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RE-EVALUATION OF THE DYNAMIC STABILITY OF EXISTING EARTH-FILLED DAMS

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SUMMARY

Ample investigations for re-evaluation of seismic stability of existing earth dams in R. Macedonija have been carried out. The methodology used for that purpose involved: re-evaluation of seismic hazard, dynamic analysis of dams exposed to seismic effects and probabilistic estimation of their seismic safety. Seismic hazard analyses have been performed for formulated mathematical models of seismic sources defined recurrence relations and selected alternative models of ground motion. The results from the seismic hazard analyses are spectra with equal annual probability of exceedence of 0.01, 0.001, 0.0001 and 0.00001. These define the seismic input for the dynamic analysis of the dams represented by time histories. Re- evaluation of seismicity of dam sites and seismic stability of the dams is practiced worldwide, due to: acquired new knowledge on seismogen zones, their activity and effect upon the dam sites; modification of the characteristics of materials build-in the dam after a longer period; phenomena manifested in the dam causing a decrease in the degree of the seismic stability; the necessity to control and define the seismic stability of the structure after a longer period. Application of the finite element approach with the discretization of the dam models was done by using two-dimensional isoparametric plane strain finite elements. A dynamic analysis was performed applying the nonlinear behavior of materials present in the dam body. Several possible scenarios for dam stability were accounted for: vertical and horizontal settlement of the dam crest, stability of the upstream and downstream slope against sliding, propagating tensile stresses in the dams and risk of crushing of gallery concrete from increased concrete compression. The conditional probability of failure have been obtained for each seismic level. The total probability of failure of each dam has been obtained as an integration of the conditional probabilities of failure and the seismic hazard curve for the dam site.

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INTRODUCTION

Re-evaluation of the seismic hazard of the sites of dams and consequently re-evaluation of the seismic stability of the dams are frequently practiced worldwide. These processes are imposed from many reasons, among which:

- acquired new knowledge on seismogene zones, their activity and their effect upon the dam sites;
- modification of the characteristics of materials built-in the dam body after a relatively longer period of their existence;
- phenomena manifested in the dam body that might cause a decrease in the degree of their seismic stability;
- the necessity to control and more accurately define the seismic stability of the structure after a longer period.

Re-evaluation of the seismic hazard and re-reevaluation of dynamic stability of existing dams was performed on three earth fill dams (“Shpilje”, “Tikvesh” and “Mavrovo” Dam).

SEISMOLOGICAL INVESTIGATIONS

Detail seismological and other relevant investigations related to the conditions of occurrence of earthquakes have been performed. The results from these investigations represent the main input for computation of seismic hazard. Seismological investigations are performed for seismogene zones in and around Republic of Macedonia, while seismic hazard analysis is performed for the site of each of three existing earth fill dams: Shpilje, Tikvesh and Mavrovo. Here, results from seismological investigations and seismic hazard analysis for Shpilje dam, are presented.

The wider region considered for the Shpilje dam from the aspect of its seismic activity is within coordinates 40.00^o - 42.50^o North and 19.00^o - 23.50^o East. The results from previous and the latest investigations proved that the considered region is one of the seismically most active regions in the Balkan both historically and throughout the XXth century. In the historic period prior to 1900, 40 strong earthquakes of $6.0 \leq M \leq 7.0$ were recorded and filed. These historic earthquakes coincide, according to the position of their locations, with the locations of recent strong earthquakes that occurred in the period 1901 – 1995. The seismic activity within the considered region is completely defined by the following epicentral areas: Pehchevo, Thessaloniki, Valandovo, Veles; Skopje - Uroshevats; Tetovo-Gostivar; Peshkopiya - Debar; Ohrid - Korcha; Drach - Lushnja; Vlora - Telepene - Girokastro; and Skadar. The epicentral areas of Peskopiya-Debar-Ohrid-Korcha are of the greatest importance for the Shpilje dam, since the very site of the dam is between these areas.

The macroseismic effects on the Shpilje dam site are VI to IX degrees at distances from earthquake epicentres of 0 to 210 km. The most intensive effects are from the epicentral Debar-Peshkopiya area, at distance from 0 - 15 km (IX degrees) and the south coast of the Ohrid Lake, at a distance of 75 km, with intensity of VIII degrees.

The results from seismotectonic investigations show that the seismic activity is clustered in individual epicentral areas of particularly expressive recent tectonic activity. These areas are tectonic knots where faults of different order and direction intersect. The following seismogene areas are distinguished in the considered region: Pehchevo, Thessaloniki, Valandovo, Veles, Skopje - Uroshevats, Tetovo, Bitola - Kozani, Peshtani - Ohrid - Struga, Peshkopiya - Debar, south coast of the Ohrid Lake - Korcha, Drach - Elbasan - Lushnja - Tepelene - Vlora - Fieri - Girokastro and Skadar. The greatest seismic effects upon the dam are exerted from the Drim seismogene zone (Peshkopiya - Debar - Struga - Ohrid - Korcha) in which is located the Shpilje dam. Presented below shall be the characteristics of the seismogene areas relevant for the Shpilje dam.

Debar - Peshkopiya seismogene area. This seismogene area represents a tectonic knot where faults of meridian stretching direction associated with the Drim graben zone intersect with other faults transverse to their direction. This graben area is surrounded by mountainous massifs bounded by the submeridian-oriented Drim, Korab and Debar fault. In the Debar depression, the Korab fault is contrastively expressed as a marginal fault in the depression relief. Running transversely to this fault and to this area is the Debar - Elbasan fault whose activity is particularly expressed in Albania. The intersection point of these faults in the south part of the Debar depression represents the epicentral area of the Debar earthquake of 1967. These faults are characterized by intensive tectonic activity manifested by frequent occurrence of strong earthquakes.

