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STATIC AND DYNAMIC ANALYSIS OF STRESS AND DEFORMATIONS OF RĂSTOLIŢA DAM

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ABSTRACT

Large Dams are a particularly important case of seismic risk assessment. On the one hand, the dams themselves have a high value, having implications for the whole economy, through the production of electricity, water supply systems for irrigation and flood prevention etc. On the other hand, structural damage of a dam can lead to major disasters, the population exposure to effects caused by sudden floods. The situation in Romania is such that attention should be paid to the future safety of existing dams. The first reason is that these dams were designed and constructed on the basis of technical rules, which the majority are no longer in force; a second reason is the major climate changes in the last period, which have led to the accumulation of a large volume of water in increasingly large lakes. A third reason is, logically, the length of existing dams. In this paper is analysed the stress - deformation state that occurs in Răstoliţa dam body according to the type of rockfill; calculations were done for two cases, namely the completion of construction and, respectively, at the first filling of dam with water. The results show that after completion of construction, the maximum settlement is recorded in the central area of the dam, below the middle third; horizontal displacements of downstream prism are significantly higher compared to deformations of the upstream prism, in the area where the used material has a higher compressibility. Maximum principal normal stress registers some local distortions within acceptable limits; minimum principal normal stress presents important gradients in the contact zone downstream dam slope in the Ist stage with tuff-pyroclastic embankment layer and also in the first three layers of intercalated filling disposed near the slope. Stress increases due of hydrostatic pressure after the first filling does not lead to occurrence of stress concentrations in other zones than those reported at the completion of construction.

KEYWORDS: dam, static analysis, dynamic analysis, stress, deformations

1. Geological and geotechnical characteristics of dam emplacement

The dam was conceived as having 38 million m^3 available storage of water, which is done with a normal retention to the elevation 760 mdM, to minimum geometrical dimensions, to assure the hydroelectric power functionality of hydrotechnics schema. The solution proposed for Răstoliţa dam was to realize an impounding with normal retention level at 720 mdM, imposed by elevation and hydraulic load conditions of the adduction - energetic tap at elevation 700 mdM [9]. In order to optimize through the constructive solutions and investment parameters, the achievement in stages of Răstoliţa dam was provided; in the first stage, this was achieved with normal retention to elevation 720 mdM. To create the conditions of achieving the storage reservoir of the stipulated parameters, namely the retention level to the elevation 760 mdM, all parts afferent to the dam were sized according to the resistance and hydraulic criteria corresponding to the dam with normal retention (NNR) to the 760 mdM elevation. The dam is under construction on Răstoliţa river, right tributary of Mures, in the area of Topliţa – Deda clough. The constructive solution of Răstoliţa dam is rockfill dam with reinforced concrete apron (lutting wall) [1-3]. Data concerning the geology and hydrogeology of the studied area have highlighted that the rocks of Răstoliţa dam emplacement are composed of volcanic agglomerates (pyroclastics) and of volcanic ashes, where, locally, it intercalates hard cracked andesite and sometimes altered. There were analysed the rocks intercepted by drillings F2 and F4 (see Figure 1), rocks consisting of pyroclastics appearance microconglomeratic, about 87 % of samples, volcanic ash cemented, about 7 % and andesites in a percentage 6 % [9].

