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CRACKS AT MATKA ARCH DAM – A CASE STUDY*

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SUMMARY

The oldest and the only dam built in Republic of Macedonia before World War II, is the Matka reinforced concrete arch dam, which still serves its purpose - forming a reservoir and a head for the production of electric power. It dams the gorge of the River Treska, at a narrow dam site with a V-form, composed of sound and impermeable rock. The dam consists of 10 arches with different radii of curvature, each 3 m high. The thickness of the lowermost arch is 1.6 m, while that of the uppermost is 1.0 m.

In July 2012, two cracks in the upper part of the dam were visually recorded, located in the immediate vicinity of the right abutment. Through the cracks a small amount of water licked. The first crack (Crack 1) was on the arch IX, and the second one (Crack 2) on the arch VIII. The visual inspection of the dam, performed at almost full reservoir condition, has shown that Crack 1 was extended

* *Fissures au barrage-voûte de Matka - étude de cas*

along the entire height of the arch IX, while the start point of Crack 2 was 90 cm below the upper edge of the arch VIII, and the end point at the bottom of this arch. The width of Crack 1 was estimated to 1 mm, and of Crack 2 up to 2 mm. Water leakage was visible in the lower part of Crack 1, and throughout the whole length of Crack 2. The presence of limescale and moss suggested that the leakage is continuous and that the cracks are of an older date. In order to find the possible reasons for appearance of the cracks, main attention was paid to the analysis of the measured displacements on the downstream dame face, as well as to the dam and reservoir conditions in the months before the appearance of the cracks. The displacements recorded in the last two series of measurements (2012/2011) were in order of magnitude up to 9 mm, which were also recorded earlier, so that they were rejected as the cause of the cracks. The analyses of the dam and reservoir conditions in the months before the appearance of the cracks showed that since June 16 to June 26, 2012, the reservoir water level was kept low, and it was bellow the cracks. In the same time the air temperature was extremely high for the usual Matka dam site conditions, reaching a maximum value of 33-36 C°. On June 26 and 27, the reservoir was quickly filled with relatively cold water, which caused high temperature stresses in the previously heated upper section of the dam. They widened the cracks, for which there were indications that thay occurred earlier.

Despite the two recorded cracks did not jeopardize the stability of the dam, it was decided to be repaired, first of all in order to protect the surrounding concrete from aging and the reinforcement from corroding under the influence of the water that penetrates. Firstly, in May 2013, one-axial gauges for measurement of the crack's width were installed. Then thermal imaging of the cracks was performed, as well as their injecting with a colored liquid to obtaining important knowledge for the preparation of the remediation solution. Finally, in July 2016, the restoration of the cracks was successfully performed by grouting.

RÉSUMÉ

Le barrage-voûte de Matka est le plus ancien et l'unique barrage construit en Macédoine avant la deuxième guerre mondiale en béton armé, et il sert encore pour son principal but – la formation d'un réservoir et d'une hauteur de chute pour la production d'électricité. A un endroit étroit, il barre la gorge de la rivière Treska en forme de V, constitué d'une roche solide et imperméable. Le barrage est composé de 10 voûtes avec différents rayons de courbure et d'une hauteur de 3 m. L'épaisseur de la voûte la plus basse est 1,6 m tandis que celle de la plus haute est 1,0 m.

En juillet 2012, deux fissures ont été observées dans la partie supérieure du barrage, juste à côté du côté droit, avec écoulement d'une petite quantité

d'eau. La première fissure (numéro 1) se trouvait sur la voûte IX, et la deuxième fissure (numéro 2) sur la voûte VIII. L'inspection visuelle du barrage, effectuée à réservoir presque plein, a montré que la fissure 1 s'étend à travers toute la hauteur de la voûte IX, tandis que le point de départ de la fissure 2 se trouvait 90 cm en dessous du bord supérieur de la voûte VIII, et le point final était au fond de cette voûte. La largeur de la fissure 1 a été estimé à 1mm et celle de la fissure 2 jusqu'à 2 mm. La présence de calcaire et de mousse suggérait que la fuite existait déjà et que les fissures sont d'une date plus ancienne. Pour trouver les raisons de l'apparition des fissures, l'attention s'est penchée sur l'analyse des déplacements mesurés du barrage et aussi sur les conditions du barrage et du réservoir pendant les mois précédant l'apparition des fissures. Les déplacements enregistrés pour les deux dernières séries de mesure (en 2011/2012) étaient restés, avec 9 mm, constants, et ils n'ont pas été considérés comme la raison de ces fissures. Les analyses du barrage et les conditions dans le réservoir effectuées avant les fissures ont montré que du 16 au 26 juin 2012 le niveau de l'eau du réservoir était situé à une cote basse, sous les fissures. En même temps la température de l'air était extrêmement élevée pour cette période, jusqu'à 33-35 °C. Le 26 et le 27 juin, le réservoir s'est rempli rapidement avec l'eau relativement froide ce qui a causé de fortes différences de température dans la partie inférieure chauffée du barrage. Tout cela a étendu les fissures vraissemblablement apparues plus tôt.