Struga - Ohrid - Peshtani seismogene area. This area is characterized by a number of faults running in the submeridian direction: Peshtani-Petrinje fault stretching along the east margin of the Ohrid depression, the Jablanitsa fault running along the west margin of this depression and the Drim and Sateska faults. This area is characterized by occurrence of relatively slighter earthquakes with $M \leq 5.6$.

South part of Ohrid Lake - Korcha seismogene area. The south segments of the Peshtani-Petrinje faults and the Jablanitsa fault define the intensive tectonic activity of this area that conditions the occurrence of strong earthquakes.

Drach - Girokastro seismogene area. In the tectonic sense, this area is characterized by a system of submeridian faults and other transverse faults and by intensive tectonic activity conditioning the occurrence of strong earthquakes.

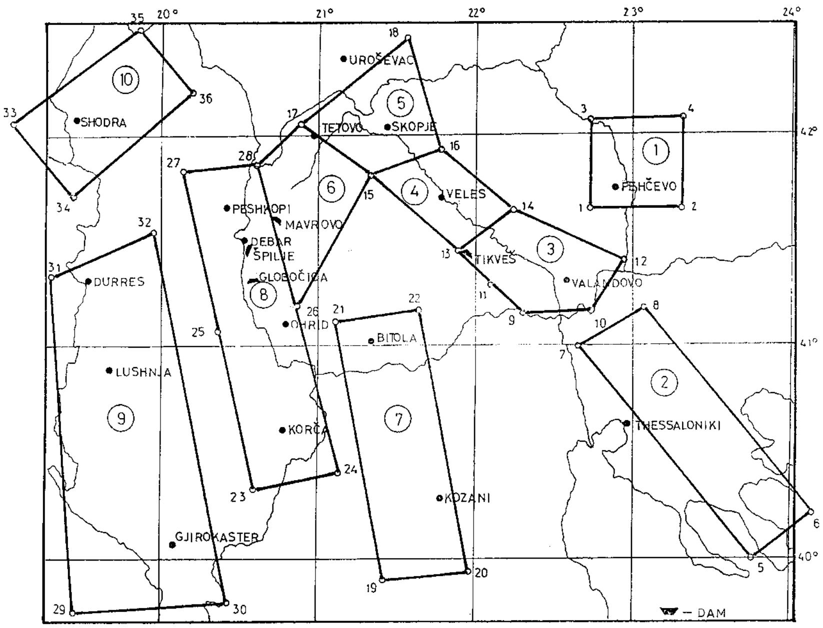
The Tetovo - Gostivar seismogene area situated 55 km northeast from the Shpilje dam and the Bitola area which is about 90 km southeast from the Shpilje dam are characterized by slighter earthquakes.

RE-EVALUATION OF SEISMIC HAZARD

Models of Seismic Sources

Definition of the geometry and maximum expected magnitude of seismic sources is of a particular importance for the seismic hazard assessment. The method applied for determination of the geometry of seismic sources and Mmax is based on geological criteria about the seismicity and has been compared to the results available from seismological observations. These geological criteria are: tectonic faults and motions along them, geological evolution of individual tectonic morphostructures and time of most intensive tectonic activity. Based on these criteria, neotectonic zoning has been done for the Neogene-Quaternary and morphostructures of uplifting and subsidence have been defined.

On the basis of the empirical seismological, seismotectonic and geological data, 10 seismic sources are defined in the considered region. They involve the epicentral areas of strong historically known and recent earthquakes, as well as areas of intensive tectonic activity with complex intersection of faults.
The position, the size and the form of seismic sources and their maximum magnitude M_{max} are presented in Fig. 1. These seismic sources are the following: Pehchevo ($M_{max} = 7.9$); Thessaloniki ($M_{max} = 7.0$); Valandovo ($M_{max} = 6.9$); Veles ($M_{max} = 6.0$); Skopje ($M_{max} = 6.5$); Tetovo ($M_{max} = 6.0$); Bitola - Kozani ($M_{max} = 6.5$); Debar - Ohrid ($M_{max} = 6.9$); Durres - Lushnja - Girokastro ($M_{max} = 7.0$); and Skadar ($M_{max} = 7.0$). Earthquakes at individual seismic sources of the considered region are shallow, with hypocentres with an average value of 10 - 26 km. The remaining part of the region between the seismic sources is characterized by a maximum magnitude $M_{max} \leq 5.7$ and average depth of earthquakes h = 10 km.



Legend:

① Pehchevo
② Thessaloniki
③ Valandovo
④ Veles
⑤ Skopje
⑥ Tetovo
⑦ Bitola-Kozani
⑧ Debar-Ohrid
⑨ Durres-Lushnja-Gjirokastro
⑩ Skadar

Fig. 1 Model of seismic sources

Recurrence Relationships

The Gutenberg-Richter's formula (Eq. 1) has been used as the relationship between the cumulative number of earthquakes N occurring in a seismically active region within a certain time period and the magnitude (M) of those earthquakes,

$$\log N = a - bM \qquad (1)$$

in which a and b are the parameters defining the degree of seismic activity (a) and the inclination of the recurrence relationship graph (b).

The recurrence relationships have been defined according to the Weichert's [2] method by maximum reliability computation. Number (n) of earthquakes in the considered period of 95 years has been distributed according to magnitude at intervals of 0.4 magnitude units, starting with $M_L \geq 4.5$. These numbers have been defined for all the seismic sources and for the "background", separately.

According to Weichert method, the number of earthquakes is reduced to a cumulative time standardized number N. For each magnitude interval, a centre of that interval has been defined and the return time period (T) (in years) of occurrence of earthquakes with magnitudes $M_L \geq 6.1$ has been assessed by statistic processing of historic and instrumental data. The assessment refers to the interval for T=150 years as the lower limit and T=250 years as the upper limit. For computation of the seismic hazard, the more conservative alternative was taken, i.e., the lower limit for the return period T.