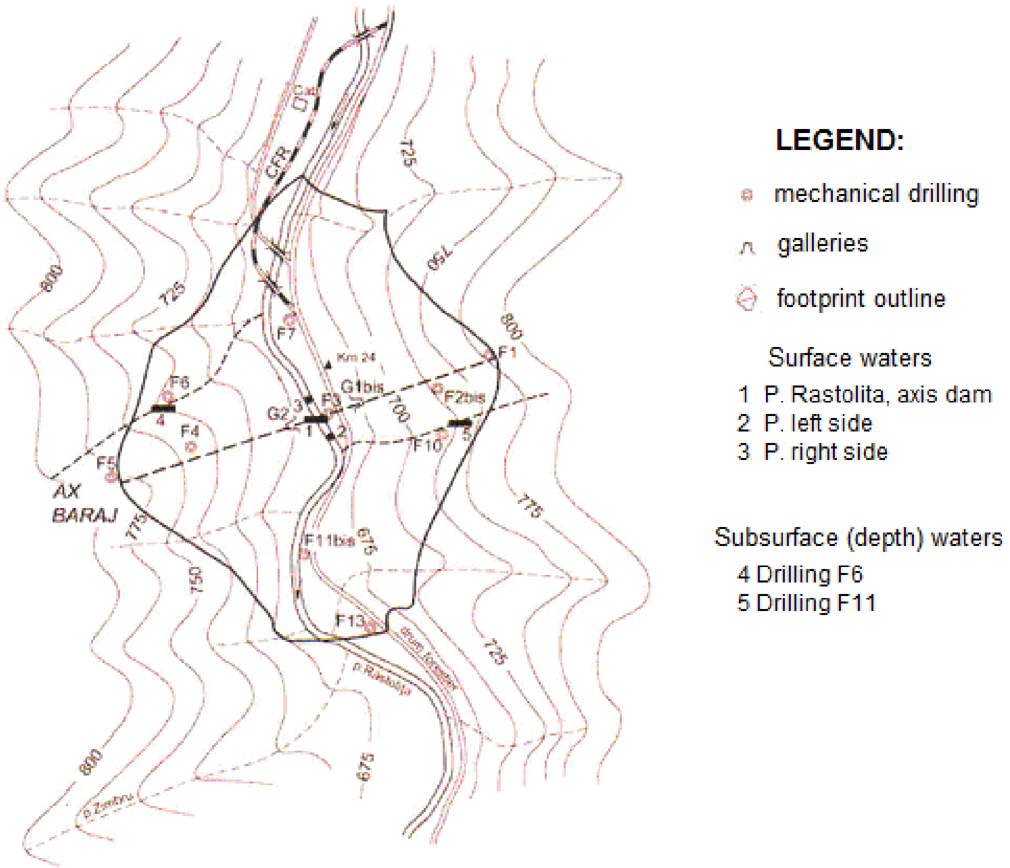

***Fig. 1.** Map of drillings of rock' sampling*

Compared to the studied samples from drillings F3 and F7, where the percentage of rocks types mentioned above were 70 %, 12 % and 18 %, in drilling F2 have been identified pyroclastics areas that were more altered with a reddish rusty colour, cracked and damaged. The number of processed and studied samples and specimen from F2 and F4 drillings were:

a) drilling F2, from 2 m to 47.3 m; 26 samples; 73 specimens;

b) drilling F4, from 7.3 m to 21.2 m; 9 samples; 21 specimens.

Laboratory tests consisted in determining the following geotechnical characteristics: apparent specific density, porosity, absorption of water at normal pressures and temperatures, compressive breakage strength, shear breakage strength, velocity propagation of sonic waves, static and dynamic modulus of elasticity, dynamic Poisson's coefficient.

For all laboratory tests, samples provided from drillings have been processed by core drilling machine equipped with diamond disc and water cooling system. The shape and size of specimens were those indicated by standards, namely, there were carried out cubic samples with a side dimension of 5 cm, respectively, prismatic samples with dimensions of 4 x 4 x 16 cm, respecting the test methodology according to standards. The values of physical – mechanical and elastic characteristics are shown in Table 1. The values obtained show that the rocks provided from drillings F2 and F4 of Răstoliţa footprint dam, left side and right one, have similar characteristics with rocks intercepted by drillings F3 and F7, dam - bottom footprint, drawing in ranges of variation shown in Table 1, where between brackets are given the values obtained in stage I of research, drillings F3 and F7.

By analysing these values, it is noted a wide range of variation of characteristics established in laboratory, especially for pyroclastics and volcanic ashes, which cannot be correctly separated as kind of petrographic types. In very different percentages in same pyroclastic sample occur fragments of andesite (as number and size) relating to cementing material composed of volcanic ash. Moreover, for samples resulted from cores extracted from F2 drilling also appear altered pyroclastics areas, identified between 2.00 m and 20.00 m which contributes to diminishing of mechanical characteristic values.

