Design experience on slope stability for rockfill dams, Turkey

Hasan Tosun

Professor, Eskisehir Osmangazi University, Turkey

Email: hasantosun26@gmail.com

Abstract

Turkey has a good practice in construction of embankment dams. Up-to now, 95 percent of all dams, which have been constructed by various organizations, are categorized into earthfill or rockfill dams. In this study, slope stability of seventeen large rockfill dams having a height of 70 m to 169 m from river bed were re-analyzed by means of software as based on material properties given in their planning reports. In the context of this study, there are large dams located on very active seismic regions as well as large dams on the sites having low seismic activity. Analyses includes end-of-construction stage for downstream and upstream slopes, rapid drawdown stage from maximum water level and gate level, operation stage for partly and fully storage, and earthquake stage for end-of-construction and operation stages. This study indicates that deviation on safety factors increases for the cases located on site having low seismic activity. For the area having low seismic activity, rapid drawdown case is more critical when considered upstream slope stability. In Turkish design practice, downstream slope is selected as little steeper than upstream slope for rockfill dams for usual cases.

Keywords: Dam, pseudo-static analysis, seismic coefficient and slope stability.

1. INTRODUCTION

Dams with large reservoirs pose a high risk for downstream life and property when they are built near urbanized area. Therefore, dams are considered as critical structures for public safety, designed, constructed and operated due to specific requirements. These structures must have design and construction measures for both static and dynamic loading conditions. Damages and failures resulted by recent earthquakes indicate that more conservative requirement should be considered for dams during design stage.

For an embankment dam, conventional slope stability analyses, which compare the forces and moments tending to cause instability of the mass with those tending to resist instability, are commonly used. Most procedures consider a two-dimensional (2-D) cross section and plane strain conditions for analysis. Successive assumptions are made regarding the potential slip surface until the most critical surface (lowest factor of safety) is found. All of the methods used for computing slope stability are termed “limit equilibrium” methods. In these methods, the factor of safety is calculated using one or more of the equations of static equilibrium applied to the soil mass bounded by an assumed, potential slip surface and the surface of the slope.

This study introduces design experience on slope stability of 17 rockfill dams constructed in Turkey. Seventeen large rockfill dams are considered and each of them was analyses by the Simplified Bishop method with considering actual soil properties and local conditions. Table 1 gives the list of dams and their physical properties. Dams considered for this study were selected from different regions of Turkey and their heights from river basin range from 70 m to 169 m. Their construction was completed and they were designed for different purposes such as ırrıgation, energy, flood control, domestic water and industrial use. Their total reservoir capacity changes within a wide range of 31 hm^3 to 47 800 hm^3. A general view from Akkopru dam considered for this study is given figure 1.

Table 1. The dams considered for this study and their typical properties.

Dam #	Dam Name	River	Height from river bed (m)	Purpose (*)	Completed year	Embankment volume (hm^3)	Maximum reservoir volume (hm^3)
1	Adıguzel	B.Menderes	144	I+E+F	1990	7. 13	1 076
2	Akkopru	Dalaman	113	I+E+F	2011	12.99	385
3	Akyar	Bulak	71	D	1999	2.93	56
4	Altınkaya	Kızılırmak	137	E	1988	16.00	5 763
5	Ataturk	Fırat	169	I+E+D	1992	84.50	48 700
6	Batman	Batman	73	I+E+F	2003	7.18	1 250
7	Derinoz	Derinoz	74	I	2003	3.25	19
8	Dicle	Maden	75	I+E+D	2001	3.10	595
9	Ikizdere	Ikizdere	101	I+D	2010	7.10	196
10	Kavsakkaya	Ovacayı	71	D	2007	4.70	90
11	Kıgı	Peri	146	E	2017	23.00	1 200
12	Koprubasi	Mengen	108	E+F	2011	9.01	199
13	Kralkızı	Maden	113	I+E	1988	15.17	1 919
14	Ozluce	Peri	124	E	2000	2.14	1120
15	Nilufer	Nilufer	74	D	2007	3.70	31
16	Uzunçayır	Munzur	70	E	2010	2.25	308
17	Vezirkopru	İstavloz	74	I	2005	2.57	52

(*) I:Irrigation E: Energy Production F:Flood Control D:Domestic Water

2. MATERIAL AND METHODS

The various limit equilibrium methods can be used for slope stability analysis of embankment dams [1, 2, 3, 4, 5]. They consider different assumptions to make the number of equations equal to the number of unknowns and also differ with regard to which equilibrium equations are satisfied. According to U.S. Army Corps of Engineers [6] the Ordinary Method of Slices, the Simplified Bishop Method, and the Modified Swedish Methods do not satisfy all the conditions of static equilibrium while methods such as the Morgenstern and Price's and Spencer's do satisfy all static equilibrium conditions [6]. Methods that satisfy static equilibrium fully are referred to as "complete" equilibrium methods. The slope stability analysis methods have been compared in detail in literature [7, 8, 9, 10].