The recurrence relationships have been computed and graphically presented. Figs. 2 and 3 show the recurrence relationships for seismic sources Debar-Peshkopiya and Struga-Ohrid. Figures show the cumulative number of earthquakes standardized to one year (N, i.e., N'). The thin line shows the relationship obtained by the maximum reliability method, computed from equation (1), whereas the thick line shows the relationship in the computation containing the maximum magnitude (Mmax) corresponding to each seismic source. Number N', has been computed according to the following formula:

$$N' = N \frac{1 - exp\left[- \beta \left(M_L - M_{L\min}\right)\right]}{1 - exp\left[- \beta \left(M_{Lmax} - M_{Lmin}\right)\right]} \tag{2}$$

where $M_{Lmin} = 4.5$, $\beta = b \ln 10$

whereat, the frequency of earthquakes has the following form:

$$f(M_L) = \frac{\beta \, exp\left[- \beta \left(M_L - M_{Lmin}\right)\right]}{1 - exp\left[- \beta \left(M_{Lmax} - M_{L\min}\right)\right]} \tag{3}$$

Presented in each figure is the analytical expression of the recurrence relationship, the value of coefficient β (indicated by BETA in the figure), and the value of maximum magnitude (M_{max}).

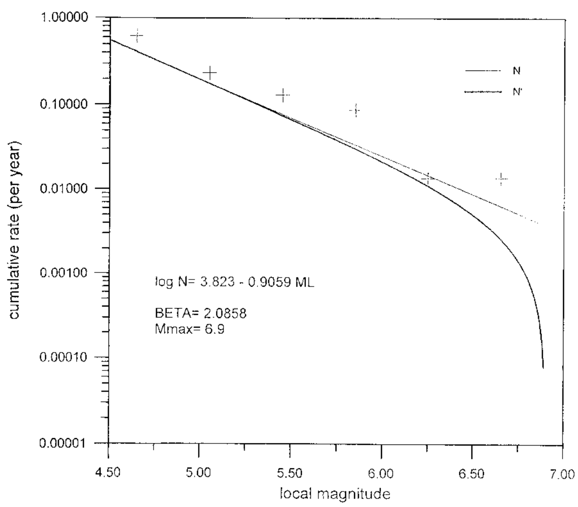


Fig. 2 Recurrence model for seismic source Debar-Ohrid

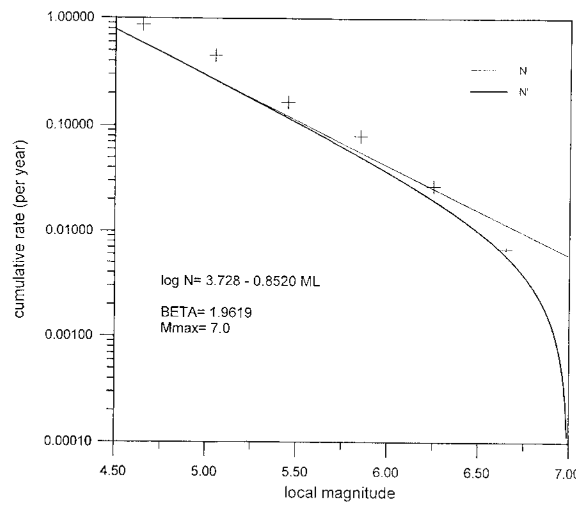


Fig. 3 Recurrence model for seismic source Lushnje-Girokastro

Due to insufficient number of data, the recurrence relationship has not been statistically computed for the seismic sources of Veles and Tetovo (Fig.1). For these two sources, the recurrence relationships have been derived from the relationship for the Skopje source. Coefficients a and b in the recurrence relationship (1) have been defined by reduction, in accordance with the ratios between the cumulative number (N) of earthquakes with magnitude ML ≥ 4.1 from the seismic sources of Veles, Tetovo and Skopje. These ratios are 6/40 for Veles, and 8/40 for Tetovo. In that way, the recurrence relationships are LogN = 3.981 - 1.2146 M_L for Veles and LogN = 4.106 - 1.2146 M_L for Tetovo.

The values of coefficients a and b in formula (1) and the other characteristics computed for each seismic source separately are shown in Table 1. For the purpose of computing the seismic hazard, this table also displays all the necessary parameters for all the ten seismic sources and for the "background" as well.

Table 1. Characteristics of seismic sources

Seismic source		β	SDβ	b	SDb	Num. of earth.	a	N4.5 rate	M_L max	Depth (km)
Name	Source contour									
Pehchevo	1,2,3,4,	1.9263	0.291	0.8366	0.127	31	3.220	0.285	7.9	26
Salonika	5,6,7,8	1.8075	0.330	0.7850	0.143	31	2.995	0.290	7.0	16
Valandovo	9,10,11, 12,13,14	2.5651	0.357	1.1140	0.155	51	4.683	0.468	6.9	17
Veles	13,14,1 5,16	2.7968	0.587	1.2146	0.255	-	3.981	0.033	6.0	10
Skopje	15,16,1 7,18	2.7968	0.587	1.1246	0.255	24	4.805	0.218	6.5	10
Tetovo	15,17,2 6,28	2.7968	0.587	1.2146	0.255	-	4.106	0.044	6.0	10
Bitola-Kozani	19,20,2 1,22	2.3672	0.478	1.0281	0.208	26	4.007	0.240	6.5	16
Debar-Ohrid	23,24,2 5,26,27	2.0858	0.267	0.9059	0.116	60	3.823	0.558	6.9	18
Durres-Lushnja-Girocastro	29,30,3 1,32	1.9619	0.214	0.8520	0.093	84	3.728	0.783	7.0	19
Skadar	33,34,3 5,36	1.8628	0.376	0.8090	0.163	25	3.009	0.234	7.0	20
Background		2.6718	0.857	1.1604	0.372	43	3.885	0.046	5.7	10

$\log N = a - bM$; $\beta = b \ln 10$
SD_β = standard deviation of b
N4.5rate – annual rate of earthquakes with magnitude $M \geq 4.5$

Ground Motion Models

The models of ground motion provide data on the attenuation of ground motion parameters from the seismic source to a given location. The selection of the ground motion models is of significant importance for the final results from the seismic hazard analyses. Here, three alternative models have been selected as representative ground motion models. These are Sabetta & Pugliese [8], Ambraseys et al. (1996) [7] and N. Naumovski (1984) [5] since they have been obtained by records from occurred strong earthquakes, which have been estimated as records that more realistically represent the expected parameters of the investigated site.