***Table 1**. Variation range of geotechnical characteristics of rocks from Răstoliţa dam area*

No	Geotechnical characteristic		Rock and variation range of characteristic		
			Pyroclastic	Volcanic ashes	Andesite
1.	Specific density, g/cm³		2.73 – 2.76 (2.72)	2.73 (2.70)	2.81 (2.80)
2.	Apparent specific density, g/cm³		1.58 – 2.66 (1.90 – 2.40)	1.76 – 2.01 (1.53 – 1.99)	2.20 – 2.48 (2.3 – 2.73)
3.	Porosity, %		13.0 – 34.0 (11.0 – 30.0)	27.5 – 28.5 (26.0 – 40.0)	12.5 – 16.2 (3.0 – 10.0)
4.	Absorption of water at normal pressures and temperatures, %		5.4 – 21.5 (2.2 – 13.7)	- (3.65)	1.5 (0.8 – 5.2)
5.	Compressive breakage strength of rocks in natural state, daN/cm²		27 – 220 (50 – 300)	89 – 155 (100 – 150)	280 (300 – 1170)
6.	Shear parameters	φ, grade	13 – 42 (15 – 43)	40 (10 – 40)	- (17 – 34)
		C, daN/cm²	14.9 – 49.3 (4.2 – 50.0)	12.2 (16 – 30)	- (170 – 265)
7.	Longitudinal velocity of sonic wave, m/s		1700 – 4100 (1,300 – 3,600)	2,200 – 2,600 (1,600 – 2,500)	4,400 – 4,700 (2700 – 4,400)
8.	Static modulus of elasticity, daN/cm²		57,000 – 12,4000 (33,000 – 190,000)	5,500 – 39,600 (-)	51,0000 (447,000 – 640,000)
9.	Shock strength, daN/cm²		(6 – 12)	(-)	(-)

2. Răstoliţa dam characteristics

Răstoliţa dam is under construction, on the river with the same name, right affluent of Mureş River, in the area of Topliţa – Deda Clough. The solution proposed and approved for achieving this dam is of rockfill, with reinforced concrete apron; the characteristics of dam are presented in Table 2.

Dam body is made of rolled rockfill in layers of 1 m. In cross profile of transversal type, from upstream to downstream, the following zones were adopted:

1.B. – *rockfill protection layer* made in the upstream face of protection prism;

2.B. – *dusty – clayey material* in upstream prism, with the role to prevent the infiltrations by any accidents to the joint fireplace – concrete apron, in the most loaded region of dam;

1.A. – *reinforced concrete apron*. Reinforced concrete apron designed for Răstoliţa dam is a reinforced concrete element of variable thickness between 0.30 m to crest of wave and 0.50 m to the lowest level of concrete apron, namely to 662.00 mdM. On the dam height, the thickness variation of concrete apron is linear:

$$t = 0.30 + K\ H \quad [m] \qquad (1)$$

***Table 2.** Main characteristics of Răstoliţa dam*

Crest of wave level (mdM)	Large dam (crest of wave at 765 mdM)	Dam – IInd stage (crest of wave at 725 mdM)
Maximum height, m	103	63
Crest of wave length, m	320	240
Total volume of dam, m³	3400,000	895,000
Ist type rockfills - andesite, m³	1580,000	795,000
Support layer concrete apron, m³	87,000	37,000
Transition layer, m³	104,000	34,000
Other zones (upstream prism, downstream protection), m³	129,000	29,000

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Where: t is the concrete apron thickness; K = 0.002; H – depth measured from the maximum water level, that in case of Răstoliţa dam is 103 m (H = 765 – 662 = 103 m).

Between reinforced concrete apron and rockfill prism are provided two zones, namely:

2.A. *Support layer of concrete apron*: crushed material graded Φ = 0 – 70 mm, and the coefficient of permeability $K = 10^{-3} – 10^{-4}$ cm/s. The role of this zone is:

a) to ensure uniform and resistant support of reinforced concrete apron;
b) to avoid deviations from the theoretical profile of reinforced concrete apron;
c) by controlled distribution of sizes, it ensures a semi-permeable barrier that prevents the important infiltrations, even in case of preferential leak paths in cracks of concrete or defects joint sealing of reinforced concrete apron.