Bien que les deux fissures enregistrées n'aient pas mis en danger la stabilité du barrage, il a été décidé de les réparer, principalement afin de protéger le béton du vieillissement et l'armature de la corrosion sous l'influence de l'eau pénétrée. En mai 2013 des jauges ont été posées sur un axe pour mesurer la largeur des fissures, après avoir effectué un enregistrement thermique et injecté un liquide coloré pour avoir des données essentielles pour la préparation de l'assainissement. Finalement, en juillet 2016, la restauration des fissures a été terminée avec succès.

1. INTRODUCTION

The oldest and at the same time the only dam built in R. of Macedonia before World War II (1935-38), is the Matka reinforced concrete arch dam (near Skopje), which still serves its purpose - forming an reservoir and a head for the production of electric power. It dams the gorge of the River Treska, at a narrow dam site with a V-form, composed of sound and impermeable rock. The dam consists of 10 arches with different radii of curvature (Fig. 1), each 3 m high. The thickness of the lowermost arch is 1.6 m, while that of the uppermost is 1.0 m. Below the lowermost arch, in the foundation, there has been constructed a massive concrete foundation. The concrete, of which arches have been carried out, contained 325 kg of high-strength low-setting cement. Between individual arches there have been carried out horizontal joints with several coatings of bitumen and a thin zinc sheet. For achieving water-impermeability, there has been built in a copper sheet of 0.5 mm, which has penetrated some 25 cm into the neighbouring arches. On the right-hand side there have been constructed a spillway structure and an outlet works, while on the left-hand side there has been located the intake structure to the power house of the near-dam electric power plant. The dam in which there have been incorporated 3000 m^3 of concrete and 150 t of reinforcing steel, impounds a reservoir of 3.55 million m^3 [1]. The original HPP, in operation since 1938 to 2008, had an installed capacity of 4.5 MW with maximum discharge 19.5 m^3/s. Then, reconstruction works have been carried out, and now hydro scheme Matka is a 10 MW project equipped with two Kaplan turbines, operating under a rated head of 23 m, with total discharge 42 m^3/s and installed power output 12 MVA. The new plant was constructed adjacent to the original one [2].

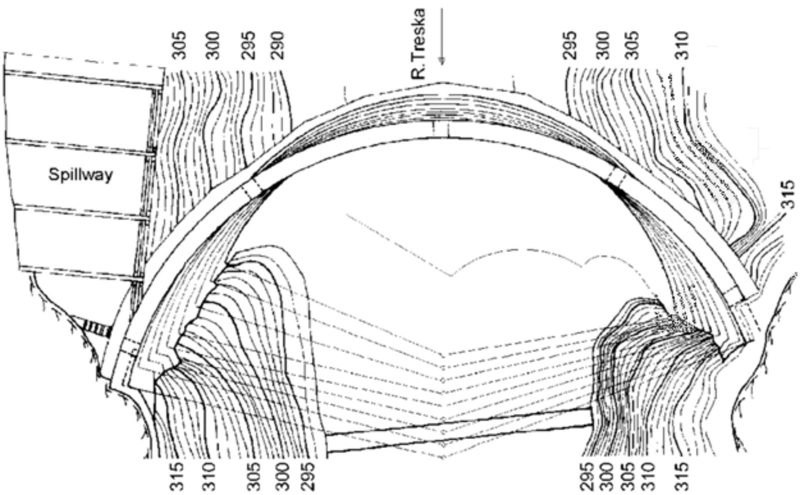

Fig. 1
Plan of the Matka dam, *H* = 30 m (R. of Macedonia)
Plan du barrage Matka, H = 30 m (R. de Macédoine)

2. CRECKS REGISTERED IN JULY 2012

During the regular annual measurement of the movements of the dam's body in summer conditions, carried out in July 2012, two cracks in the upper part of the dam were visually recorded, located in the immediate vicinity of the right abutment, through which a small amount of water licked. The first crack was on the arch IX near the measuring point 13, and the second one on the arch VIII, under the measuring point 13, Fig. 2. On July 26, 2012, the author and the first coauthor of this paper performed a visual inspection of the dam, with special atantion to the zone of the cracks, took photographs and gained certain data from the responsible person of the dam. In Fig. 3, the cracks at the ends of the arches IX and VIII near the right abutment can be seen. During the inspection of the dam, the reservoir was almost full, that is, the upper water level was at elevation 315.83 m.a.s.l. On July 31, 2012, with appropriate equipment, we came to the cracks zone on the downstream dam side making a direct inspection of the cracks. Thus, we came to the following important findings:

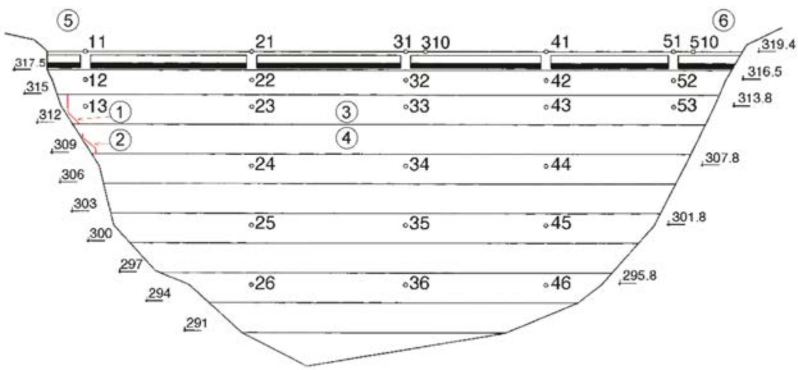

Fig. 2
Point for measurement of the displacements on the downstream dam face
Point de mesure des déplacements sur la face du barrage en aval

1	Crack 1	*1*	*Fissure 1*
2	Crack 2	*2*	*Fissure 2*
3	Arch IX	*3*	*Arc IX*
4	Arch VIII	*4*	*Arc VIII*
5	Right side	*5*	*Côté droit*
6	Left side	*6*	*Côté gauche*

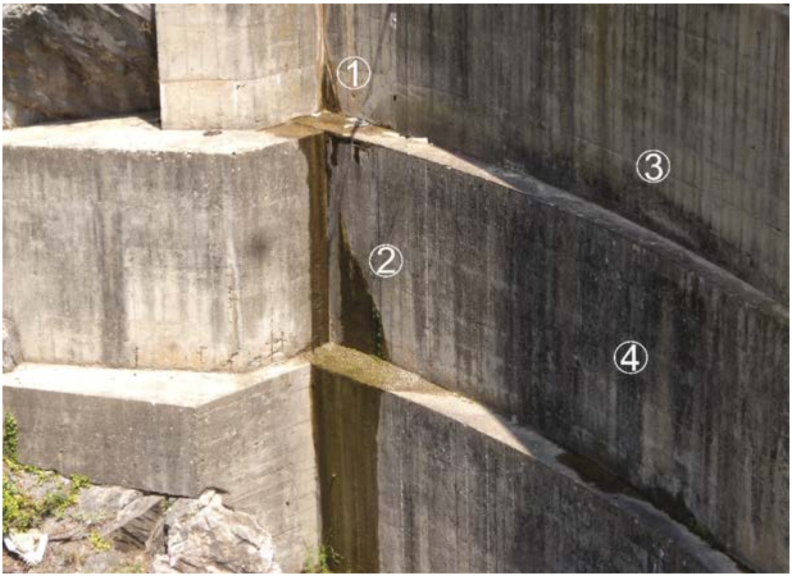

Fig. 3
Location of the cracks
Emplacement des fissures

1	Crack 1	*1*	*Fissure 1*
2	Crack 2	*2*	*Fissure 2*
3	Arch IX	*3*	*Arc IX*
4	Arch VIII	*4*	*Arc VIII*

Crack 1 was extended along the entire height of the arch IX, from the elevation 315.00 m.a.s.l. (upper edge of the arch) to the elevation 312.00 m.a.s.l. (lower edge of the arch). The crack first was extended vertically just near the contact between the arch and the foundation block, from the elevation 315 to the elevation 313 m.a.s.l, to which it became inclined to the end at the lower arch edge. The vertical part of this 190 cm-long crack was dominantly dry, while the sloping section, 117 cm long, was wet or with little leakage. On the vertical part, the width of the crack was considerably less than 1.0 mm, while on the sloping, moist part, it was estimated that in several places it reaches 1.0 mm.

- The start point of Crack 2 was 90 cm below the upper edge of the arch VIII, and the first 20 cm were almost vertical, and then the crack was inclined in a length of 140 cm. After that there was a nearly vertical part, 56 cm long. At the upper end, at an elevation of 311.10 m.a.s.l., the crack was of low width, but going down its width increased continuously up to 2 mm. Water penetration was visible throughout its whole length.

- At the time of the inspection the surface of the concrete around the vertical part of the crack 1 was dry, but a thin layer of limescale was a sign that occasionally there was a penetration of water and that the crack is of an older date. The surrounding area of the inclined crack part was wet, and a slight water leakege was evident. A layer of deposited limescale around the sloping part of the crack was noted, up to 3 mm thick, suggesting that the leakage was continuous and that the crack was from the older date.
- The surface around the crack 2 was wet over the entire length of 216 cm, and a clear water leakage was visible. Around the lower, finished vertical part of the crack, there was a surface with a green developed moss. Deposits of limescale along the crack reached a thickness of 5 mm, and even more. All of this suggested that the leakage was continuous and that the crack is of an older date.

3. POSSIBLE REASONS FOR THE APPEARANCE OF CRACKS

3.1. General

The appearance of cracks in the body of concrete dams during their service period often occurs [3]. Effective reasons for the appearance and development of cracks may be different, but for arch concrete dams, most often these are the water loads and the temperature changes. In the case of the dam Matka, they were about individual cracks on the arches VIII and IX, in part as vertical, and in part as inclined, appearing on the downstream dam face, right next to the contact with the rock foundation, with a small width (under 0.5 mm), and a mean one (0.5-2) mm. They were located next to the zone in which the concrete arches are embeded in the rock, which emphasizes the possibility of significant temperature differences in the part of the concrete exposed to the air and in the part embeded in the rock, but also on a different freedom in terms of the possibilities for moving into radial direction. Vertical cracks in the downstream face of the arches adjacent to the end-fixed zone are typical for hot weather conditions, combined with low reservoir water level.

