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DISCUSSION ON THE SAFETY FACTORS OF SLOPES RECOMMENDED FOR SMALL DAMS

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Abstract

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The design and assessment of the slope stability of small embankment dams is usually not carried out using slope stability calculations but rather by the comparison of proposed or existing dam slopes with those recommended by technical standards or guidelines. Practical experience shows that in many cases the slopes of small dams are steeper than those recommended. However, most of such steeper slopes at existing dams do not exhibit any visible signs of instability, defects or sliding. For the dam owner and also for dam stability engineers, the safety of the slope, expressed e.g. via a factor of safety, is crucial. The aim of this study is to evaluate the safety margin provided by recommended slopes. The factor of safety was evaluated for several dam shape and layout variants via the shear strength reduction method using PLAXIS software. The study covers various dam geometries, dam core and shoulder positions and parameter values of utilised soils. Three load cases were considered: one with a steady state seepage condition and two with different reservoir water level drawdown velocities – standard and critical. As numerous older small dams lack a drainage system, variants with and without a toe drain were assessed. Calculated factors of safety were compared with required values specified by national standards and guidelines.

Keywords: small water reservoirs, slope stability, factor of safety

INTRODUCTION

Small dams are dams with limited height and storage volume. The values of these parameters vary according to national conventions and standards. For example, in the Czech national standard CSN 75 2410 (UNMZ, 2011), small dams are those with a reservoir volume smaller than 2 million m^3 and with a maximum dam height of 9 m. According to the USBR, small embankment dam height does not exceed 15 m (about 50 feet) and volume does not exceed 765 thousand m^3 (1 million yd^3) (Design, 1987). The ICOLD bulletin on small dams (Bulletin 2011) uses a definition based on maximum dam height and on potential hazard classification. This system combines two parameters, namely the maximum height h of the dam above the river bed in metres, and its water storage capacity at full supply level V in millions of cubic meters (Degoutte, 1997). According to ICOLD (Bulletin 2011), small dam height ranges between 2.5 and 15 m with the combination of $h^2 \times 15\ V^{0.5} < 200$. Slope angles are often recommended in technical standards and guidelines for small dams. Most of these recommendations are based on the type of the dam, its height and soil classification.

Land survey data is usually available for the safety assessment of existing dams. It is very often true that real-world slopes are steeper than those recommended in national standards, though no signs of instability are identified. It can be expected that recommended slopes include a certain safety margin which is not quantified in the standards or guidelines.

The aim of this study is to quantify the safety margin for the recommended slopes proposed by the CSN 75 2410 – Czech national standard for small embankment dams (UNMZ, 2011). The safety factor was assessed for five types of homogenous dams and for five zoned embankments with different cross section layouts. Both steady state and unsteady state seepage conditions were taken into account. Slope stability computations were based on the shear strength reduction method employed with the use of the finite element method by PLAXIS.

I: *Recommended slope angles of small embankment dams according to CSN 75 2410*

Type of cross section	Soil classification		Slopes	
	Sealing (core) material	**Shell material**	**Upstream**	**Downstream**
Thin central core	GM, GC, SM	Quarry stone	1:1.75	1:1.50
	SC, CG, GM	GW, SW	1:2.80$^{1)}$	1:1.75
	ML-MI, CL-CI	GP, SP	1:3.00$^{1)}$	1:1.75
Thin inclined core	GM, SM	Quarry stone	1:3.00	1:1.50
	GC, SC, MG, CG, MS, CS	GW, SW	1:3.20	1:1.75
	ML-MI, CL-CI	GP, SP	1:3.40	1:1.75
Thick central core	GM, GC, SM, SC, MG, CG, MS, CS	Quarry stone	1:3.00	1:1.20$^{2)}$
		GW, SW	1:3.20	1:1.20$^{2)}$
	ML-MI, CL-CI	SW, SP	1:3.40	1:2.20$^{3)}$
Homogenous embankment	GM, SM		1:3.00	1:2.00
	GC, SC		1:3.40	1:2.00
	MG, CG, MS, CS		1:3.30	1:2.00
	ML-MI, CL-CI		1:3.70	1:2.20

1) With very permeable soil, with respect to the drawdown rate, this may be increased to 1 : 2.25.
2) If dam subsoil contains material with min. $\phi_{ef} = 37°$, this may be increased up to 1 : 1.80.
3) If dam subsoil contains material with min. $\phi_{ef} = 37°$, this can be increased up to 1 : 2.00.
4) At dams with height less than or equal to 4 m, upstream slope may be increased up to 1 : (x – 0.50).