Composition of zone ensures the workability on layer.

3.A. *Transition layer from crushed material* graded Φ = 0 – 300 mm, and the coefficient of permeability $K = 10^{-2}$ cm/s. Zone 3A works as an inverse filter between zone 2A and rockfill and also has the role to ensure free drainage of eventual water infiltrated by zone 2A.

3.B. *Quarry rockfill type I (andesite)* deposited in layers of 1 m.

Faces of wall slopes of resistance prisms are established based on verifying calculations through stability, deformations and stresses, having the following values:

Upstream	1:1.4 until level 1:2.5 until thalweg from 600 mdM and until thalweg situated at approximatively level of 622.00 (the prism is carried out after constructing dam concrete apron)
Downstream	1:1.7

Downstream face slope is a theoretical slope, without taking into account the access road that is carried out on the downstream face.

In order to achieve Răstoliţa dam, the followings have been considered:

- crest of wave level, 725 mdM
- NNR, 720 mdM
- V_{lake} = 6.5 mil. m^3
- $V_{embankment}$ = 889.176 m^3

In order to achieve the calculations, for the characteristics of component materials of embankment were used theoretical values shown in Table 3.

***Table 3**. Theoretical values of materials characteristics of embankment*

Material	Material characteristics				
	$E_s(x)$, [tf/m^2]	$Y_d(x)$, [tf/m^2]	μ(x)	Φ [degree]	C, [tf/m^2]
Support layer Φ = 0 – 70 mm, $K = 10^{-3} – 10^{-4}$ cm/s	7,000	2.0	0.30	37.5	2.0
Transition layer Φ = 70 – 300 mm, $K = 10^{-2} – 10^{-3}$ cm/s	5,000	2.0	0.30	37.5	2.0
Rockfill sorted drain	5,400	2.02	0.35	37.5	3.1
Rockfill type I (andesite)	5,400	2.02	0.35	37.5	3.1
Rockfill type II (pyroclastic)	3,000	1.72	0.30	33.5	4.4
Protection rockfill type	5,400	2.02	0.35	37.5	3.1
Dusty-clayey local material	1,900	1.46	0.40	9.0	11.2
Alluvium and altered pyroclastics (xx)	100,000	1.8	0.36	-	-
Unaltered pyroclastics (bedrock) (xx)	150,000	2.05	0.31	-	-

3. Limiting solutions of support deformations of concrete apron dam

Adopted solutions are considering limiting the deformations of concrete apron support to values that can be taken over by reinforced concrete element, Fig. 2 – Fig. 5. Essentially, dam deformations are shown out below.