The two actual cracks were registered in the second half of July 2012, but they occurred, that is, they began to form earlier. The proof of this is the fact that during their observation from the immediate vicinity, presence of limescale, and in places moss, has been found. The reason that the cracks were not observed earlier probably lies in the fact that before June 2012 they were narrower, and the leakages through them were small and periodic. Namely, they are located on high arches, in which the pressure of the water is low.

Taking into account that the most important influence in the arch dams is caused by the forces from the temperature changes and the hydrostatic pressure, the analysis of the problem was directed towards these phenomena. Since the only measured values in the body of the Matka dam have are the displacements in points located on the downstream dam face, we are keeping on them in order to get to their possible connection with the appearance of the cracks.

3.2. Analysis of the displacements

The first measurement of displacements of Matka dam was carried out in 1971, after which, up to July 2012, a total of 30 series were recorded. In the recent reports, the registered movements were compared with the corresponding results of Series 6, recorded on April 13, 1985, when the reservoir was empty and the average daily air temperature was +10°C, which correspond to the medium annual air temperature. Two original measuring points on the dam's crest were replaced with new ones: 31 by 310 (July 1991) and 51 by 510 (April 1993), Fig. 2. Taking into account that the cracks in arches VIII and IX were observed during the performance of the latest recording, we will first compare the measured movements in the series 30 (July 2012) with ones measured in the series 29 (November-December) 2011), Table 1a.

From the displayed displacement values it can be notice that the vertical displacements (Dz) are relatively small, mostly directed downward, which is logical, taking into accoumt that the series 29 was recorded at full reservoir, while the series 30 was recorded relatively short time after the reservoir filling, after about two months of low water level. The horizontal displacements in the longitudinal direction (Dy) are also of small values, and the largest occurs in point 41 and is 3.8 mm, directed towards the left bank. At the same point there is a noticeable horizontal displacement in the transverse direction of the dam, (Dx), with a value of 7.9 mm, directed towards the reservoir. The biggest displacement in the x-direction is registered at point 310, with a value of 8.1 mm. It should be borne in mind that points 41 and 310 are located on the dam crest and are relatively far from the zone of the cracks formed in arches VIII and IX. Also other points in which there are larger displacements in the x-direction, for example over 4 mm, are located on the upper three arches (32, 33, 42, 43) and are relatively far from the cracks. Closer to them is point 21, with Dx = 5.5 mm.

Table 1
Movements: a) Series 30/29; b) Series 30/6

a)

POINT	ΔDY	ΔDX	ΔDZ	ΔDP	ΔDV
	[MM]	[MM]	[MM]	[MM]	[MM]
11	0,0	-1,6	-2,4	1,6	2,9
12	0,0	-0,6	-1,0	0,6	1,2
13	0,1	-0,7	-1,5	0,7	1,7
21	-2,9	**5,5**	0,0	6,2	6,2
22	-1,8	**3,9**	0,9	4,3	4,4
23	-0,9	2,2	0,2	2,4	2,4
24	-1,1	2,2	-0,5	2,5	2,5
25	-1,9	2,3	-1,9	3,0	3,5
26	-1,5	1,3	-1,9	2,0	2,7
32	0,4	**5,8**	0,6	**5,8**	**5,8**
33	0,1	**4,1**	0,0	4,1	4,1
34	-0,1	**3,2**	-0,8	3,2	3,3
35	-0,1	**3,3**	-1,4	3,3	3,6
36	-0,4	**3,3**	-1,6	3,3	3,7
41	**3,8**	**7,9**	1,5	**8,8**	**8,9**
42	2,5	**5,8**	0,3	**6,3**	**6,3**
43	1,3	**4,0**	-0,4	4,2	4,2
44	1,1	**2,9**	-0,8	3,1	3,2
45	1,0	**2,9**	-1,8	3,1	3,6
46	0,6	2,0	-0,8	2,1	2,2
52	2,6	2,5	-1,6	3,6	3,9
53	0,1	1,3	-1,7	1,3	2,1
310	0,8	**8,1**	1,0	**8,1**	**8,2**
510	0,6	1,3	0,5	1,4	1,5

b)