Seismic Hazard Analyses

To compute the seismic hazard at the Shpilje dam site, the computer programme EQRISK [1] has been used. It is based on the Cornell's approach [9]. According to this approach, the seismic hazard for a given location is defined on the basis of spatially defined seismic sources, activity of the seismic sources and given ground motion models. The activity of each seismic source is defined by a recurrence relationship.

Table 1 shows the characteristics of the seismic sources necessary for definition of the input for the EQRISK computer programme. The input for the EQRISK computer programme has been completed by the regression coefficients and the standard deviations of the ground motion models.
The following empirical relationship of magnitudes has been used for the Ambraseys et al., and Sabetta & Pugliese models:

$$Ms = 1.13\ M_L - 1.08 \tag{4}$$

The seismic hazard analyses have been done for maximum ground acceleration and acceleration response spectra. The spectra are defined for seven models with natural periods of 0.1, 0.2, 0.3, 0.4, 0.50, 1.0 and 2.0 seconds, for damping of 5% of the critical, separately for the horizontal and the vertical direction. The return periods are 100, 1000, 10 000 and 100 000 years. The response spectra of acceleration for return period of 1000 years are graphically presented in Fig. 4 for horizontal direction and Fig. 5 for the vertical direction. Presented in these figures are three response spectra with equal probability of exceedence for the horizontal direction and two response spectra with equal probability of exceedence for the vertical direction. Mean spectra with equal probability of exceedence have also been computed. In the figures, these are presented with a solid line. These mean response spectra are the spectra according to which the artificial time histories have been generated for the dynamic analyses of Shpilje dam.

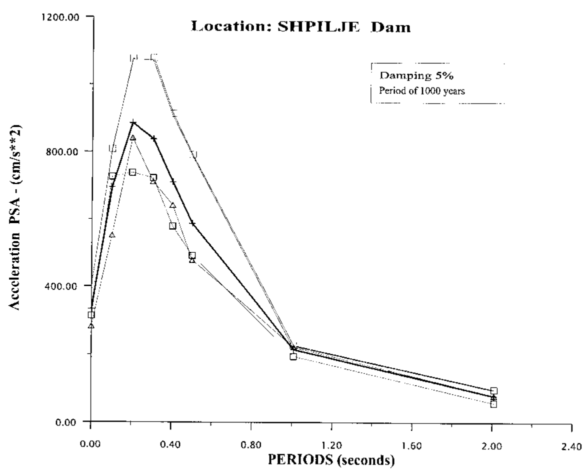


Fig. 4 Horizontal spectra

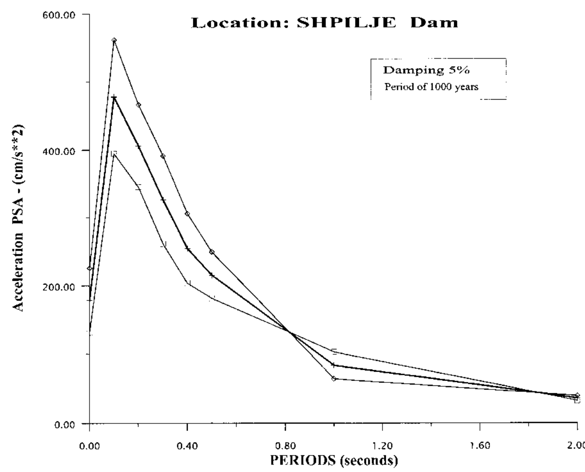


Fig. 5 Vertical Spectra

Generation of Time Histories of Acceleration of Ground Motion

The procedure that has been used for generation of artificial accelerogrammes is based on a methodology that enables compatibility with a given spectrum [6]. A recorded accelerogramme is used as an initial time history of acceleration. Compatibility with the given spectrum is achieved by appropriate modification of the amplitudes of harmonic components of time history in frequency domain. The process is iterative and convergent and a time history with spectrum compatible with the given one is obtained after a certain number of iterations.

Generated were 3 artificial accelerogrammes for each level of probability of exceedence (0.01, 0.001, 0.0001 and 0.00001) in horizontal and vertical direction. Used as initial accelerogrammes for each artificial accelerogramme were the two horizontal components and the vertical component of a three-componental record from an occurred earthquake. These were the following records: Ulcinj - Albatros from the Montenegro earthquake of April 15, 1979, Taft Lincoln from the Kern County earthquake of July 21, 1952 and the El Centro from the Imperial Valley earthquake of May 18, 1940.

In that way, a three-componental accelerogramme compatible with the spectrum defined for the Shpilje dam site has been obtained. Such an artificial accelerogramme contains the original phase angle and time duration of the intensive part of the actual earthquake accelerogramme.

DESCRIPTION OF THE MAIN CHARACTERISTICS OF THE STRUCTURE

Geometrical and Geomechanical Characteristics of Shpilje Dam

Shpilje dam is situated in the west part of Macedonia, near Debar. It was constructed in the period 1964-1969 as the second energetic level on Tsrni Drim river.