Fig. 2. *Solution to achieve the dam concrete apron*

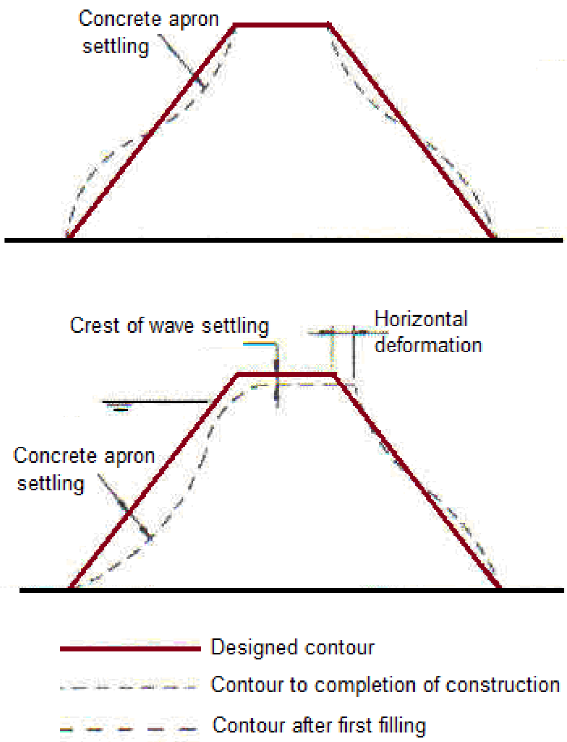


Fig. 3. *Diagrams of deformation for rockfill dam (according to Mori, 1999)*

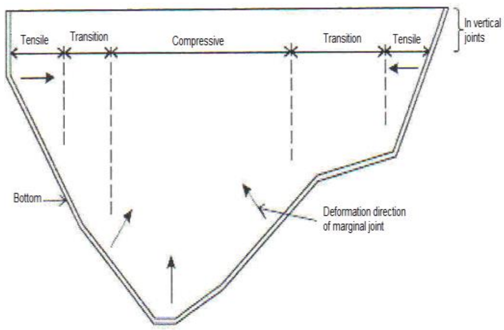


Fig. 4. *Upstream view of dam concrete apron: deformation directions and stresses types that appear*

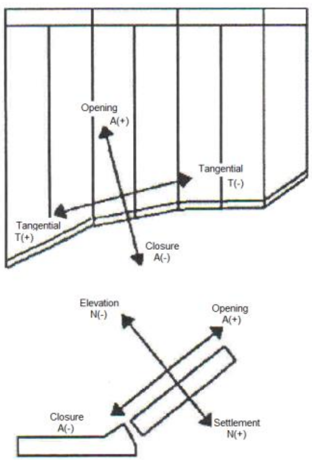


Fig. 5. *Deformation directions of marginal joint*

3.1. Static analysis of stresses and deformations

The existence of an important layer of tuff as lower quality rock from Albu rockfill quarry, which must be removed or used in a certain way, in order to enable its continuing exploitation, imposed the achievement of specific calculations of efforts and deformations, calculations to model the use of tuff in an appropriate zone of the dam body and the impact on the behavior at the first filling, namely the behavior in current exploitation [4-7]. Thus, it was modelled the use of tuff deposited in layers of 0.75 m thickness in the downstream prism of 3C zone of dam, intercalated with pyroclastic layers, operation that seeks a massif with better physical - mechanical characteristics than the weakest material, appropriate to the structure and stresses state from the area of deposit [6-8]. Analysis took into account the following:

- assessing horizontal and vertical movements during depositing the fillings layers from dam body at the end of construction and at the first filling of lake;
- assessing through static and dynamic stresses and deformations state in dam body;
- Establishing the maximum number of layers, its geometrical positioning and assessing stress and deformations state so that whole dam presents a good behavior without stress concentrations or the occurrence of plastic parts in all stages of analysis.

Stress and deformations state analysis in body dam was carried out by assuming nonlinear - elastic (hyperbolic) behavior of the material of dam body based on Duncan – Chang model, which admits elastic - plastic Mohr – Coulomb failure criterion. Hyperbolic characteristics obtained from triaxial tests both with determining of shear and Duncan - Chang parameters of volcanic tuffs were analysed by GEOTEC, the purpose of these determinations being motivated by the planning works of quarry on Albu creek which revealed layers of material with unexplored qualities until then have, namely volcanic tuff. Through the same study, were also supplied the basic static and dynamic geotechnical parameters of material from the rockfill quarry (Fig. 6).

Calibration of secant modulus for andesites and pyroclastics was made from curves analysis of vertical stresses - specific deformations by interpreting the measurements from DVT placed in the filling carried out at given time in dam footprint.

Peer values of stress – vertical specific deformation appropriate of fillings level allowed plotting stress - deformation curves for both prisms. In the first phase, secant modulus of rockfill resulted directly from plotted curves that have proved very low values due to the fact that calculated specific deformations include also deformations from creep; this is the consequence of slow execution and big breaks to achieve the fillings.