POINT	DY	DX	DZ	DP	DV
	[MM]	[MM]	[MM]	[MM]	[MM]
11	2,6	-2,0	0,9	**3,3**	**3,4**
12	0,5	0,0	0,7	0,5	0,9
13	0,5	-1,0	-0,1	1,1	1,1
21	1,3	2,9	2,9	**3,2**	**4,3**
22	0,1	2,2	3,0	2,2	**3,7**
23	1,8	1,0	2,3	2,1	**3,1**
24	**3,3**	-0,8	1,6	**3,4**	**3,8**
25	2,2	-0,7	-1,3	2,3	2,6
26	1,6	-0,2	-2,3	1,6	2,8
32	**3,9**	2,9	3,1	**4,9**	**5,8**
33	**3,5**	1,4	2,7	**3,8**	**4,6**
34	2,9	-1,5	1,0	**3,3**	**3,4**
35	2,3	-1,5	0,3	2,7	2,8
36	2,5	-0,8	-1,7	2,6	3,1
41	7,9	6,9	1,9	10,5	10,7
42	**6,8**	**5,9**	2,3	**9,0**	**9,3**
43	**5,6**	**3,8**	2,1	**6,8**	**7,1**
44	**3,8**	0,7	0,4	**3,9**	**3,9**
45	**4,1**	0,9	-1,2	**4,2**	**4,4**
46	**3,4**	0,3	-0,9	**3,4**	**3,5**
52	**6,4**	**3,4**	-0,7	**7,2**	**7,3**
53	**3,7**	1,3	-0,5	**3,9**	**4,0**
310	1,5	-1,6	-0,1	2,2	2,2
510	0,8	1,6	1,8	1,8	2,5

(*)

- Dy = longitudinal horizontal displacement; (+) in the direction from the right to the left bank, (-) in the direction from the left to the right bank.
- Dx = cross-horizontal displacement; (+) in the direction downstream-upstream (towards the reservoir), (-) in the direction upstream-downstream.
- Dz = vertical displacement; (+) upward, (-) downward.
- Dp = $(Dx^2 + Dy^2)^{0.5}$ (total horizontal displacement).
- Dv = $(Dx^2 + Dy^2 + Dz^2)^{0.5}$ (total vertical displacement).
- Dx, Dy, Dz, Dp и Dv refer to cumulative displacements (for multiple series).
- ΔDx, ΔDy, ΔDz, ΔDp и ΔDv refer to partial displacements (when comparing the values between two consecutive series of measurements).

All of these points, like most of the rest, are displaced towards the reservoir, even though the measurement in the series 30 was carried out after raising the reservoir water level from the elevation 309.83 m.a.s.l. to the elevation higher than 315 m.a.s.l. Only the points 1, 12 and 13 (with values -1.6, -0.6 and -0.7 mm), which are closest to the zone of the cracks, are moved downstream, and the point 13 is in their immediate vicinity. This indicates the complexity of the external influences on the behavior of the dam. Namely, although the series 29 and 30 are recorded at a similar water level, that is, at full reservoir, other elements, such as air and water temperature, the fact that shortly before the recording of the series 30 the reservoir was longer at a low water level at high outside temperatures - left an appreciable reflection to the behavior of the dam.

Table 2
Partial horizontal displacements ΔDx at certain points measured in series in which relatively high absolute values are obtained

POINT	SERIE/	RECORDED	ΔDX	POINT	SERIE/	RECORDED	ΔDX
		MONTH, YEAR	[MM]			MONTH, YEAR	[MM]
21	10/9	VII 1991 - I 1988	**8,0**	41	10/9	VII 1991 - I 1988	**8,5**
	11/10	IV 1993 - VII 1991	-5,6		11/10	IV 1993 - VII 1991	**-7,2**
	30/29	VII 2012 - XI 2011	5,5		30/29	VII 2012 - XI 2011	**7,9**
22	10/9	VII 1991 - I 1988	6,6	42	10/9	VII 1991 - I 1988	**7,4**
	11/10	IV 1993 - VII 1991	-4,6		11/10	IV 1993 - VII 1991	-6,4
	30/29	VII 2012 - XI 2011	3,9		30/29	VII 2012 - XI 2011	5,8
32	10/9	VII 1991 - I 1988	**7,1**	43	10/9	VII 1991 - I 1988	6,0
	11/10	IV 1993 - VII 1991	-5,9		11/10	IV 1993 - VII 1991	-5,3
	30/29	VII 2012 - XI 2011	5,8		30/29	VII 2012 - XI 2011	4,0
33	10/9	VII 1991 - I 1988	5,7	44	10/9	VII 1991 - I 1988	5,0
	11/10	IV 1993 - VII 1991	-5,3		11/10	IV 1993 - VII 1991	-4,7
	30/29	VII 2012 - XI 2011	4,1		30/29	VII 2012 - XI 2011	2,9
34	10/9	VII 1991 - I 1988	4,5	45	10/9	VII 1991 - I 1988	4,9
	11/10	IV 1993 - VII 1991	-4,8		11/10	IV 1993 - VII 1991	-4,7
	30/29	VII 2012 - XI 2011	3,2		30/29	VII 2012 - XI 2011	2,9
35	10/9	VII 1991 - I 1988	5,2	46	10/9	VII 1991 - I 1988	4,8
	11/10	IV 1993 - VII 1991	-5,2		11/10	IV 1993 - VII 1991	-4,3
	30/29	VII 2012 - XI 2011	3,3		30/29	VII 2012 - XI 2011	2,0
36	10/9	VII 1991 - I 1988	4,9	310	11/10	IV 1993 - VII 1991	**-7,4**
	11/10	IV 1993 - VII 1991	-4,6		30/29	VII 2012 - XI 2011	**8,1**
	30/29	VII 2012 - XI 2011	3,3				

Table 1b shows the cumulative displacement between the series 30 and the series 6 (recorded in April 1985). The horizontal cumulative displacements reach up to 7.9 mm for Dy, or 6.9 mm for Dx (point 41). These values are also reflected in correspondingly higher values for total cumulative horizontal displacements Dp (max 10.5 mm) and total vertical displacement Dv (max 10.7 mm). It should be noted here that in Table 1b the cumulative values for the displacements in points 310 and 510, set in addition, refer to the series recorded in 1991 (for point 310) and 1994 (for point 510).

