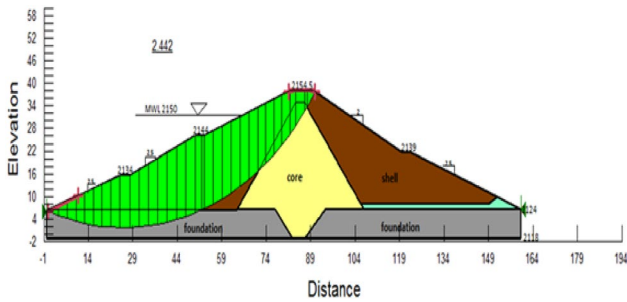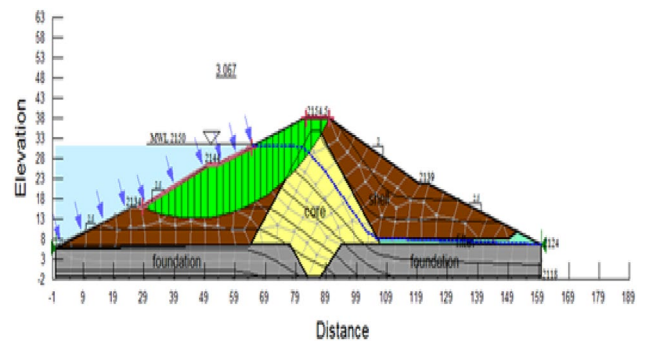

Fig. 26 F.S determaine by Spencer method

Table 3 Results of Grindeho Dam stability analysis by Geo-studio with limits of (USACE 2003) and (BDS 1994)

Critical stability condition	Case (1) full reservoir condition		Case (2) Empty reservoir construction		Case (3) drawdown condition
	Upstream	Downstream	Upstream	Downstream	Upstream
USACE (2003)	1.5	1.5	1.3	1.3	1.3
BDS (1994)	(1.5–1.3)		(1.5–1.3)		(1.3–1.2)
Bishop's	2.517	1.985	2.441	2.235	3.048
Janbu's	2.421	2.015	2.215	2.219	2.724
Morgenstern-Price	2.692	1.702	2.442	1.950	3.048
Spencer	2.692	2.013	2.448	2.240	3.067
Remark	Stable	Stable	Stable	Stable	Stable

program-based Finite Element Method through Geo-studio (2012) software.

The outcome of the stability analysis carried out showed that for all potential loading and operation scenarios, all parts of the dam are safe within the specified set of safety factors. But all the critical slip surfaces pass through the dam shell section, which means that this region represents the weaker region based on stability. The grindeho dam project is planned to harvest 4,283,238.9 m^3 of water from a catchment area of about 78.03 km^2 to introduce a modern irrigation practice downstream side of the dam.

The result of seep/w analysis showed 15,291.5 m^3/year seepage loss during a reservoir drawdown case and 22,818.56 m^3/year seepage loss though the dam during full reservoir case. This means during drawdown and full reservoir case, the seepage loss in 50-year design period is 1,140,928 m^3 and 764,573 m^3, respectively.

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