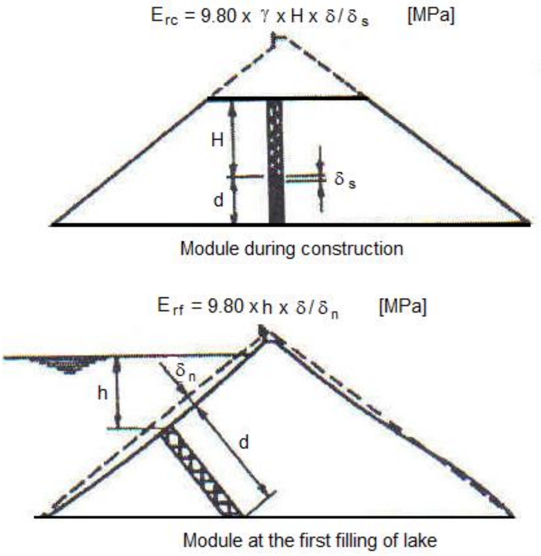


Fig. 6. *Rockfill modulus defining E_{rc} and E_{rf} (according to Fitzpatrick et al., 1985)*

Model calibration and the choice of final secant modulus were carried out admitting certain instantaneous specific deformations affected with (40 – 70 %) from measured total deformation; within a certain error, parametrical calculation have validated the adopted model (Table 4, Table 5, Fig. 7).

According to geotechnical study, all rockfill types (andesites, pyroclastics, volcanic tuff) are characterized by a wide range of variation of physical - mechanical characteristics; this is a reason why in calculations it was associated with a set of pessimistic values of basic geotechnical parameters (bulk density, angle of internal friction, static and dynamic Poisson’s coefficient) and also Duncan – Chang parameters for volcanic tuff already established from geotechnical study developed by GEOTEC (Fig. 8).

Table 4. *Laboratory tests results*

σ [kN/m^2]	$\varepsilon_{instantaneous}$	E_{def} [kN/m^2]	ε x 1000
14.52	0.0002	72,600	0.20
29.05	0.0004	72,625	0.40
43.57	0.000575	75,774	0.575
56.02	0.000725	77,269	0.725
72.61	0.0009	80,678	0.90

Table 5. *Determining the initial tangent modulus of deformation - measured values of vertical settlement cells (CV)*

Plaque	Settlements Time [months]			h [m]	Deformations			$Y_{rockfill}$	Stress, σ [kN/m²]	Deformation module E_d [kN/m²]
	0	7	10		ε = Δh/h [mm]	$\varepsilon_{instantaneous}$ (absolute value)	ε x1000			
CF	0	-13	-476							
P1	0	-10	-143	2.384	-0.004195	0.000419	0.419	20.30	48.395	115,374
P2	0	-10	-136	2.914	-0.003432	0.000515	0.515	20.30	59.154	114,917
P3	0	-9	-161	2.963	-0.003037	0.000456	0.456	20.30	60.149	132,016
P4	0	-16	-76	3.877	-0.004127	0.000619	0.619	20.30	78.703	127,138
P5	0	-19	-169	2.955	-0.00643	0.000964	0.964	20.30	59.986	62,194