Present state review

The Czech national standards related to small dams have been used since 1964, when CSN 73 6824 was introduced. It was later upgraded in 1978 (UNM. 1978), finally being replaced in 1997 by the newest version, CSN 75 2410 (upgraded in 2011) (UNMZ, 2011). These standards recommend slopes of a certain maximum steepness according to dam materials and their zoning in the embankment. In 1978, the US Bureau of Reclamation issued the second edition of the internationally respected general guidelines for small dams (Design, 1987), (Royet, Peyras, 2010). In 2005 the ICOLD Committee on small dams was established and in 2011 the Bulletin (2011) was completed for the design, surveillance and rehabilitation of small dams. French guidelines (Degoutte, 1997) propose general recommendations for small dams but do not recommend slope angles related to the material of small embankment dams.

The assessment of the slope stability of embankment dams should be performed in accordance with Eurocode 7 (CNI, 2006). According to the Czech standards, the traditional factor of safety may be used for the basic assessment and quantification of the slope stability of small dams (UNM, 1978), (UNMZ, 1997), (UNMZ, 2011). The present version of the Czech standard for small dams (UNMZ, 2011) accepts assessment via the equilibrium method using both the factor of safety and also the limit state method, employing reliability factors. Another contemporary procedure uses the shear strength reduction method (Dawson *et al.*, 1999), where strain-stress analysis is carried out via the finite element method (Zienkiewicz, Cormeau, 1974). It is true that, today, numerical methods prevail in the safety assessment of small embankment dams (Cheng *et al.*, 2007), (Preziosi, Micic 2014).

Recommended slopes may be used under specific conditions such as the sufficient bearing capacity of a subsoil, a toe drain at the downstream slope, a rapid drawdown of 0.15 m/day, and others.

Similar recommended slopes for small dams are mentioned in American reference (Design, 1987), or summarized in ICOLD reference (Bulletin, 2011). Some data are mentioned in Tab. II and III.

As a rule the steepest downstream slope recommended by foreign guidelines (e.g. in (Design, 1987)) is 1 : 2.00, while in the Czech standard it may even be 1 : 1.50 in the case of a rockfill downstream shoulder.

MATERIALS AND METHODS

In this study, typical dam shapes and layouts were selected according to recommendations in CSN 75 2410. The materials and their properties and parameters were assigned according to the composition of the cross section of the dam, and also in accordance with the recommendations of the standard. Three load cases were analysed for each dam shape and material composition variant. Slope stability was numerically assessed for each of the individual variants.

Adopted assumptions

General slope stability calculations were carried out with a traditional two-dimensional (2D) model assuming plane strain analysis. The considered material properties are assumed to be for the materials after compaction, and are defined by the characteristic values of each parameter (bulk density, hydraulic conductivity, strength

II: *Recommended slopes for homogenous dams according to the USBR (Design, 1987)*

Type	Purpose	Drawdown > 0.15 m/d	Permeability of foundation	Soil classification	Upstream slope	Downstream slope
Homogenous or modified homogenous	Detention or storage	No	Thin core; imperv. or shallow perv. foundation with cutoff trench	GW, GP, SW, SP	Pervious, unsuitable	
				GC, GM, SC, SM	1:2.50	1:2.00
				CL, ML	1:3.00	1:2.50
				CH, MH	1:3.50	1:2.50
Modified homogenous	Storage	Yes	Thick core; deep perv. foundation without cutoff trench	GW, GP, SW, SP	Pervious,unsuitable	
				GC, GM, SC, SM	1:3.00	1:2.00
				CL, ML	1:3.50	1:2.50
				CH, MH	1:4.00	1:2.50