Below is given an analysis of the partial horizontal displacements Dx, measured in series in which relatively high absolute values are obtained at the selected points, Table 2. The values for Dx at an absolute value greater than 7 mm are given in bold, to show the points in which partial values close to the maximum measurements in the series 30/29 has appeared, namely 8.1 mm (point 310) and 7.9 mm (point 41), Table 1a, when cracks were registered in the arches VIII and IX. It can be seen that similar values (from 7.1 to 8.5 mm) appeared in the series 10/9 in points 21, 32, 41 and 42, then in series 11/10, again in points 41 (-7.2 mm) and 310 (-7.4 mm), but in reverse direction. This may be an indication that the larger partial values of horizontal displacements measured in 2012 compared to 2011, compared to the corresponding values registered in the previous years, do not cause the occurrence of cracks in the arches VIII and IX, but that the reason probably should be searched in high stresses caused by temperature changes.

3.3. ANALYSIS OF DAM AND RESERVOIR CONDITIONS IN THE MONTHS BEFORE THE APPEARANCE OF THE CRACKS

During the winter period 2011/2012, the reservoir Matka was mainly full and by the middle of March 2012 the water was above the arc IX. The temperature of the water ranged from 4 to 7 C°, and of the air from 0 to 14 C°. On March 16, the water level was lowered to an elevation of 311.98 m.a.s.l., i.e. 2 cm below the lower edge of the arch IX, at an air temperature of 2-17 C°, and on the water 7 C°. By the end of March, the water elevation varied from the minimum 311.78 m.a.s.l. on March 29, at T_{water} = 11 C° and T_{air} = 8-22 C°, up to the maximum of 313.73 m.a.s.l. on March 19, at T_{water} = 6-9 C° and T_{air} = 7-22 C°. It can be concluded that during March 2012 there were no major variations and differences in water and air temperature that could cause appreciable stresses in the concrete dam. During April 2012, the reservoir elevation was relatively constant and varied between 311.50 and 312.32 m.a.s.l., i.e. it was held around the lower edge of the arch IX, at a water temperature of 9° C to 13° C, and in the air from 0 C° to 29 C°. The last days of April were warmer than usual for that time of the year, so from April 26 to April 30, the water temperature was 12 C°, while the air temperature ranged from 9 C° to 29 C°. During that period, as well as during almost the entire month of April, the arch IX was exposed to heat from the air on both sides.

May 2012 is interesting from the aspect of exposure of the arch IX on temperature effects. From 1 to 13 May the high temperatures of the air, occurring in the last 5 days of April, continue, and the minimum ranges from 13 C° to 16 C°, and the maximum from 26 C° to 31 C°. In addition, the upper water level, as well as for almost the entire month of April, was located around the lower edge of the arch IX, and had a temperature of 12-14 C°. In the second half of May, the upper water level was higher and ranges from 312.08 to 314.07 m.a.s.l. From May 17 until May 31 it was practically at a constant elevation of 314 meters, which means 1 m below the upper edge of arch IX. At the same time, the air temperature was somewhat lower, compared to the first 12 days of the month, and ranges from a minimum of 9 C° to a maximum of 27 C°, while the water temperature was similar to that in the previous period and ranges from 11 to 14 C°.

Table 3
Temperature of the water, air, and water elevation in the days from 9 to 30 June 2012

DATE	T_{WATER}	T_{AIR}	WATER ELEVATION
	MIN - MAX	MIN - MAX	MIN - MAX
D/M/Y	C°	C°	[M.A.S.L.]
09.06.2012	14	18 - 33	314,00
10.06.2012	14 - 15	19 - 34	313,51 - 314,03
11.06.2012	14 - 15	17 - 32	311,95 - 313,51
12.06.2012	15 - 16	17 - 34	311,99 - 312,01
13.06.2012	15 - 16	19 - 35	311,98 - 312,01
14.06.2012	15 - 16	16 - 32	311,94 - 311,99
15.06.2012	15 - 16	15 - 33	311,83 - 311,94
16.06.2012	15 - 16	17 - 34	311,65 - 311,83
17.06.2012	15 - 16	20 - 34	311,43 - 311,66
18.06.2012	16	20 - 34	311,17 - 311,44
19.06.2012	16	18 - 35	310,88 - 311,17
20.06.2012	16	20 - 36	310,52 - 310,88
21.06.2012	16 -17	21 - 36	310,11 - 310,52
22.06.2012	16 - 17	19 - 36	309,88 - 310,11
23.06.2012	17	19 - 36	309,84 - 309,89
24.06.2012	17	19 - 34	309,79 - 309,84
25.06.2012	17	20 - 32	309,83 - 309,84
26.06.2012	17	20 - 30	309,81 - 312,29
27.06.2012	16 - 17	18 - 29	312,29 - 315,12
28.06.2012	12 - 13	18 - 32	315,27 - 315,69
29.06.2012	11 -13	20 - 35	315,38 - 315,69
30.06.2012	11 - 13	20 - 35	315,38 - 315,69

