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Assessment on the Technical State of Spillway Concrete Gravity Dams in Lithuania

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Spillway concrete gravity dams are exposed by loads and environment causing deterioration process. The article presents the concrete structure deteriorations, defects and technical state evaluation results of 34 Lithuanian spillway concrete gravity dams performed in 2006–2018. The typical deteriorations are: in piers'– crumbled protective layer of concrete, its corrosion, reinforcement corrosion, cracks in concrete, chipped edges; in spillway constructions'– concrete corrosion, bio–corrosion, concrete corrosion caused by cavitation; in outflow constructions – concrete corrosion, bigger cracks and deformations. According to results of technical state research, it was found that only 3% (1 SCGD) dams are in good technical state, 27% (9 SCGD) – moderate, 47% (16 SCGD) – satisfactory, 12% (4 SCGD) – unsatisfactory and 12% (4 SCGD) – in critical state.

Keywords: deterioration, environmental impact assessment, spillway concrete gravity dams, technical state.

Introduction

Spillway concrete gravity dams (hereinafter – SCGD) are rather popular because they are good enough to a pass a greater floodwater discharges and ice. In Lithuania's conditions such discharges are over 100–150 m^3/s (Damulevičius and Vyčius 2008, Damulevičius et al. 2009, Ruplys 1988). Abroad various propositions are presented (Hydraulics of Dams and River Structures 2004, Novak et al. 2007, Tanchev 2005).

Lithuanian SCGDs are designed, built and maintained in accordance with the requirements of construction technical regulations (STR 2.02.06:2004 2004, STR 2.05.15:2004 2004, STR 2.05.14:2005 2005, STR 2.05.18:2005 2005, STR 1.03.07:2017 2017, Hidrotechnikos statinių projektavimas 2001, Hidrotechninė statyba 2000).

SCGDs are usually included into the combined hydroscheme, which include, for example, embankment dam, hydropower plant (hereinafter – HPP) structure and other hydraulic structures. Such and the most remarkable Lithuanian SCGD is in the hydroscheme of Kaunas HPP. Its maximum afflux (head difference) reaches 20 m, the design flood discharge is 3990 m^3/s. Nowadays here are possibilities to build a navigation sluice or lift in Kaunas HPP hydroscheme and fish pass or fish lift.

Worldwide SCGDs that are more impressive are built. The tallest of them are: the Grande Dixence in Switzerland with 285m height (Grande Dixence dam 2020) and Diamer Basha (formerly called Basha) with 272m height (Big Dams 2020). Many rather large SCGDs are built in USA, Russia and in other countries which are mountainous and where strong, rocky soils prevail. These dams are designed in accordance with the requirements of construction technical regulations (EM 1110–2–1603 1990, EM 1110–2–2104 2003, EM 1110–2–2100 2005, EM 1110–2–2200 1995, EM 1110–2–2201

1994, SNiiP 33–01–2003 2004). All the hydraulic structures (hereinafter – HS), including spillway concrete gravity dams, are used in complicated conditions of the environmental impact: they are affected by natural (atmosphere, freezing–thawing cycles, ice and swimming solids or sediments abrasive impact, atmospheric precipitation, wind and storm, wave blows; periodical wetting; solar radiation, collapsing impacts; rockslides, earthquakes, etc.) and various technological factors. Due to these factors, various deteriorations appear in the HS constructions; they reduce the bearing capacity of constructions (or spillway) to water pressure, technical state of SCGD constructions decreases. Causes of distress and deterioration of concrete are described very detail in Standard EM 1110–2–2002 (EM 1110–2–2002 1995). It is known, concrete ageing, vibrations in the foundations, accumulation of sediments, water erosion are main factors that reduces dams resistance to failure (Safety of Existing Dams – Evaluation and improvement 1983, ICOLD 1995). The threats (initiating events), 48 hazards, defined may lead to the different modes of failure, are described in work (Almog 2011), but some of them – for example, earthquake loading are not actual in Lithuania.

The numbers of large dams are growing - taking only the approximately 36 000 large dams listed in the World Register of Dams there have been around 300 reported accidents (ICOLD 1995), (ICOLD 2020, Chanson 2000). Some safety evaluation methods of HPP are described in scientific literature (Safety of Existing Dams – Evaluation and improvement 1983).