III: *Recommended slopes for zonal dams according to the USBR (Design, 1987)*

Type	Purpose	Drawdown > 0.15 m/d	Shell soil classification	Core soil classification	Upstream slope	Downstream slope
Thin central core	Any	Not critical	Rockfill, GW, GP, SW, SP	GC, GM, SC, SM, CL, ML, CH, MH	1:2.00	1:2.00
Central core, slope 1:1 – 1:1.50	Detention or storage	No	Rockfill, GW, GP, SW, SP	GC, GM	1:2.00	1:2.00
				SC, SM	1:2.25	1:2.25
				CL, ML	1:2.50	1:2.50
				CH, MH	1:3.00	1:3.00
Thick central core	Storage	Yes	Rockfill, GW, GP, SW, SP	GC, GM	1:2.50	1:2.00
				SC, SM	1:2.50	1:2.25
				CL, ML	1:3.00	1:2.50
				CH, MH	1:3.50	1:3.00

parameters) for a given part of the cross section (core, shoulders, subsoil, toe drain). Isotropic and constant hydraulic conductivity are assumed for each material (subdomain). The dam and subsoil are assumed to be linear elastic – perfectly plastic (Dawson *et al,* 1999), (Brinkgreve *et al.,* 2014). This assumption can be adopted in the case of small strains and could be adequate for the computation of global stability. According to Jozsa (2011), the linear elastic – perfectly plastic model may be used for slope stability assessment, while the use of an advanced material model (e.g. the Hardening Soil Model) is proposed for the detailed analysis of dam behaviour.

Solution of the problem

PLAXIS 2D software was used for the slope stability analysis and to determine the factor of safety using the shear strength reduction method. The method and software was selected based on references (Cheng *et al.* 2007), (Rabi, 2014) and a comparison of the finite element method and limit equilibrium method (Vrubel, Říha, 2015). The shear strength reduction method provided the most unfavourable slip surface position, and this solution could be widely used for different types of soils. The strain – stress analysis employs the finite element method (Zienkiewicz, Cormeau 1974). A detailed description of the governing equations for PLAXIS software are described in (Galavi, 2010) and in scientific manual (Brinkgreve *et al.,* 2014). The formulation of the shear strength reduction method is proposed by (Dawson *et al,* 1999), (Brinkgreve, Bakker, 1991) and (Brinkgreve *et al.,* 2014). In this method, the position of the slip surface is localised via the stepwise reduction of shear strength parameters and the redistribution of stress in the places at which the strength of the material was locally exhausted. The factor of safety is defined as the ratio of the original (not reduced) to the reduced shear strength parameters:

$$SF = \frac{c}{c_{red}} = \frac{tg\phi}{tg\phi_{red}}\ , \qquad (1)$$

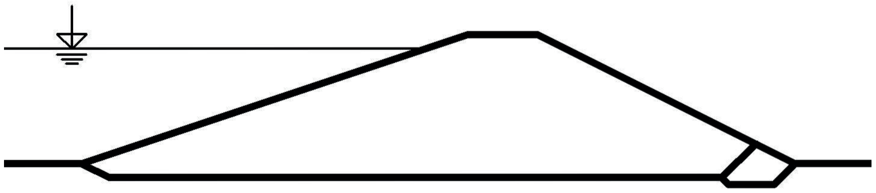
where φ and c, are the friction angle and cohesion, and φ_{red} and c_{red} are their reduced values. The other input parameters are Young's modulus E, Poisson's ratio μ and unit weight γ. The dilatancy angle ψ mainly influences the volumetric strain of the soil. In the study its value was assumed to be zero for all materials (Griffiths, Lane, 1999).