From the beginning of June 2012 to June 10, the water in the reservoir remained at a constant level of 314 m.a.s.l., as well as in the majority of the second half of the previous month. At the same time, the temperature of the air increased and on June 10 reached 34 C°. In parallel, the water temperature also increased, from 11 C° on June 1, at 15 C° on June 10. Table 3 presents the temperature of the water for the days from June 9 to June 30, air, and elevation of the upper reservoir water, respectively. On June 10 and 11, the reservoir water level was lowered to 313.51 m.a.s.l, and 311.95 m.a.s.l., respectively. Next days, until June 15, the water level practically stagnated at 312.00 m.a.s.l., i.e. at the lower edge of the arch IX, at high maximum daily air temperatures of 32-35 C°, minimum of 17-19 C°, and water temperature of 14-16 C°. On June 16, the water level droped, and from 311.83 pm, after 7 days, on June 22, it fell to 309.88 m.a.s.l., which was less than 1 meter above the lower edge of arch VIII. A similar elevation, below 310 m.a.s.l., with negligible variations, was held until June 26, Table 3. During this period (June 15-22), the air temperature was extremely high for the region of the Treska canyon, reaching a maximum value of 33-36 C° and a minimum of 15-21 C°. At an elevation slightly below 310 m.a.s.l., the water level stagnated for the next few days, until June 26. And in these few days, the air temperature was high and it was 30-36 C°, with minimum daily values of 19-20 C°, while the water temperature was 16-17 C°.

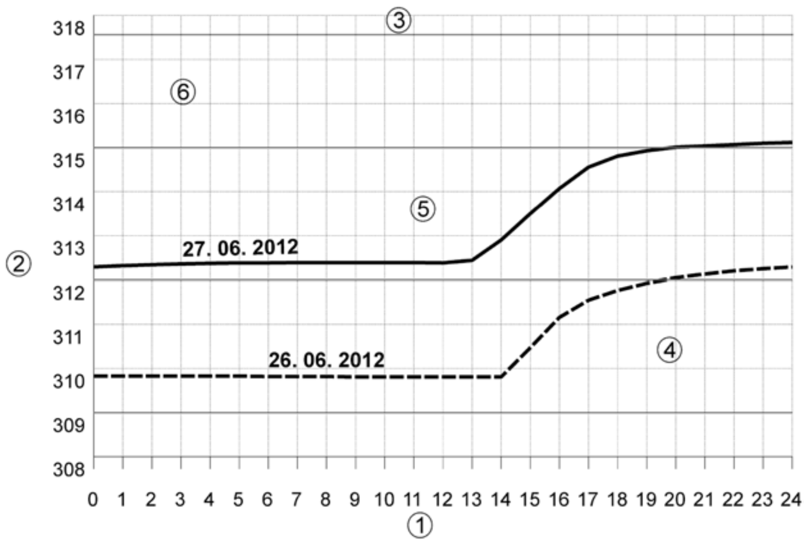

Fig. 4

Graphical presentation of the Matka reservoir filling on June 26 and 27, 2012

Présentation graphique du remplissage du réservoir Matka les 26 et 27 juin 2012

1	Hours	*1*	*Heures*
2	Water level (m)	*2*	*Niveau d'eau (m)*
3	Dam crest	*3*	*Crête de barrage*
4	Arch VIII	*4*	*Arc VIII*
5	Arch IX	*5*	*Arc IX*
6	Arch X	*6*	*Arc X*

On June 26, in the afternoon, the reservoir filling started, when the water level was raised from the elevation 309.81 m.a.s.l. to an elevation of 312.29 m.a.sl., or a total of 2.46 m. The highest growth rate was observed from 14 h to 16 h, in the amount of 0.66 – 0.69 m/h, after which in the next two hours it dropped to 0.39 m/h. On that day, the air temperature ranged from a minimum of 20 C° to a maximum of 30 C°, while the water temperature was 17 C°. Raising the upper water level continued on June 27, when it was increased from elevation 312.29 m.a.s.l. to elevation 315.12 m.a.s.l, which means a total of 2.83 m, with a highest intensity from 13 h to 17 h, 0.46 – 60 m/h.

Figure 4 gives a graphical representation of the reservoir Matka filling, carried out on June 26 and June 27, 2012. The drawing also shows the edges of the top three arches of the dam – VIII, IX and X. From the graphs it is clearly visible that on June 26, between 14 h and 19 h, the water submerged the upper 2/3 of the arc VIII, previously exposed to warm air. The next day, with the greatest intensity between 13 and 17 o'clock, was also completely submerged the upper arch IX. In the next three days, from June 28 to June 30, the upper water level was increased to 315.69 m.a.s.l., the temperature of the air remained high, while the drop in the water temperature from 17 C° to 11-13 C° was noticeable, due to the fact that the reservoir Matka was filled with cold water supplied from the upper hydroelectric power plant in the frame of the hydraulic scheme Kozjak.