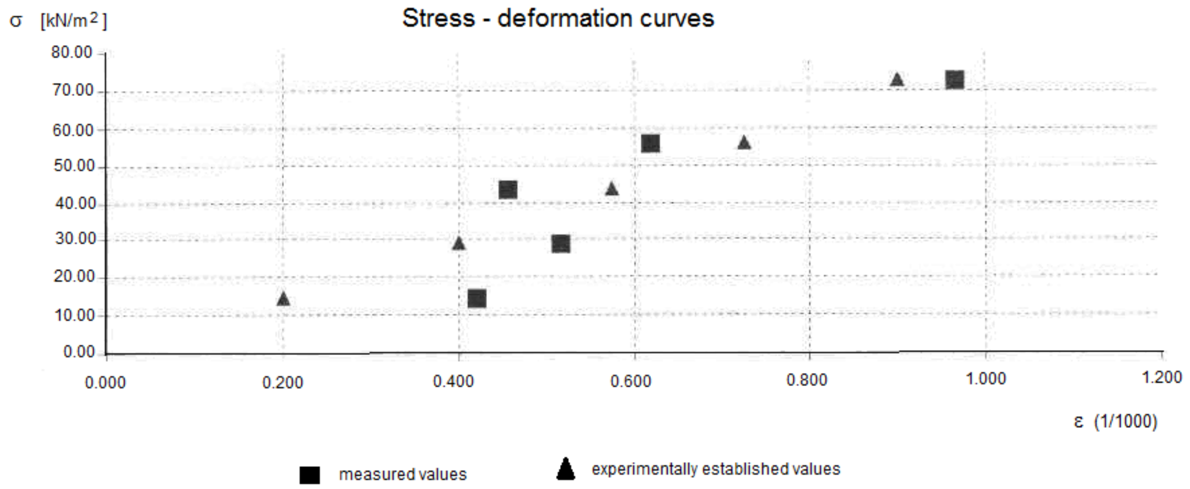
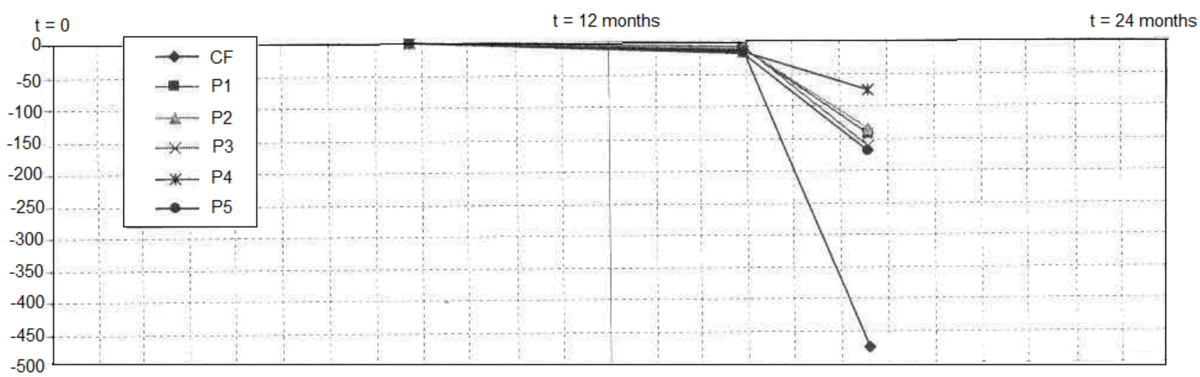