Three main loading conditions are defined for static stability analyses of embankments dams. These are (1) construction conditions, (2) Steady-state seepage conditions and (3) Operational conditions. In the first stage, the end-of-construction condition is analyzed for a new dam. It can also be necessary to analyze stability for partial completion of fill conditions. According to USBR manual [11] the stability of the downstream slope is analyzed at the reservoir level that will control the development of the steady-state seepage surface in the embankment for steady-state seepage conditions. For operational conditions, the stability of downstream slope is analyzed under maximum reservoir loading while the upstream slope is analyzed for rapid drawdown conditions.

Figure 1. A general view from Akkopru dam considered for this study.

Slope stability analyses are made in terms of total and effective stresses. The USBR Manual states that the end-of-construction condition can be examined either by effective stress concepts or by undrained shear strength concepts [11]. The effective shear strength value is needed for the stability analysis for operational conditions. Author and his co-workers evaluate the shear strength of materials and their tests in detail and summarize the country design practice for embankment dam [12, 13, 14].

In slope stability analysis, the factor of safety is defined as the ratio of total available shear strength of the soil to shear stress required to maintain equilibrium along a potential surface of sliding. The factor of safety indicates a relative measure of stability for various conditions, but does not precisely indicate actual margin of safety [11]. Table 2 summarizes the minimum factor of safety (F_S) for each loading condition [6].

Table 2. The required safety factors for different loading conditions

Case	Description	Slope	Required Factor of Safety
I	End-of Construction	Downstream Upstream	1.3
II	Rapid drawdown	Upstream	1.1-1.3*
III	Operation	Downstream Upstream	1.4-1.5**
IV	Earthquake	For end-of Construction Downstream Upstream For operation Downstream Upstream	1.0

(*) F_S = 1.1 applies to drawdown from maximum surcharge pool
F_S = 1.3 applies to drawdown from maximum storage pool.
(**)F_S = 1.4 applies to operation from maximum surcharge pool
F_S = 1.5 applies to operation from maximum storage pool.

For the end-of-construction loading condition, a minimum factor of safety of 1.3 is adequate when the analysis is carried out in terms of total shear strength for both slopes. For rapid drawdown condition, a minimum factor of safety of 1.3 should be obtained when used minimal shear strength envelope. It is recommended for downstream slope that the minimum factor of safety should be 1.4 for maximum surcharge loading and 1.5 for condition having maximum water level. For earthquake loading condition a minimum factor of safety of 1.0 is adequate according to Corps of Army Manual [6]. USBR Manual recommends a minimum factor of safety of 1.1 for earthquake loading conditions [11]. Tosun and Batmaz [12] evaluates the factor of safety concept and mentions the critical issues for stability analyses of embankment dams. In this study seventeen existing dams are considered and the slope stability analysis was performed for each dam by simplified Bishop Method for different loading conditions by means of professional software. For each loading condition a factor of safety is calculated. The minimum value of safety factor obtained from analysis was compared to obtain exceedance ratio for each dam.

3. ANALYSES

Evaluation of slope stability of dams was performed for four design conditions such as the end of construction, steady state seepage, sudden drawdown and earthquake loading. The first three conditions are static; the fourth involves dynamic loading. Summaries concerning the analysis of slope stability for the loading conditions are given in Table 3. In this this table, I-U and I-D represents end-of construction conditions, while IV-D and V-U mean the operational stage conditions. II-U is the analysis for rapid drawdown conditions of upstream slope. Pseudo-static analyses were represented by four cases (I-DE, I-UE, IV-DE and V-UD). This table also introduces the seismic coefficient (k-value) for each dam.

The end-of-construction condition was examined by undrained shear strength concepts for all dams. For operational conditions the stability of the downstream slope was analyzed at the reservoir level that will control the development of the steady-state seepage surface in the embankment. However, the stability of the upstream slope was analyzed under partial reservoir loading condition. Effective shear strength parameters were considered for both slopes under operational conditions. For sudden drawdown, the effective shear strength parameters were considered at minimum case. For upstream and downstream slopes, pseudo-static analyses were performed for end-of construction and operational stages by considering a seismic coefficient. Seismic coefficient (k-value) was selected according the simplified method as based on the national earthquake map used before 2012.

The factor of safety values for end-of condition are too much greater than the required values. This study indicates that the values belonging to upstream slope are generally higher than those of downstream slope in Turkish design practice. Same evaluation can be made for operational conditions. For rapid drawdown conditions the calculated factors of safety provide safely the required value given in the specifications. Minimum factors of safety were obtained for all dams under earthquake loading conditions of operational stage (case of IV-DE and V-UD). The values of factor of safety range from 1.00 to 1.75 for downstream slope, while those are between 1.03 and 1.65 for upstream slope, as based on slope inclination and other physical conditions.