There are about 620 potentially dangerous ponds with hydraulic structures (if water head is 4 m or more or in ponds accumulated water volume is more then 100000m^3) in Lithuania (Tvenkinių katalogas 1998). In Lithuania, dams' observations and, to a certain extent, researches have been carried out since the dams were built, nevertheless the greatest attention has been focused on the field observations of earthfill dams (Damulevičius 2001, Damulevičius and Vyčius 2007, Šadzevičius et al. 2013). The biggest hydroschemes in Lithuania are: Kruonis PSHEP and Kaunas HEP. The technical state of these objects is monitored, controlled using regulations for maintenance (Šikšnys 2007, Skripkiūnas et al. 2006).

Technical state over 300 dams in Lithuania were investigated by the specialists of Water and Land Management Faculty at the Vytautas Magnus University (hereinafter – VDU). Main attention has been paid to these reinforced concrete (hereinafter –RC) hydraulic structures and constructions: RC slabs for earthfill dams slope protection (Damulevičius and Vyčius 2007), (Šadzevičius 2002, Šadzevičius et al. 2011); culverts and service bridges (Natūrinių ir anketinių duomenų... 2009); service bridges in spillways (Šadzevičius and Mikuckis 2010); retaining (wing) walls (Šadzevičius et al. 2009). At the same time studies of HS technical state evaluation were carried out (Damulevičius et al. 2001, Damulevičius and Vyčius 2007, Šadzevičius et al. 2013, Šadzevičius et al. 2001, Patašius et al. 2009). The researches of the SCGD reinforced concrete constructions state were carried out in 1999–2005 by the specialists of the Department of Building Constructions in Lithuanian University of Agriculture; the results were generalized in the report (Natūrinių ir anketinių duomenų... 2009) and in the paper's (Damulevičius et al. 2009), (Šadzevičius et al. 2013). Analysis of these, early performed investigations results, shows that currently valid dams' maintenance regulations should be improved, because of insufficient information about the technical state evaluation process, deterioration of concrete on the safety and reliability of RC hydraulic structures.

The purpose of this research is to describe the main indices and causes of deteriorations appearing in Lithuanian spillway concrete gravity dams, to evaluate the changes of technical state of dams and according to the results of investigation propose the expressions for selecting proper covering concrete layer of designing new reinforced concrete spillways.

Materials and Methods

In 2006–2018 the spillway concrete gravity dams were inspected in 15 districts of Lithuania: Kėdainiai (8 dams), Marijampolė (6 dams) and in some other regions of Lithuania. Taking into account the materials used for construction, the acting head and ground soil, the investigated objects belong to the consequence classes CC1 and CC2 (STR 2.02.06:2004 2004).

The following constructions' diagnostic methods were used during the investigation of deteriorations' state changes in spillways:

1. documentation review;
2. visual–instrumental method;
3. Nondestructive (instrumental with a rebound hammer of concrete) and destructive (core sampling) methods were used for the estimation of concrete compressive strength in accordance with normative documents EN 12504-1:2009, EN 12504–2:2012, CEN/TR 17086:2020, EN 206:2013+A1:2017, laboratory tests for evaluation density (EN 12390-7:2019/AC:2021), water absorbability (LST 1413.10:1997/P:2020), frost resistance (LST 1428-17:2016), but all results are not presented in this paper due the size of paper.

Documentation review – the analysis of design (work drawings and construction projects) and other archival documentation (technical maintenance records, rules of dam maintenance, inspections reports).

Visual–instrumental method (Durcheva 1988, Malakhanov 1990) is applied for SCGD field investigations. Noticed defects (broken corners or edges of surface, stratified concrete, etc.)) and deteriorations (deteriorated and destroyed concrete covering layer, steel corrosion, etc.) and their intensity were analyzed according to dams' maintenance regulations (EM 1110–2–2002 1995, The Norwegian regulations for planning... 1996, EM 1110–2–4300 1987). During expeditions and field investigations the location of damaged constructions, the types of deteriorations and their geometrical data (area, depth) were determined. Using simple instruments (a ruler, sliding caliper, etc.) the detrioration of concrete surfaces, depths and paterns of cracks, deformations, scour, pittings, etc. were established. The photos of typical deteriorations of SCGD were taken.