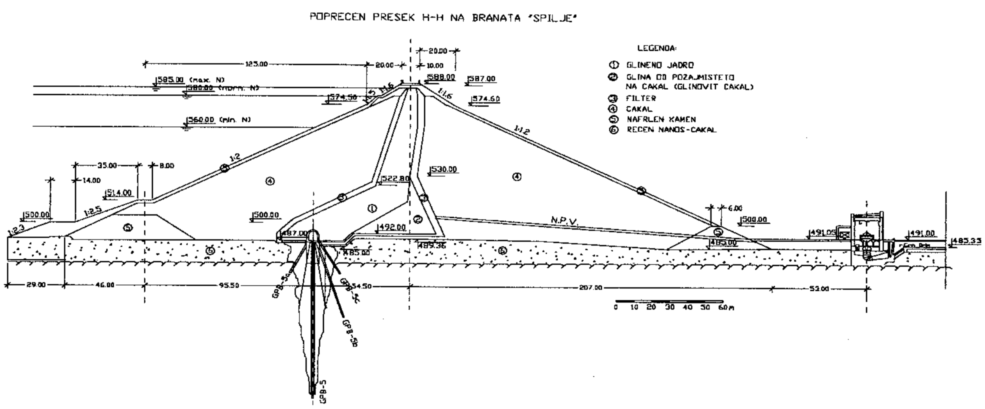


Fig. 6 Central cross section of Shpilje Dam

Shpilje dam is gravel-earth fill dam with a central clayey core and zoned cross-section. It has the following main proportions:

- Construction height 112.00 m
- Crest width 10.00 m
- Base width 432.00 m
- Crest length 330.00 m
- Inclination of the upstream slope 1 : 2
- Inclination of the downstream slope 1 : 2

Shpilje dam is constructed of natural materials. The deposits of these materials are located in the near vicinity of the structure. Fig.7 shows individual zones of the dam body indicated by numbers from 1 to 13 at which are separately defined the elastomechanical characteristics of materials.

Six types of different materials are included in modeling of dam body. The dam core is modeled by two materials clay and gravel-clay in certain zones. Sand and gravel are located in the filtration zones, in front and behind the core. The dam body is modeled by gravel material which is supported by alluvial deposit. Reinforced concrete is used for modeling of structure of the gallery.

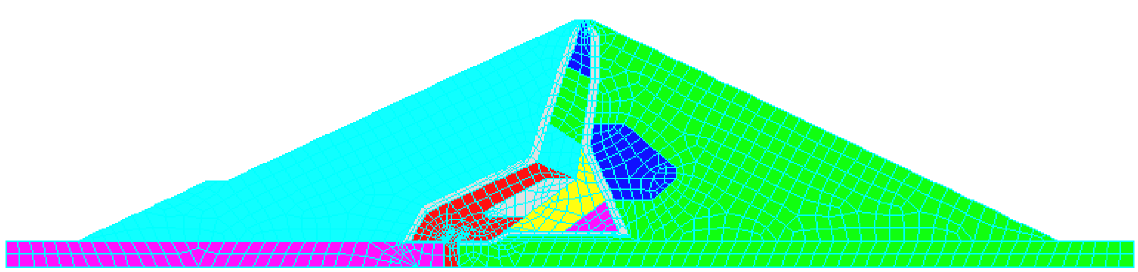


Fig. 7 Zones of different material properties

Geometrical and Geomechanical Characteristics of Tikvesh Dam

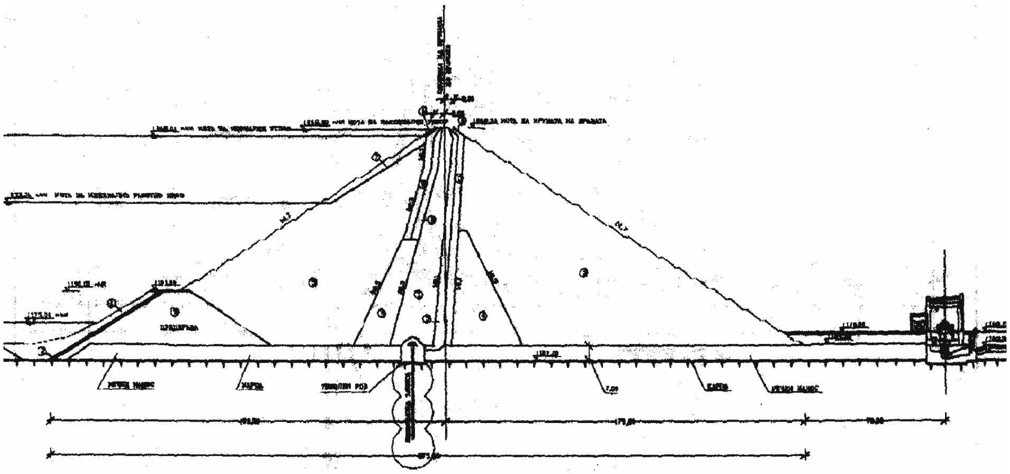


Fig. 8 Central cross section of Tikvesh Dam

Tikvesh Dam represents a rock-fill dam with central narrow clayey core, retaining parts of tipped stone and reinforced concrete control gallery (Fig. 8). It is constructed along Tsrna Reka river, at a distance of 3 km upstream the village of Vozartsi and serves for accumulation of water for land reclamation and energetic purposes.

It has the following main proportions:

- Construction height 113.50 m
- Crest width 10.00 m
- Base width 373.00 m
- Crest length 338.00 m
- Inclination of the upstream slope 1 : 1.16
- Inclination of the downstream slope 1 : 1.16

The fast construction of the dam and the large variations of the water level of the lake have resulted in relatively large deformations of the dam body during the first three years of its serviceability life. These deformations have exclusively been manifested as settlement of the dam crest. Therefore, the dam crest was stepped for 1.85m in the central part, by gradual decrease of height to zero at the ends of the dam.