4. RESULTS AND DISCUSSION

This study indicates that most critical case is earthquake loading condition for rockfill dam with central core in Turkey. Table 4 shows the slope inclinations, which were considered in design stage for all dams, and the minimum values of safety factors, which were calculated throughout this study. This table also introduce exceedance ratio for each dam. The exceedance ratio means comparison between the actual and the required value given in the specification (F_S =1.1). Its negative (-) value shows the calculated factor of safety which is less than that of required value.

Table 3. Safety factors of four loading conditions for each dam considered throughout the study

Dam		Güvenlik Sayısı*									Seismic coefficient,k
No	Name	I-U	1-D	II-U	IV-D	V-U	I-DE	I-UE	IV-DE	V-UD	
1	Adıguzel	2.50	2.29	2.01	2.14	2.05	1.54	1.70	1.41	1.16	0.15
2	Akkopru	2.46	2.06	2.23	1.70	2.24	1.39	1.69	1.0	1.25	0.17
3	Akyar	2.22	2.10	1.61	2.10	1.79	1.44	1.45	1.07	1.03	0.15
4	Altınkaya	1.71	1.62	1.52	1.55	1.52	1.47	1.55	1.40	1.31	0.04
5	Ataturk	1.94	2.01	1.78	2.00	1.88	1.66	1.61	1.65	1.39	0.07
6	Batman	2.83	1.66	2.25	2.32	1.69	1.59	2.13	1.57	1.40	0.04
7	Derinoz	2.40	2.82	2.22	2.38	2.00	1.71	1.47	1.42	1.31	0.17
8	Dicle	1.59	1.45	1.51	1.45	1.45	1.38	1.50	1.38	1.36	0.02
9	Ikizdere	2.60	1.57	2.37	1.53	2.38	1.23	1.47	1.02	1.26	0.20
10	Kavsakkaya	1.74	2.08	1.61	1.68	1.76	1.31	1.56	1.28	1.22	0.12
11	Kıgı	2.19	2.08	2.01	2.09	1.98	1.39	1.44	1.00	1.20	0.15
12	Koprubasi	2.90	2.64	2.58	2.64	2.74	1.84	1.97	1.75	1.65	0.13
13	Kıralkızı	1.97	1.83	1.76	1.81	1.78	1.54	1.65	1.51	1.48	0.05
14	Ozluce	1.77	1.71	1.65	1.69	1.70	1.24	1.27	1.22	1.04	0.14
15	Nilüfer	2.12	2.41	1.83	2.49	1.88	1.63	1.36	1.32	1.11	0.20
16	Uzunçayır	2.63	2.15	1.60	1.64	1.68	151	1.76	1.15	1.07	0.13
17	Vezirkopru	2.09	2.00	1.76	1.86	2.26	1.56	1.65	1.20	1.43	0.10

(*) I-U: End-of construction for upstream slope
I-D: End-of construction for downstream slope
II-D: Rapid drawdown for upstream slope
IV-D: Operation stage for downstream slope
V-U: Operation stage for upstream slope
I-DE: End-of construction for downstream slope with earthquake
I-UE: End-of construction for upstream slope with earthquake
IV-DE: Operation stage for downstream slope with earthquake
IV-UE: Operation stage for upstream slope with earthquake

In Turkish design practice, upstream slope has an inclination (Horizontal/ Vertical) of 1 /2.0 and 1 /2.5 for rockfill dam. Similar inclinations are considered for downstream slope. However, the inclination of downstream slope is little stepper than that of upstream for most of rockfill dams. It is not acceptable for the dams located on very active seismic region. Minimal values of safety factor were generally obtained for upstream slope of the rockfill dams considered for this study. The 65 percent of values for safety factor belongs to upstream slope, while others for downstream slope. The values of factor of safety take place within a wide range (1.04-1.65) for upstream slope, whereas the related values range from 1.00 to 1.20 for downstream slope. The variation for the values of upstream slope is very small. The exceedance ratio ranges from -9.1 to 50.0 percent for both slope. The negative values of exceedance ratio generally belong to downstream slope (% 67.7). It means that the downstream slope is more critical when considered earthquake loading conditions.