Material properties

Types of appropriate soils were allocated to particular parts of cross sections according to the layouts chosen. For the stability analysis, material properties were specified according

IV: *Material properties of the cores of heterogeneous dams*

Soil	Unit weight [kN/m³]	Hydraulic conductivity [m/s]	Friction angle [°]	Cohesion [kPa]	Young's modulus [MPa]	Poisson's ratio [-]
GW Well-graded gravel	19.5	$1.0\ 10^{-4}$	44	0	120	0.25
GM Silty gravel	20.0	$1.0\ 10^{-6}$	34	5	70	0.30
GC Clayey gravel	20.5	$1.0\ 10^{-6}$	27	5	70	0.30
SW Well-graded sand	19.5	$5.0\ 10^{-5}$	41	0	90	0.30
SP Poorly- graded sand	18.5	$1.0\ 10^{-4}$	37	0	70	0.30
SM Silty sand	18.0	$1.0\ 10^{-7}$	34	5	10	0.30
CS Sandy Clay	18.5	$7.0\ 10^{-8}$	25	5	10	0.30
CL Clay with low plasticity	21.0	$1.0\ 10^{-8}$	25	5	5	0.30



1: *Homogenous embankment dam*

to characteristic values given by the standard CSN 75 2410. The material properties for cores, shells and for homogenous embankment dams are listed in Tab. IV.

Geometry and load cases

In all cases the dam height is 9 m. Ten combinations of different geometry and material properties were considered. Five of them relate to homogeneous dams (Fig. 1). This type represents the majority of small embankment dams.

Three types of heterogeneous dams were studied, namely with a thin central core, a thin upstream core and a thick central core (Fig. 2).

Dam crest thickness was 5 m, the foundation was 1 m below the original terrain level, and the toe drain and core were founded 0.5 m below this level.

The load case of the dry embankment dam wasn't assessed. It is assumed that a dry embankment dam would be more stable than a dam loaded by any kind of seepage. The following three load cases were assumed based on Czech standard CSN 75 2410 and the study (Vrubel, Říha, 2015):

I. The reservoir water level is 1 m below the crest; the seepage in the dam body is steady. The steeper downstream slope is more critical. For this load case, two different situations were considered:

a) a dam without a toe drain; a seepage face could appear here (Ia),

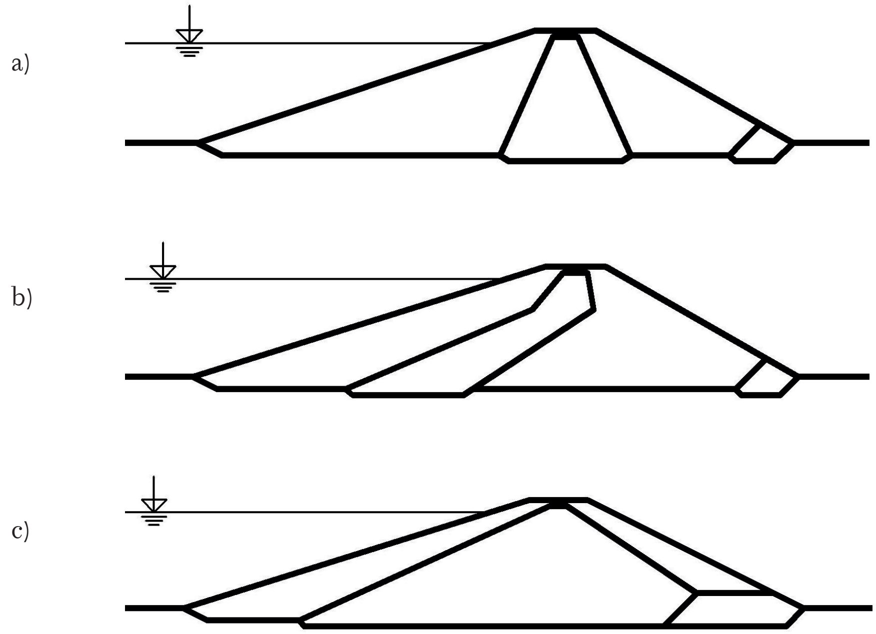
b) a downstream slope equipped with a toe drain made of a permeable material (Ib).

II. The reservoir water level drawdown is at a constant velocity of 0.5 m/day from the maximum water level to a level two meters above the reservoir bottom.