Tikvesh Dam is constructed of natural materials. The deposits of these materials are located in the near vicinity of the structure. The following materials are present in the dam body:

- Clayey material in the dam core
- Sand and gravel in filtration zones
- Gravel clay in transitional zones
- Tipped stone
- Autochthonous material from deposit in riverine body
- Surface rock material

Geometrical and Geomechanical Characteristics of Mavrovo Dam

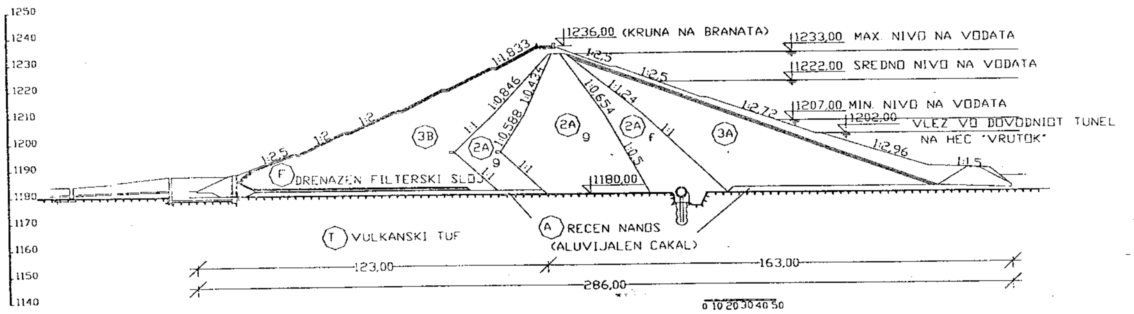


Fig. 9 Central cross section of Mavrovo Dam

Mavrovo dam is situated at about 25 km from Gostivar, at the beginning of the gorge of Mavrovska Reka river. Its was constructed in the period 1948 - 1958. Since then, it has regularly been operational.
Mavrovo dam is an earth-fill dam, with a central clayey core and zoned cross-section (Fig. 9). Its main proportions are the following:

- Height 61,00 m
- Crest width 6,00 m
- Base width 286,00 m
- Crest length 210,00 m
- Inclination of upstream slope 1 : 2,5 to 1 : 2,96
- Inclination of downstream slope 1 : 2,5 to 1 : 1,83

The soil media as are the clayey material, the filtration materials, the transitional zones, the tipped stone, the bedrock, behave in the nonlinear range under the effect of gravity and remaining loads. To treat adequately the nonlinearity of materials, it is necessary to define, as realistically as possible, the parameters of nonlinear behavior of materials. The main data on the nonlinear nature of individual materials present in the dam body are the results from the triaxial laboratory tests on samples taken during the incorporation of the materials. In practice, samples of the same material are taken from several places from each constructed layer. In principle, a certain variation of the results from the laboratory tests of the samples should be expected. From these reasons, there is usually statistic processing from which the mean value, the standard deviation and the variation of the results are defined.

DEFINITION OF MATHEMATICAL MODEL OF DAMS

Application of the finite element approach with the discretization of the dams model was done by using two-dimensional isoparametric plane strain finite element. Fig.10. shows the final finite element mesh od Spilje Dam. Present in the model are finite elements with 4 nodal points. The density of the mesh is sufficiently refined to present the stress and deformation fields with a sufficient accuracy. All the degrees of freedom of motion are fixed along the base.

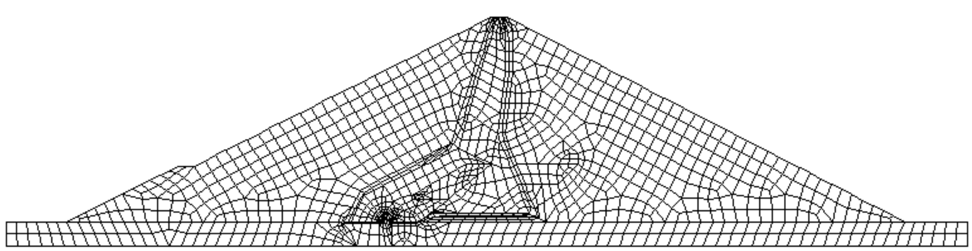


Fig. 10 Finite element model of Shpilje Dam

DEFINITION OF INDIVIDUAL POSSIBLE SCENARIOS OF EVENTS IN THE DAM BODY THAT MIGHT BE FACTORS FOR OCCURRENCE OF INSTABILITIES AND FAILURE OF THE DAM

One of the possible phenomena manifested during an earthquake is vertical and horizontal settlement of the dam crest. In this case, the evaluation of the level of these total and permanent deformations is of importance if we want to protect the dam against spilling of water over the dam crest during an earthquake, particularly in the case when the reservoir water level is kept relatively high and the variation of the maximum level is relatively low in the course of the year. This phenomenon is called Scenario No.1. The evaluation of the stability of the upstream and downstream slope against sliding during an earthquake effect is of particular importance for evaluation of the local stability of the structure.

During the earthquake effect, the safety coefficient against sliding for individual sliding plains may have a value of less than Fs = 1. This means, that at certain time moments, the mass of the wedge is instable and experiences sliding along the geometrically defined sliding surface. Since a probabilistic approach is treated in evaluation of the dam stability, we consider that the variation of the allowable permanent deformations ranges between ± 25%. This phenomenon is called Scenario No.2.

During the earthquake effect, manifestation of tensile stresses is possible in the media of individual zones of the structure, and consequently occurrence of cracks (most frequently in the stone prisms that are considered brittle media). During earthquakes of higher intensity of ground acceleration, zones of tensile stresses are possible at the contact between the clayey core and the filtration layer as well as at the contact between the stones and the filtering layer, indicating that cracks might be expected in those zones. The monitoring of the propagation of the zones where tensile stresses are manifested in the media is defined as possible event, Scenario No.3.