According to the results of field investigations the technical state of SCGD and whole hydroscheme was evaluated in accordance with deteriorations registered during the field observation and using the methodology given in the Lithuanian construction technical regulations (STR 1.03.07:2017 2017): SCGD and hydroscheme were evaluated as functionally related elements - main structures and auxiliary structures. Technical state evaluation was performed using quantitative indices and calculating averages of defectiveness points (Bu,) in ten points criterion system (0 points – ideal state, 10 points – element's emergency state) following evaluation criteria given in Lithuanian construction technical regulations (STR 1.03.07:2017 2017). If one of main elements which determines SCGD reliability is evaluated from 8.1 to 10.0 defectiveness points, then the technical state of the whole hydraulic structure is evaluated by the same points. If the main elements with defectiveness points from 8.1 to 10.0 are absent, overall (total) points (Bu) of HS technical state are calculated according to the following formula:

$$B_u = \frac{B_1 + B_2 + \ldots + B_n}{n} \quad (1)$$

where: B_1, B_2, ..., Bn – evaluation points of separate HS elements; n – number of evaluated HS elements.

The calculated points of HS technical state (Bu) are rounded up or down in limits of 0.1(STR 1.03.07:2017 2017).

Results

In this paper the results of research and analysis of 34 SCGD technical state in 15 districts of Lithuania are presented.

The oldest SCGD was built in 1847, the last one in 1997. The investigations were performed in 2006–2018. During the field observation, the main SCGD defects were determined; the general evaluation of SCGD technical state in defectiveness points were calculated (Table 2) in accordance Lithuanian construction technical regulations (STR 1.03.07:2017 2017). The data of investigated SCGD are presented in Table 1 and Fig. 1.

Table 1

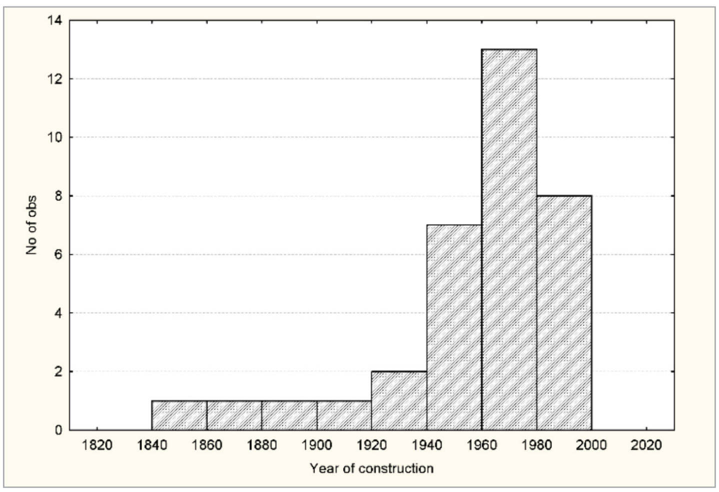
The data of spillway concrete gravity dams

No.	Name of hydroscheme	Year of construction (* year of reconstruction works)	Year of research	General evaluation of SCGD state *Bu*, points
1	2	3	4	5
		Alytus district		
1	Kumečiai	1968	2009	4.4
		Jonava district		
2	Lokys	1988	2011	5.4
3	Markutiškiai	1989	2011	6.7
		Kėdainiai district		
4	Akademija – Dotnuva	1968 2006*	2011	4.6
5	Angiriai	1980 2000	2006	3.2
6	Kruostas	1953	2013	10
7	Labūnava I	1977 2004	2012	4.7
8	Labūnava II	1991	2010	10
9	Kėdainiai city	1972	2012	4.0
10	Juodkiškis	1980 2001*	2011	4.7
11	Urkos	1997	2010	9
		Kretinga district		
12	Darbėnai	1932	2009	3.2
13	Kretinga park I	1878 1987	2006	3.9
		Lazdijai district		
14	Kapčiamiestis	1956	2007	4.1
		Marijampolė district		
15	Antanavas	1957 2004*, 2011*	2011	5.2
16	Kazlai I	1991	2009	3.8
17	Kazlai II	1935	2006	7.8
18	Marijampolė I	1957 2008*	2011	4.5
19	Marijampolė II	1974 2004*	2011	4.4
20	Netičkampis	1951, 1991*	2009	7.3
		Pakruojis district		
21	Dvariukai	1982	2011	3.7
		Panevėžys district		
22	Factory „Ekranas“	1980	2018	3.4