III. The reservoir water level drawdown is at a critical constant velocity of 2 m/day from the maximum water level to the level causing the most unfavourable slope stability.

The free water surface in the toe drain was assumed to be at the level of the original terrain. The hydraulic conductivity of the toe drain was set to $5.0.10^{-4}$ m/s, the friction angle was 44° and the material was assumed to be cohesionless. The height of the toe drain was 1.5 m above the original ground. The shear stress resistance of the subsoil was assumed to be in accordance with the shear stress resistance of the dam body, friction angle was 35° and cohesion 5 kPa.

The maximum reservoir water level was specified as a level 1 m below the crest of the dam. The free groundwater table downstream of the dam was assumed to be 0.7 m below the terrain. The rate of reservoir water level drawdown in the second load case was 0.5 m/day, in the third one (rapid drawdown) 2 m/day. The resulting steady state seepage obtained for the first load case was applied as the initial condition for both the second and the third load cases.



2: *Heterogeneous embankment dams a) with thin central core, b) with a thin inclined central core, c) with a thick central core*

RESULTS

The resulting factors of safety for individual slopes, load cases, geometries and corresponding materials of the dam body are given in Tab. V.

It can be seen that critical slip surfaces occur for load cases I and Ib at the upstream faces, while for load cases II and III they occur at the upstream faces due to the water level drawdown.

The required factor of safety of dam slopes is traditionally assumed to be $SF \geq 1.5$ (UNMZ, 2011), (Degoutte, 1997), (Bulletin, 2011) for the first load case corresponding to standard dam operation. In the case of load case Ia without the downstream toe drain, the resulting safety factor values are between 1.0 and 1.29 for homogeneous dams, and between 1.0 and 1.58 for heterogeneous dams. The stability of homogeneous dams made from clayey gravel and sandy clay, and also of heterogeneous dams made from well-graded sand with a clayey gravel core, was close to the limit equilibrium. For three cases (marked with a * in Tab. VII) without the toe drain the factor of safety was less than 1.0. The safety factor values in the cases with a toe drain (load case Ib) ranged between 1.2 and 1.71 according to material properties.

For all load cases II (relatively slow drawdown) for a homogenous dam made of silty gravel and heterogeneous dams with a thin central core, an inclined thin central core and a thick core with a shell made from well graded rock, $SF > 1.5$ is satisfied. Other geometries and layouts provide values between 1.11 and 1.44.

For load case III (rapid drawdown of 2 m/day), the safety factor varies between 1.08 for sandy clay and 1.70 for a zoned dam with a shell made from well graded gravel. Here the most critical state for the slope stability for all variants is when drawdown extends from the maximum water level to the reservoir bottom.

In summary it can be concluded that in the majority of load cases the safety factor was smaller than for standard large dams where $SF \geq 1.5$ is required. The recommended slopes for lower dams probably result from longstanding experience with small dams so they provide quite variable safety factors when assessed by contemporary computational methods. Due to the lower “importance” or “consequence” classes involved, the slope stability requirements are not so strict as those for large dams. Real dam safety is probably even better than it might appear due to the presence of a safety margin in slope stability assessment methods and also due to the more conservative characteristic values of the shear strength parameters specified in the guidelines based on soil classification.