In dams constructed of local materials, there is a gallery space constructed as a reinforced-concrete structure. The occurrence of an earthquake additionally affects the modification of the original stress state of the gallery elements and also increases the tensile stresses in the concrete. The monitoring of these phenomena in the gallery area under the earthquake effect is defined as event, Scenario No.4.

Considered as a criterion that failure of the structure might take place under an earthquake is the realization of scenario no.1 or only scenario no.2, or simultaneous occurrence of both.

RESULTS FROM PERFORMED ANALYSES

A dynamic analysis was performed applying the nonlinear behavior of materials present in the dam body. Several possible scenarios for dam stability were accounted for: vertical and horizontal settlement of the dam crest, stability of the upstream and downstream slope against sliding, propagating of tensile stresses in the dam and risk of crushing of gallery concrete from increased concrete compression.

Analysis of Mode Shapes and Natural Vibrations of the System

The first step in determination of the seismic response of the dam is analysis of the natural vibrations of the system. The results from the performed analyses have been compared to the corresponding values of fundamental mode shapes and periods are obtained by experimental in situ testing of the dam performed by IZIIS. Figure 11 shows the first fundamental mode shape of natural vibrations of Shpilje Dam.

The analytically obtained values for the first two modes of vibration for 2D analysis are for Spilje, Tikvesh and Mavrovo Dam are presented in Table 2.

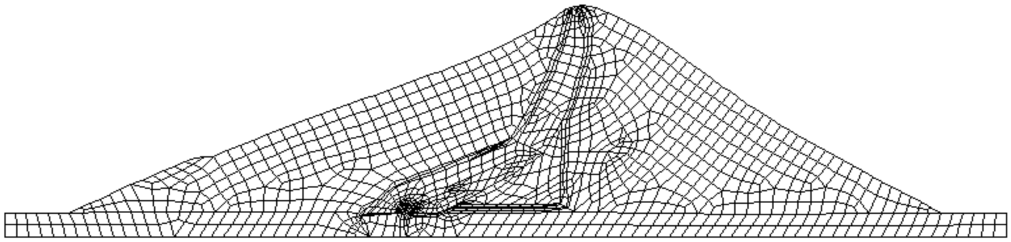


Fig. 11 First mode of vibration of Shpilje Dam

Table. 2 Analytically and experimentally obtained value of vibrations

Dam	2D FEM Model		Experimentally	
	First Period T1 [sec]	Second Period T2 [sec]	First Period T1 [sec]	Second Period T2 [sec]
Shpilje	0.494	0.354	0.349	0.274
Tikvesh	0.617	0.390	0.4485	0.653
Mavrovo	0.400	0.270	0.36	0.286

It may be concluded that there is a very good correlation between the analytically and experimentally obtained values for the first fundamental modes of natural vibrations.

Analysis of Stress-Deformation State under Effect of Main Static Loads (DL- dead weight + HP - hydrostatic pressure) for Average Water Level

The deformation state along the contour of the dam is considered to be the total deformation state from the moment of completion of construction until the moment of oscultation geodetic measurements performed in 1997. This means that the presented total deformations should be treated as total secondary consolidation deformations neglecting the primary consolidation deformations that have taken place in the course of construction of the dam. Comparing the intensity of deformations at the dam crest and generally along the dam contour obtained analytically with the corresponding total deformations obtained by geodetic oscultation, it may be concluded that there practically isn't any greater difference which points the fact that the stiffness characteristics of the dam have been adopted with a satisfactory accuracy.

Then maximum vertical settlements and the maximum horizontal displacements for the characteristic cross-section of the dams are presented in Table 3.

Table. 3 Vertical settlements and horizontal displacement of Shpilje, Tikvesh and Mavrovo Dams

Dam	2D FEM Model		Geodetic oscultation	
	Vertical settlement [cm]	Horizontal displacement [cm]	Vertical settlement [cm]	Horizontal displacement [cm]
Shpilje	46-48	18.5-19.5	40-43	18-19
Tikvesh	118	30-35	117	35-37
Mavrovo	28-32	22-24	25-28	25-30

Analysis of Stress-Deformation State under the Effect of Seismic Forces

For nonlinear dynamic analysis of the dam, in addition to the already mentioned static loads (dead weight and hydrostatic pressure), the already generated synthetic earthquakes according to the hazard for equal probability of exceedence and the hydrodynamic pressure as reservoir effect upon the dam body are added.

A part of the results obtained by nonlinear analyses of the dam for the effect of an earthquake with annual probability of exceedence of 10^{-3}, 10^{-4}, 10^{-5} are presented.

Presented in Tables 4 and 5 are the most unfavorable displacements in X-direction "Dx" and strains "γ_{xy}" for the crest and the upstream side as well as the maximum acceleration at the crest for each earthquake level.

Table 4 Results obtained by nonlinear analyses of Spilje Dam

Earthquake	Dx_{pl} (crest)	Dx_{cikl} (crest)	$Accx_{max}$ (crest)	Dx_{pl} (upstream)	γ_{xy} (crest)	γ_{xy} (upstream)
	m'	m'	m/sec^2	m'	%	%
Level 10^{-3}	0.01-0.02	0.05-0.06	4.19	0.15	0.3	2.0
Level 10^{-4}	0.07-0.09	0.06-0.07	8.01	0.45	0.7	4.4
Level 10^{-5}	0.12-0.15	0.15-0.20	13.40	1.25	1.7	7.9

Table 5 Results obtained by nonlinear analyses of Tikvesh Dam

Earthquake	Dx_{pl} (crest)	Dx_{cikl} (crest)	$Accx_{max}$ (crest)	Dx_{pl} (upstream)	γ_{xy} (crest)	γ_{xy} (upstream)
	m'	m'	m/sec^2	m'	%	%
Level 10^{-3}	0.04-0.06	0.02-0.03	2.80	0.22	0.8	3.2
Level 10^{-4}	0.06-0.08	0.06-0.08	5.00	0.26	0.9	3.3
Level 10^{-5}	0.10-0.12	0.12-0.14	9.10	0.36	1.1	3.7

The greatest deformations under the effect of earthquake with probability of occurrence of 10^{-5} of Shpilje Dam are presented in Fig 12 and Fig 13.