No.	Name of hydroscheme	Year of construction (* year of reconstruction works)	Year of research	General evaluation of SCGD state *Bu*, points
23	Jotainiai	1987	2008	4.5
Pasvalys district				
24	Pasvalys city	1895	2008	5.1
25	Švobiškis	1919	2008	5.2
Prienai district				
26	Jundeliškes	1958	2011	6.1
Raseiniai district				
27	Paupys	1972	2012	5.5
Šilutė district				
28	Vilkenai	1847	2007	2.8
Ukmergė district				
29	Taujėnai	1985	2010	4.0
30	Vepriai	1974	2010	5.6
Utena district				
31	Satarečius	1975 2008*	2010	1.0
Telšiai district				
32	Pasruojė	1964	2012	9.0
33	Sukončiai	1953	2012	4.2
34	Ubiškė	1977	2012	4.5

Fig. 1

The histogram of construction years of investigated objects



Graphically the results of the SCGD erection are presented in Fig. 1.

The most intensive period of SCGD constructing was in 1960–1980. During this period were built 13 investigated objects. According to the data presented in Fig. 1 main part of investigated SCGD are more than 40 years old, only few objects are exploited less than 30 years.

The distribution of the number of investigated SCGD in Lithuania by district is shown in Fig. 2.

The results of 34 SCGD technical state investigations are presented graphically in Fig. 3. Summarized results showed that only 3% (1 SCGD) dams are in good technical state, 26% (9 SCGD) – moderate, 47% (16 SCGD) – satisfactory, 12% (4 SCGD) – unsatisfactory and 12% (4 SCGD) – in critical state.

The maximum of dams in critical state (3) was founded in Kėdainiai district. SCGD in unsatisfactory or critical state can be potencialy dangerous for the dam surroundings and repair works must be performed immediately. Kruostas, Labūnava II, Urkos SCGD in Kėdainiai district and Pasruojė SCGD in Telšiai district must be rehabilitated or demolished as quick as possible.

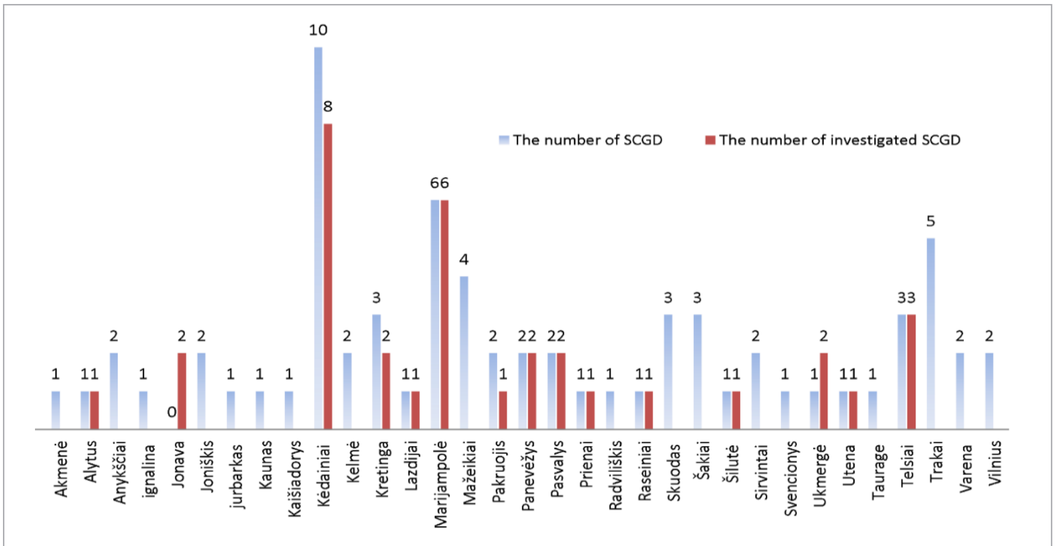


Fig. 2

Distribution of investigated SCGD by district

Analysing results of pier constructions' technical state research it was established that after reconstruction, the state of piers' constructions in Akademija–Dotnuva, Antanavas, Marijampolė I and Marijampolė II and another SCGDs improved, however in hydroschemes, where the reconstruction haven't taken place, the state of piers worsens, it has especially worsened in Kruostas, Netičkampis SCGD. Main piers' deteriorations in the investigated SCGDs are the following: crumbled protective layer of concrete, its corrosion, reinforcement corrosion, cracks in concrete, chipped edges, etc.