V: *Factors of safety for assumed load cases and geometry layouts*

Soil classification		Geometry	Slope		Load case	Toe drain	Safety factor
Core	**Shell**						
GM **Silty gravel**		Homogenous	1 : 2.00	downstream	Ia	No	1.29
			1 : 2.00	downstream	Ib	Yes	1.45
			1 : 3.00	upstream	II	Yes	1.62
			1 : 3.00	upstream	III	Yes	1.35
SM **Silty sand**			1 : 2.00	downstream	Ia	No	1.19
			1 : 2.00	downstream	Ib	Yes	1.50
			1 : 3.00	upstream	II	Yes	1.37
			1 : 3.00	upstream	III	Yes	1.26
GC **Clayey gravel**			1 : 2.00	downstream	Ia	Ne	*
			1 : 2.00	downstream	Ib	Yes	1.22
			1 : 3.40	upstream	II	Yes	1.44
			1 : 3.40	upstream	III	Yes	1.35
CS **Sandy clay**			1 : 2.00	downstream	Ia	No	*
			1 : 2.00	downstream	Ib	Yes	1.18
			1 : 3.30	upstream	II	Yes	1.16
			1 : 3.30	upstream	III	Yes	1.08
CL **Clay with low plasticity**			1 : 2.20	downstream	Ia	No	1.06
			1 : 2.20	downstream	Ib	Yes	1.25
			1 : 3.70	upstream	II	Yes	1.11
			1 : 3.70	upstream	III	Yes	1.03
CL Clay with low plasticity	SP Poorly-graded sand	Thin central core	1 : 1.75	downstream	Ia	No	1.27
			1 : 1.75	downstream	Ib	Yes	1.26
			1 : 3.00	upstream	II	Yes	1.70
			1 : 3.00	upstream	III	Yes	1.56
CL Clay with low plasticity	SP Poorly-graded sand	Thin central core incline	1 : 1.75	downstream	Ia	No	1.22
			1 : 1.75	downstream	Ib	Yes	1.23
			1 : 3.40	upstream	II	Yes	1.54
			1 : 3.40	upstream	III	Yes	1.46
GC **Clayey gravel**	SW Well-graded sand	Thin central core incline	1 : 1.75	downstream	Ia	No	*
			1 : 1.75	downstream	Ib	Yes	1.43
			1 : 3.20	upstream	II	Yes	1.74
			1 : 3.20	upstream	III	Yes	1.24
SM **Silty sand**	GW Well-graded gravel	Thick central core	1:2.00	downstream	Ia	No	1.58
			1:2.00	downstream	Ib	Yes	1.71
			1:3.20	upstream	II	Yes	1.85
			1:3.20	upstream	III	Yes	1.70
CL Clay with low plasticity	SP Poorly-graded sand	Thick central core	1:2.20	downstream	Ia	No	1.22
			1:2.20	downstream	Ib	Yes	1.49
			1:3.40	upstream	II	Yes	1.25
			1:3.40	upstream	III	Yes	1.18

*) The dam failed before the factor of safety was calculated.

CONCLUSION

The slope stability for ten typically arranged small embankment dams was assessed via the shear strength reduction method with the use of PLAXIS commercial software. The stability for each combination of dam geometry and material and each of the four load cases was expressed via a safety factor.

The results from load case I prove the importance of the position of the free water surface, especially in the case of homogenous dams. They show that the toe drain at the downstream side of a dam significantly contributes to the dam's stability. This supports the recommendation that dams should be provided with permanent storage at the toe drain. Flood attenuation reservoirs and levees where seepage does not develop in poorly permeable dam material during a relatively short flood event could be an exception to this guideline. However, such situations must be carefully analysed before omitting the toe drain.

The standard dam body layouts with a toe drain provide a safety margin that is higher than 20 % for load case Ib, except in the case of a homogenous dam made from sandy clay. The influence of the toe drain on the position of the slip surface in the case of subsoil low bearing capacity is also evident.

The safety factor values in the case of drawdown is influenced by the type of soil; the least resistant are homogenous dams made from sand and clay both in the case of slow and rapid drawdown. Standard CSN 75 2410 requires a minimal safety factor of SF > 1.1 for an upstream slope loaded by rapid drawdown from the maximal water level to the water level position which is most critical for slope stability. All assessed layouts fulfil this requirement for a drawdown velocity of 2 m/day except dams made of sandy clay and clay with low plasticity.

The presented factors of safety in the described cases do not fulfil the required value of 1.5. One explanation for this could be the definition of factor of safety. Factor of safety aggregates all uncertainties (e.g. uncertainties in material properties, loads and based on consequence category) but recommended slope angles and characteristic material property values contain their own margins based on the experience of the authors of standards. Due to this, slopes recommended by e.g. UNMZ (2011) contain a different safety reserve. Another reason could be that the traditionally required value of 1.5 is the same for all dam consequence categories.

Further research will be focused on the determination of critical slope angles corresponding to required factor of safety.

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