It is obvious that the extremely high temperatures, at which both arches were exposed, not only from the downstream, but also from the upstream side in June, especially in the period from 15 to 26 June, caused their expansion and leakage after raising the reservoir level on June 26 and 27, which made it possible to become visible. With both cracks, te arches VIII and IX, in which, like all others in the body of the Matka dam, vertical joints were not made during the construction, they formed natural joints in the zone of high tangential and tensile stresses occurring at extremely unfavorable combinations of temperature loads. Thus, the expansion of the cracks was a result of bouth climatic and human factors, because the reservoir was emptied, and then filled up at a high rate, under unfavorable environmental conditions.

3.4. Restoration of the cracks

The two recorded cracks did not jeopardize the stability of the dam. Namely, both arches VIII and IX are located in the upper part of the dam, so they are exposed to relatively low water pressure. Nevertheless, it was concluded that the cracks should be repaired, first of all in order to protect the surrounding concrete from aging and the reinforcement from corroding under the influence of the water that penetrates. To observe the behavior of the cracks, in May 2013 one-axial gauges for measurement of the crack's width and the acquisition of the data received, were installed. For the period May 2013 – December 2015, the registered characteristic widths of the cracks are shown in Table 4. In the same period no change in the length of the cracks was observed, compared with those measured in July 2012. The table shows that the measured widths of the cracks are smaller compared to the ones estimated in the July 2012 inspection.

Table 4
Width of the cracks for the period May 2013 - December 2015

CRACK'S WIDTH	MAX [MM]	MIN [MM]	MEAN [MM]	MAX-MIN [MM]
Crack 1 (on arch IX)	0,068	0,042	0,058	0,026
Crack 2 (on arch VIII)	0.575	0.111	0,262	0,464

In the second half of 2015 a basic project for repairing the cracks was made. The purpose of the rehabilitation was to ensure the two dam arches in which cracks occurred to be monolith and waterproof. In doing so, a request was made to completely stop leaks through cracks as a criterion for successful remediation. During the elaboration of the basic project, thermal imaging of the cracks was performed, as well as their injecting with a colored liquid to obtaining important knowledge for the preparation of the remediation solution. The trial boreholes were carried out in the zone of relatively dry cracks in order to determine the penetration of the liquid by the test injection. It was found that at a depth of 10 cm there is a wet zone, limited to a relatively small area. After the injection of a colored liquid with a pressure of up to 50 bars, there was no penetration of the liquid to the upstream side through the dry and wet parts of the cracks. From this it can be concluded that the cracks do not stretch over the entire thickness of the dam arches. Thermal imaging has determined surface zones of concrete at a lower temperature, which indicate that in those zones there is a filtration of water from the reservoir. By visual inspection of these zones, insignificant filtration, i.e. wetting through the body of the dam, was determined.

It was concluded the restoration of the cracks to be performed by grouting. The trial injection helped to prepare a recipe for grouting of cracks, with strong technical characteristics of the adopted materials for preventing the filtration of water through them and constructive monolithization of the concrete. Within the preparation of the basic design, the manufacturer of the grouting materials (TPH Germany) confirmed the accepted grouting mix and certificated the materials for the preparation of the grouting mass. On the basis of the basic project prepared, the grouting of the cracks was completed within ten days in July 2016, with application of the prescribed safety conditions. With the regular technical surveillance of the dam in 2016 it was concluded that in the zone of the cracks there is no moistening of the concrete. With the rehabilitation project it was recommended that if it is eventually necessary the water level in the reservoir to be significantly reduced, such operation to be done in autumn or spring, when the air and water temperatures are approximately equal.

4. CONCLUSION

At Matka arch concrete dam, the oldest dam built in the Republic of Macedonia, 29.5 m in height, in July 2012, two cracks in the upper dam arches were visually recorded, located in the immediate vicinity of the right abutment, through which a small amount of water licked. In order to find the possible reasons for appearance of the cracks, main attention was paid to the analysis of the measured displacements on the downstream dam face, as well as to the dam and reservoir conditions in the months before the appearance of the cracks. The displacements recorded in the last two series of measurements (2012/2011) were in order of magnitude up to 9 mm, which were also recorded earlier, so that they were rejected as the cause of the cracks. The analyses of the dam and reservoir conditions in the months before the appearance of the cracks showed that since June 16 to June 26, 2012, the reservoir water level was kept low, and the water surface was bellow the cracks. In the same time the air temperature was extremely high for the usual Matka dam site conditions, reaching a maximum value of 33-36 C° and a minimum of 15-21 C°. On June 26 and 27, the reservoir was quickly filled with relatively cold water, which caused high temperature stresses in the previously heated upper section of the dam. They widened the cracks, for which there were indications that had occurred earlier.

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