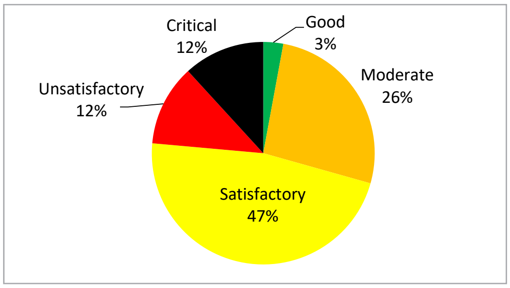


Fig. 3

SCGDs technical state category founded in 2006–2018

Analysing the results of spillway base technical state research, it was established that before reconstruction in Akademija – Dotnuva and Antanavas SCGDs, these constructions had been in an unsatisfactory (bad) technical state (6.5 – 7.0 points). The technical state of spillway base was evaluated as average in those SCGDs, where the reconstruction haven't taken place, still, the technical state of these constructions has especially worsened in Netičkampis SCGD (7.5 points, unsatisfactory (bad) state) and Kruostas SCGD where it has worsened from 5.5 points in 1999 to 10.0 points in 2005–2011. Main spillway constructions' deteriorations in the investigated SCGDs are the following: concrete corrosion, bio–corrosion, concrete corrosion caused by cavitation etc.

Analysing the results of outflow constructions' state research it was found out that before reconstruction in Akademija – Dotnuva and Antanavas SCGDs, these constructions had been in a very bad state (9.0 points) the failure of the whole structure was possible due to considerable deteriorations of the constructions. The technical state of outflow constructions in other SCGDs was evaluated as unsatisfactory (6.1–8.0 points) and only in Labūnava and Kazlai SCGDs the technical state of these constructions was evaluated as satisfactory (4.1–6.0 points). The main deteriorations of outflow constructions are the signs of concrete corrosion, noticed in all the investigated SCGDs. Deformations of retaining walls were noticed in Kėdainiai city, Kruostas, Marijampolė I, Netičkampis SCGDs. Main causes of SCGDs deformations and deteriorations are: insufficient supervision (Antanavas and Kudirkos Naumiestis SCGD), poor quality of work and low quality of used construction materials (Kruostas SCGD). Relatively rapid deterioration of Kruostas HS was due to low quality of materials – after the core drilling was found clay in some samples (specimen No.7) and laboratory testing of core samples showed the small compressive strength of concrete (Table 2).

During increased accumulation of deteriorations (in some cases of very aggressive environment (acidic brown water from exploited peatbog), insufficient supervision of HS (e.g. Kruostas, Kudirkos Naumiestis SCGD) the SCGDs technical state changing from unsatisfactory to critical.

Table 2

The main physical–mechanic properties of concrete in the Kruostas SCGD

Structure		Physical– mechanic properties of concrete					Thick-ness of damaged, surface layer, cm
Spec-imen Number	Description and location of investigated part	Compression Strength of Specimen f_{cube} (MPa)		Density of hardened concrete ρ, kg/m^3	Water absorption, w_m %	Frost resistance F, cycles	
		Non-destructive method	Destructive method (cylindrical cores)				
1	2	3	4	5	6	7	8
1	Wall of turbine hall	19.5	19.5	2227	8.32	34	0
2	Wall of HPP from LP side	20.8	14.6	2146	9.23	16	3-5
3	Right wall of HPP from LP side	25.0	35.5	2235	8.45	31	1-2
4 L	Left side of fish pass wall from LP near gates	33.6	24.4	2211	9.37	14	<1
4 R	The right side of fish pass wall from LP	30.2	15.2	2071	10.99	-	1-2
5	II pier from LP, left side	49.2	42.1	2282	6.14	118	< 1
6	III pier from LP, left side	49.1	23.4	2245	7.04	75	< 1
7	Abutment left side, external 20 cm layer	46.0	27.5	2204	9.32	29	1-10
7	Abutment left side, internal layer *	12.4	5.8	-	-	-	-

Remarks:
* Core No.7 made from two different composition of concrete
HPP – hydropower plant,
LP– lower pool side.