Fig. 7. *Stress – deformation curves*



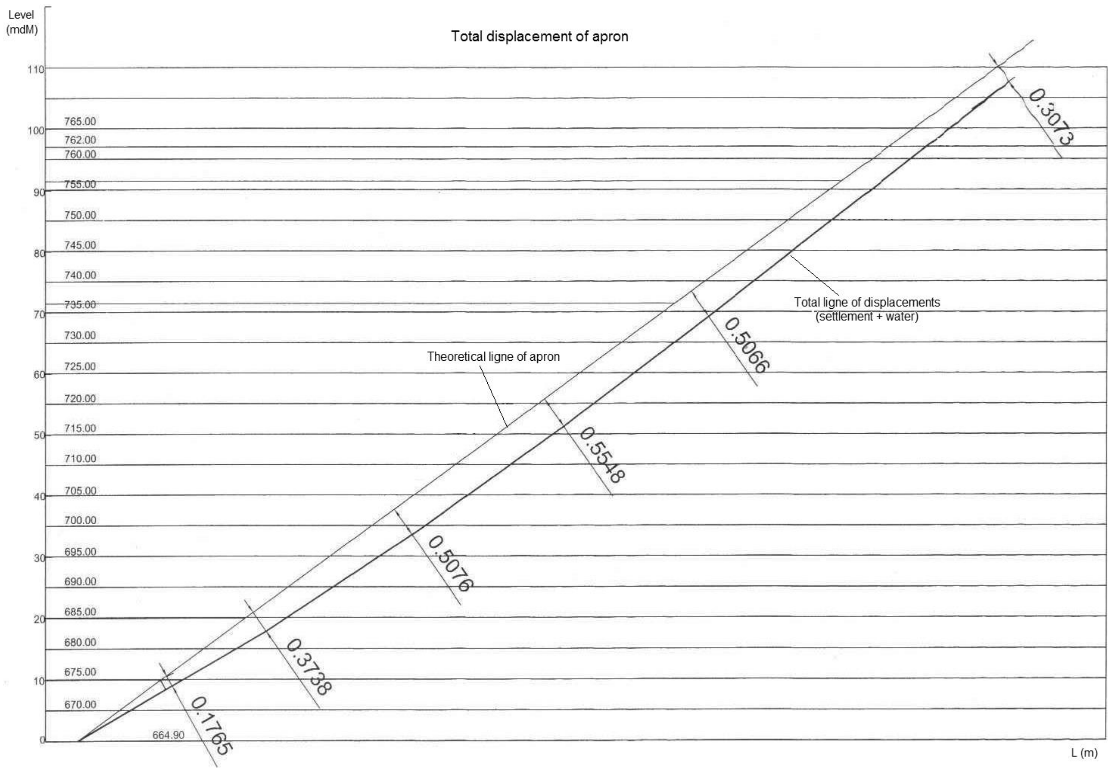


Fig. 8. *Measured settlements with CVT – fillings placed in the work and graphic of total displacement of concrete apron dam*

3.2. Obtained results

Calculus was carried out for two classical situations: completion of construction; first filling.

a) Completion of construction

Maximum settlements (- 1.07 m) are grouped in the centre of the dam, below tierce mean (H/3).

Horizontal displacements of upstream prism are in the range of values 0.09 – 0.30 m and also are arranged symmetrically in relation to those from downstream prism that are comprised in the range of values 0.10 – 0.48 m with a slight increase in relation to the upstream prism, in zone of material characterized by higher compressibility, namely tuff zone. Initial tangential elasticity modulus was significant through variations and gradients in the area of the contact surfaces between materials and along downstream face of dam from Ist stage. Distribution of elasticity modulus values (E_t) shows significant compression of material constitutes on volcanic tuff intercalated with pyroclastics. Maximum principal normal stress σ_1 (4 – 1,883 kN/m^2) is similar with σ_y, but with local distortions in accepted limits and without significant increases of equal stress lines, as a result of zoning of materials. Minimum principal normal stress of lateral confinement, σ_3 (1 – 858 kN/m^2), presents significant gradients in zone of contact downstream slope dam Ist stage – filling layer pyroclastic tuff and also in the first three layers of intercalated filling deposited near slope. The increases are not significant compared to the overall stress state of dam, but higher gradients in these areas may lead to diminishing the angle of internal friction with negative effects regarding the occurrence of local areas of instability. Shear tangential stress, τ_{xy} varies between -290 and 270 kN/m^2 and presents higher gradients through some discontinuities in downstream slope area of dam in Ist stage – filling layer of pyroclastic tuff.

b) First filling

From contribution of hydrostatic pressure maximum horizontal displacements – x direction – on upstream face of dam have the value of 0.34 m. From contribution of hydrostatic pressure maximum horizontal displacements – y direction – on upstream face of dam have the value of 0.19 m. Increases stress from hydrostatic pressure does not give rise to stresses concentrations in certain areas other than those signalled at the end of construction, maximum value of major principal normal stress being of 2,123 kN/m^2, respectively of 952 kN/m^2 for minor principal normal stress. Concreting works of concrete apron of Rastolita dam in first stage will begin after execution filling dam till 725 mdM level. Drawing works comply with general lines from performed documentation, and upstream the concrete apron being delimited by marginal joint (RP) that is defined by bottom reference axis that passes through points P1 to P8. Concrete slabs are defined by the joints of concrete apron, marked by points from 1 to 56 to the side of the bottom and also from 2 to 19 on top of the plate corresponding of small dam (crest of wave of 725 mdM).

4. Conclusions

The rockfills used in order to achieve the dam must have imposed characteristics concerning on resistance (mechanical, shock resistance), not be brittle and be resistant to the chemical action of aggressive water.

Regardless the achieved compaction degree, the voids exist; therefore, it imposes an analysis of permeability. The presence of voids indicates that these fillings are permeable. Waterproofing is ensured by baffles or concrete apron on upstream face. Concrete apron must resist of occurring loads to water pressure.

Concrete slabs will be poured on a porous equalizer concrete which allows independent deformation of rockfill in relation to the screen, concrete apron being elastic but costly.

The price increase is also due to the used materials on marginal and vertical joints: copper foil, bituminous mastics Sika, and others. Mainly, the dam's stability in time, depends of the correct application of solution depends.

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