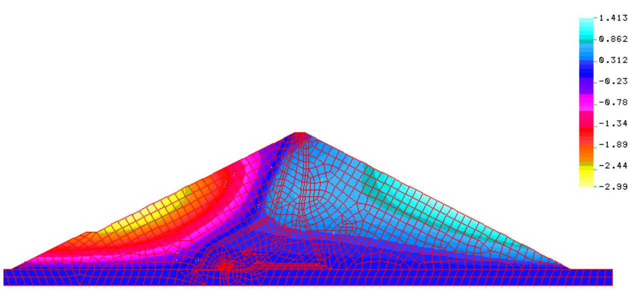


Fig. 12 Horizontal displacements at t=13 sec

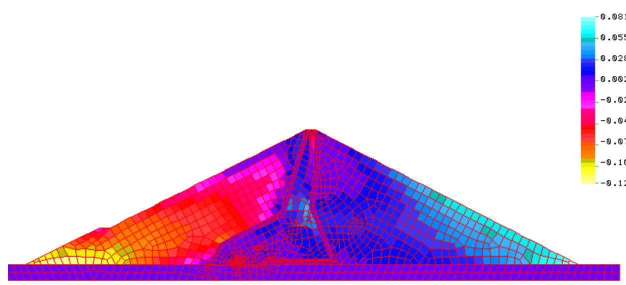


Fig. 13 Plastic shear deformations at t=13 sec

PROBABILITY OF OCCURRENCE OF DAMAGE AND FAILURE OF THE DAM

It is our opinion that the scenario as to failure of the dam shall be realized in the case the permanent deformation from sliding of the masses of the upstream and downstream slope exceeds the limits of the defined permanent sliding deformation of the masses (Scenario 2), at certain stress states of the supporting bodies of the dam. From the performed analyses, it has been determined that the stated phenomena occur almost simultaneously and are in full correlation so that the probability of failure of the dam has been computed according to the scenario of realization of residual permanent deformations of the sliding plains. The effect of the seismic level with a probability of 10^{-2} has not been considered since it cannot induce deformations that might lead to failure of the dam.

Under each seismic level (10^{-3}, 10^{-4}, 10^{-5}), the conditional probability of failure has, first of all, been defined. Here, the following values have been taken for the capacity of the dam:

- The mean value of permanent deformation capacity at the occurrence of sliding of the slopes
- The coefficient of variation of capacity is evaluated 0.25;
- The responses in the form of maximum permanent displacement of the sliding plains under seismic levels of 10^{-3}, 10^{-4} and 10^{-5} have been taken in the form of mean values obtained by dynamic analysis;
- The coefficient of variation of maximum displacements has been evaluated based on numerous dynamic analyses of structures that have so far been performed for actual seismic effects. Two alternatives of coefficient of variation have been treated: 0.75 and 1.0;
- The distribution of the probabilities of the capacity and the responses have also been considered as two alternatives: normal distribution and β distribution;
- It has been considered that there is no correlation between the capacity and the responses, which is on the safety side.

Starting from these assumptions, eight alternative values of conditional failure have been obtained for each seismic level. The mean values of the conditional probabilities of failure under seismic levels of 10^{-3}, 10^{-4} and 10^{-5} are given in Table 6.

Table 6 Conditional probabilities of failure of Shpilje, Tikvesh and Mavrovo Dams

Dam	Level of exceedence		
	Level 10^{-3}	Level 10^{-4}	Level 10^{-5}
Shpilje	0.04 %	12.80 %	59.80 %
Tikvesh	0.16 %	9.50 %	50.90 %
Mavrovo	0.03 %	12.30 %	56.20 %

The expected behavior of Shpilje dam under these effects is characterized by reliability index ranging between 1.20 and 3.30. The reliability index of Tikvesh Dam is ranging between 1.39 and 2.81, and for Mavrovo Dam it is between 1.23 and 3.38. Hence, no failure scenario is expected to be realized under these effects.

The total probability of failure of Shpilje, Tikvesh and Mavrovo is $9.45*10^{-5}$, $8.04*10^{-5}$ and $9.03*10^{-5}$, respectively, and it has been obtained as an integration of the conditional probabilities of failure and the seismic hazard curve for the dam site. The defined value of probability of failure refers to one year, i.e., total probability of failure of $9.45*10^{-5}$ means that failure of Shpilje Dam is expected once in 10582 years.

CONCLUSIONS

This approach has so far not been treated in the regulations for dam design in the world. The problem of acceptable probability has usually been solved by consensus of experts. Lately, some countries (USA, Canada) have prescribed the acceptable risk pertaining to energetic structures depending on the consequences from their failure. Applying those criteria, the probability of failure of the Shpilje, Tikvesh and Mavrovo Dams is between 10^{-4} and 10^{-5}. The probability of 10^{-5} refers to structures whose failure induces the most severe consequences.

Under the effect of earthquakes with probability of annual exceedence of 10^{-3}, no greater or important deformations are expected to take place in the dams body.

Under the effect of earthquakes with a probability of annual exceedence of 10^{-4}, permanent deformations of the dam body are expected to occur, but their intensity and scope cannot endanger the general stability of the dams.

Under the effect of earthquakes with probability of annual exceedence of 10^{-5}, development of considerable deformations of the dams body is expected to take place which endanger the stability of the dams. However the earthquakes with a probability of 10^{-5} have been considered for the purpose of defining the level of ultimate failure capacity of the dams.

It is generally concluded that the dams have a sufficient capacity to sustain earthquake effects with intensities corresponding to probability of annual exceedence of 10^{-3} and 10^{-4}.

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