The results of non-destructive testing (Table 2) shows that the highest concrete compression strength was determined in the structures of II and III piers f_{cube} = 49.2 MPa, the lowest concrete compression strength was foundend in the left abutment f_{cube} = 12,4 MPa. The results of destructive testing shows the lower values of concrete compression strength at the same structures – II pier f_{cube} = 42.1 MPa and III pier f_{cube} = 23.4 MPa, left abutment f_{cube} = 5.8 MPa. It is known (Šadzevičius et al 2015), that the rebound hammer test shows only the state of the surface of concrete. The surface of concrete has higher values (due carbonisation), so the result of compressive strength obtained by examining the drilled cores is more reliable.

Discussion

The analysis of results of Lithuania SCGD technical state evaluation performed in our research shows, that in investigated regions SCGD technical state is getting worse, due to insufficient supervision, ageing and deterioration of structures. During normal maintenance of HS the damages are accumulate slowly, so the technical state has remained unchanged than repair works performed in some SCGD.

Analysing the results of SCGDs constructions' technical state research it was established that, similar deteriorations are mentioned in the generalized report of state researches of 287 SCGDs in Norway, which can be found in scientific literature (Jensen 2001). On the basis of these researches, the main reinforced concrete deteriorations in the investigated dams and their causes were established: reinforcement corrosion (noticed in 19 % of researched dams), concrete corrosion (18 %), deteriorations caused by frost (50 %), concrete erosion (47 %), water leakage (21 %), deformations (20 %), concreting defects (43 %), vertical and horizontal cracks noticed in 53% to 56% of the investigated dams; 36% have map cracking and damages in the dam arches.

Above listed main causes of HS defects and deteriorations in Norway SCGD are typical and founded in reinforced concrete HS of Lithuania SCGD too.

The results of field investigations performed on 32 earthfill dams shows, that main damages of RC slabs for slope protection are deterioration of cover layer and collapsing of junctures, noticed in 30% and 50% of objects. (Damulevičius, V.; Vyčius 2007, Šadzevičius 2002, Šadzevičius et al. 2011).

Comparing the research results carried out in 2006–2018 with the results of previous researches (1999–2005) it was found out that the technical state has hardly changed in Kruostas, Labūnava II, Urkos Marijampolė II, Antanavas, Pasruojė SCGDs; the technical state has worsened in Akademija–Dotnuva, Juodkiškis, Kazlai, Jundeliškes, Markutiškiai and Netičkampis SCGDs; the state has improved due to reconstruction in Marijampolė I SCGD. The worst technical state was established in Kruostas and Labūnava II (10.0 points), Urkos and Pasruojė (9.0 points) SCGDs.

The data of research presented are given for designing new reinforced concrete (hereinafter –RC) spillways or repairing the deteriorated parts of structures timely. 30 - 40 mm concrete covering layer, protecting reinforcement from corrosion and its condition shows the durability of whole structure. During research it was noticed the 30 mm concrete covering layer (constructed according design norms of former USSR) of reinforced concrete structures was deteriorated very often. If HS are made from concrete with low quality of materials RC surfaces are damaged much more (Šadzevičius 2007). The maximum speed of deterioration (pitting) deepening (3.67 ÷ 5.06 mm/year) was noticed in structures made of concrete with low average concrete compression strength f_c = 5.1 ÷ 7.1 MPa from Antanavas and Kazlai old SCGD. Nowadays covering layer of RC structures must be 40 mm and made from concrete, which compression strength 37 MPa (STR 2.05.18:2005 2006). Using our estimated durability indices T_{40mm} (Šadzevičius et al. 2010) for designed reinforced concrete spillways, can be chosen concrete covering layer of RC structures, that reinforcement won't uncover during foreseen time:

$$T_{40\,mm} = -17.6 + 3.33 \cdot f_c\,, \quad (2)$$

where $T_{40\,mm}$ – functioning period of a 40 mm thick covering layer of the HS expressed in years; f_c – average compression strength of concrete, MPa.

The application of proposed dependance (2) is illustrated in Fig. 4 Calculations performed on Kruostas SCGD investigation results presented in the Table.2. The new dependence Concrete compression strength ***fc***- Frost resistance *F* was created on the basis of main physical– mechanic properties of concrete in the Kruostas SCGD (Fig.4).