Table 4. Slope inclinations, minimum values for factor of safety and exceedance ratio for all dams considered throughout this study

Dam		Slope		Minimum value for factor of safety (calculated)		Exceedance ratio (%)
No	Name	Upstream (V/H) *	Downstream (V/H) *	Upstream slope	Downstream slope	
1	Adiguzel	1/ 2.25	1/ 2.0	1.16	-	5.5
2	Akkopru	1/ 2.5	1 /2.0	-	1.0	-9.1
3	Akyar	1/3.0	1/ 2.5	1.03	-	-6.4
4	Altınkaya	1/ 2.2	1/ 1.9	1.31	-	19.1
5	Ataturk	1/ 2.2	1/ 2.2	1.39	-	26.4
6	Batman	1 /2.5	1 /2.0	1.40	-	27.3
7	Derinoz	1/ 3.0	1/ 2.5	1.31	-	19.1
8	Dicle	1/ 2.5	1/ 2.0	1.36	-	23.6
9	Ikizdere	1/ 3.25	1/ 2.0	-	1.02	-7.0
10	Kavsakkaya	1/ 2.25	1/ 2.0	1.22	-	10.9
11	Kigi	1/ 2.75	1/ 2.5	-	1.00	-9.1
12	Koprubasi	1/ 3.0	1/ 2.5	1.65	-	50.0
13	Kiralkizi	1/ 2.75	1/ 2.5	1.48	-	34.5
14	Ozluce	1/ 2.25	1/ 1.50	1.04	-	-5.5
15	Nilufer	1/ 2.0	1 /2.0	-	1.11	0.9
16	Uzuncayir	1/ 2.75	1 /2.5	-	1.07	-2.7

Table 5 summaries some physical properties and slope of impervious core materials for all dams throughout this study. In the table, group symbol and name of impervious material of each rockfill dam is given as based on the Unified Soil Classification. Author thinks that there is no a clear correlation between types of impervious core material and their slope. It can be stated that the inclination ratio of low plasticity clay and sand with low plasticity clay or silt is taken within a range of 0.33 to 0.50. However, it should be confirmed using by much data.

Table 5. Some physical properties and slope of impervious core material for dams considered for this study.

Dam		Height from river bed (m)	Impervious material used		Slope for impervious core	
#	Name		Group Symbol *	Group name	(H/V) **	Ratio (H/V)
1	Adıguzel	144	CL	Low plasticity clay	1 /2.15	0.47
2	Akkopru	113	SM-MH	Silty sand (high plasticity)	1 /4.0	0.25
3	Akyar	71	SC-CL	Clayey sand (low plasticity)	1 /2.0	0.50
4	Altınkaya	137	CL	Low plasticity clay	1 /2.0	0.50
5	Ataturk	169	CH-MH	High plasticity silt-clay	1 /2.5	0.40
6	Batman	73	CL	Low plasticity clay	1 /2.0	0.40
7	Derinoz	75	CH	High plasticity clay	1/0.66	0.67
8	Dicle	75	CL	Low plasticity clay	1 /2.0	0.50
9	Ikizdere	101	SC-CL	Clayey sand (low plasticity)	1 /2.0	0.50
10	Kavsakkaya	71	CL-CH	Low-high plasticity clay	1 /2.0	0.50
11	Kigi	146	CL	Low plasticity clay	1 /3.0	0.33
12	Koprubasi	108	CL-ML	Low plasticity silt-clay	1 /2.5	0.40
13	Kiralkizi	113	CH	High plasticity clay	1 /4.0	0.25
14	Ozluce	124	CL	Low plasticity clay	1 /3.0	0.33
15	Nilufer	74	CL	Low plasticity clay	1 /3.0	0.33
16	Uzuncayir	70	CL-CH	Low-high plasticity clay	1/3.0	0.33
17	Vezirkopru	75	CL-CH	Low-high plasticity clay	1 /2.0	0.50

(*) Unified Soil Classification System
(**) V:Vertical H:Horizontal

5. CONCLUSIONS

Turkey has at least 1250 large dams with different types. The ninety-five percent of them are constructed in embankment type. More than half of embankment dams has been designed in rockfill dams. Therefore, there is a good experience in designing and construction of this dam type in Turkey. This study concludes as follows:

- It seems that upstream and downstream slopes have an inclination (Vertical/Horizontal) of 1 /2.0 and 1 /2.5 for rockfill dam throughout country. However, the inclination of downstream is little stepper than that of upstream for most of rockfill dams. Author states that it is not acceptable for the dams located on very active seismic region.
- Designers consider more flat inclination for the rockfill dams located on seismologically active region or dams having high risk potential for downstream life and properties. Sometime, these unusual cases cannot be technically explained.
- There is no good experience on selecting the slopes of impervious core material as based on material type. It seems that the inclination ratio of low plasticity clay and sand with low plasticity clay or silt is taken within a range of 0.33 to 0.50. However, it should be confirmed using by much data
- The pseudo- static analyses of large dams considered for this study were performed as considering k-values based the simplified chart of National Map of Earthquake Regions. However, these dams should

be analyzed by considering actual seismic hazard analyses used updated seismo-tectonic data, under the context of National Dam Safety Program.

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