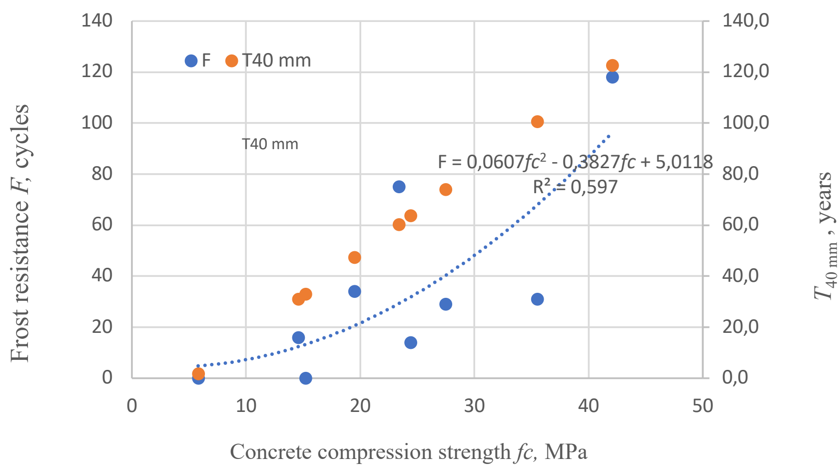


Fig. 4
The relationship between Concrete compression strength *fc*- Frost resistance *F* and Durability indices T_{40mm} based on Kruostas SCGD technical state investigations

According to the data presented in Fig. 4, a 40 mm covering layer made of weak concrete (f_c = 5.8 MPa) will be deteriorated in 5 year of functioning, while the one made of strong concrete (f_c = 42.1 MPa) will be deteriorated in 122.6 years of functioning.

The relationship between frost resistance *F* and average compression strength of concrete f_c could be expressed:

$$F = 0{,}0607 f_c^2 - 0{,}3827 f_c + 5{,}0118 \quad (3)$$

where *F* – frost resistance expressed in cycles; f_c – average compression strength of concrete, MPa.

According to the data presented in Fig. 4, the structures in Kruostas SCGD made from strong concrete (f_c = 42.1 MPa) has frost resistance *F*=118 cycles. These structures are less deteriorated.

The most suitable variant for the repair of reinforced concrete in HS is to use cement mortar modified with expansive admixture and to properly prepare the concrete surface (the minimum roughness index of concrete surface must be RI_{min}=2.92) (Skominas et al. 2017).

Conclusions

1. According to the technical state investigation of 34 Lithuanian spillway concrete gravity dams performed in 2006–2018, the main deteriorations in the structures of investigated objects are:
   - in piers'– crumbled protective layer of concrete, its corrosion, reinforcement corrosion, cracks in concrete, chipped edges;
   - in spillway constructions'–bio–corrosion, concrete corrosion caused by cavitation;
   - in outflow constructions – concrete corrosion, bigger cracks and deformations.

2. The typical causes of deterioration and deformations of spillway concrete gravity dams are:
   - lack of maintenance and insufficient supervision,
   - poor quality of work and low quality of used construction materials,
   - it was established, that main deteriorations of concrete structures are rapidly in progress and caused by the environmental factors (periodical wetting, freezing–thawing cycles, ice and swimming solids or sediments abrasive impacts, wave blows, cavitation and etc.).
3. According to results of technical state investigations of 34 Lithuanian SCGD carried out in 2006–2018 by VDU researchers, it was found that only 3% (1 SCGD) dams were in good technical state, 27% (9 SCGD) – moderate, 47% (16 SCGD) – satisfactory, 12% (4 SCGD) – unsatisfactory and 12% (4 SCGD) – in critical state.
4. The worst technical state was established in Kruostas, Labūnava II, Urkos SCGD in Kėdainiai district and Pasruojė SCGD in Telšiai district, so these dams must be rehabilitated or demolished as quick as possible.
5. According to the results of investigation proposed expressions (2 and 3) for selecting proper covering concrete layer of designing new reinforced concrete spillways. The most suitable variant for the repair of the damaged parts of reinforced concrete spillways is to use cement mortar modified with expansive admixture and to properly prepare the concrete surface.

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