This paper introduces a methodology devised for thermographic inspection of concrete technical condition inside concrete dams. Water infiltration into a dam accelerates the processes of concrete degradation, so temperature fields provide important information about the dynamics of these processes. As a result of the thermal imaging survey of the observation gallery at a historic hydraulic structure, a formalized pattern of the temperature field inside the dam was acquired and the locations of temperature anomalies associated with infiltration were identified. At the leakage points, the water temperature differed from the concrete temperature by 1.0–2.9 °C, indicating different rates of water flow through the water wall and the gallery ceiling. The temperature of the gallery areas with increased infiltration was 1–2 °C higher than the 12.7 °C selected as the reference temperature. When recording the temperature fields, the optical axis of the thermal imager was directed along the gallery, and not perpendicular to the surfaces under study, as in construction thermography. To this end, a methodological approach was devised to eliminate distortions of the resulting thermograms caused by the curvature of the gallery and other factors. To remove images of extraneous thermal radiation sources from the thermograms and accurately identify the area under study, a method of shielding a part of the image using special masks was used. The comparative thermography method made it possible to eliminate difficulties in determining the emissivity of the gallery concrete surface. The proposed method of comparative thermography made it possible to compare the intensity of filtration processes in the dam body and to link the current state of the hydraulic structure with the history of its restoration. In general, the thermographic method makes it possible to supplement existing primary natural control with a formalized pattern of temperature field inside the dam

Keywords: thermography, concrete dam, water infiltration, thermogram processing, infiltration criterion, inspection gallery

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APPLICATION OF THERMOGRAPHY TO DETECT AREAS OF WATER INFILTRATION IN THE DAM CONCRETE FOUNDATION

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1. Introduction

A large number of hydrotechnical structures in the world have a long service life, which makes them a source of possible man-made accidents and disasters. Therefore, diagnosing their technical condition is one of the most important problems in the world. It is known that during the construction of gravity dams, exothermic effect, as well as fluctuations in the temperature of the outside air, cause significant temperature stress in the concrete massif. Cracks appear as a result, which can change the scheme of static operation of the structure, increase water filtration, and thus reduce its carrying capacity [1]. The temperature of water penetrating into the dam body can be an indicator of destructive processes in concrete, therefore the non-equilibrium temperature field of the dam is one of the important informative signs. The capabilities of modern thermal imaging enable studying temperature fields, which makes it an effective tool for diagnosing the technical condition of hydrotechnical structures. Especially interesting is to investigate water infiltration through the concrete body of the dam using the thermographic method, which is relevant for many hydraulic structures.

2. Literature review and problem statement

As noted in paper [2], control over hydrotechnical structures is one of the main components of maintaining their safety. Despite relevant building regulations, the entire control system needs improvement. The study emphasizes that this is primarily needed for veteran structures, such as the Dnieper HPP dam. It is proposed to implement new methods for monitoring hydrotechnical structures. But the question of which modern methods are the most promising for controlling hydrotechnical structures remains open. The reason for this may be that a reasonable review of such methods is a separate scientific task that was not considered in the paper.

A relatively new method for investigating the internal structure of an object, namely thermography or thermal imaging, could be an option for effective examination of such objects [3]. The method is based on the fact that the quasi-stationary temperature field on the surface of any object can carry information about its internal structure. This field is recorded by a thermal imager in the form of a thermogram. Given the fact that the registration is carried out remotely, it is possible to control large surfaces at the same time, which is especially necessary when inspecting hydraulic structures.

However, the work does not consider specific issues related to the application of thermography to the study of any hydraulic engineering objects. Apparently, this is due to the fact that the author did not set such a task.

Significant progress in the area under consideration was achieved [4, 5]. In particular, paper [4] reports the results of studies using thermography of a gravity dam in order to detect delamination of the waterproofing membrane. It is shown that with the help of this method, it is possible to conduct a qualitative analysis of the state of the object based on the temperature difference on the surface. But the issue of obtaining stable quantitative indicators related to the internal temperature state of the dam remained unresolved. The probable reason is the difficulties associated with the lack of a method for recording temperature fields inside the dam. The disadvantage of the study is the lack of quantitative assessment related to water infiltration. An option to overcome difficulties is to devise a temperature criterion for infiltration, on the basis of which a quantitative assessment of the process can be obtained. All this makes it expedient to conduct a study on devising a temperature criterion for infiltration and a temperature pattern inside the dam.

Similarly, work [5] proved the effectiveness of thermography in relation to dams, but only for the detection of various surface defects (cracks, peeling) in concrete structures. During the research, only external thermography was used, which limits the possibilities of acquiring a real pattern of the condition of concrete inside the dam. Thus, the issue of using thermography to detect infiltration through concrete was not considered. In addition, it has not been fully clarified how non-stationary temperature fields can be induced in concrete, sufficient for the registration of defects by a thermal imager.

A solution to this problem is given in [6], in which the problems of thermographic survey of hydrotechnical structures are considered. It is shown that this method effectively controls reinforced concrete slabs for fixing slopes. An interesting opinion is expressed about the use of natural sources to create non-stationary temperature fields in controlled objects. The need to use special methods of processing thermograms to eliminate the influence of significant natural disturbances is emphasized. But infiltration of moisture into concrete was not considered. The reason for this may be the difficulties associated with the search for a control object in the form of a concrete dam and the development of the survey methodology.

These difficulties are partially resolved in [7], which reports the detection of infiltration and water leaks in hydrotechnical structures. It is shown that thermography provides the determination of places of increased infiltration in concrete linings, and also allows detection of leakage through earthen dams. It is noted that in order to ensure the effectiveness of thermographic examination, it is necessary to choose the appropriate natural conditions for its conduct. In particular, the temperature of the flowing water must be significantly different from the ambient temperature. However, the work does not consider the issue of moisture penetration into the thickness of concrete. And this process is fundamentally different from a similar one in earthen dams, so it is necessary to conduct relevant research specifically on concrete dams.

Paper [8] addresses this issue by reporting the results of studying the lower outer surfaces of concrete dams for the detection of water rises by the thermographic method. It is shown that it is possible to detect areas with structural anomalies or aging of materials that appear due to water seepage through the body of the dam. But issues related to temperature fields caused by water infiltration inside the dam remained unresolved. The reason for this may be the difficulties associated with the complexity and laboriousness of recording the temperature fields inside the limited spaces of the observation galleries inside the dam. The disadvantage of study [8] is the lack of a temperature pattern associated with infiltration processes inside the dam. An option to overcome related difficulties is to devise a technique for internal thermography in the inspection galleries of dams. All this gives reason to claim that it is expedient to carry out a study on identifying the places of water infiltration in the concrete base of the dam.

Summing up our review of the subject-specific literature, one should note that thermography, as a method for surveying the technical condition of hydrotechnical structures, has proven its effectiveness and potential. Moreover, there is evidence that this method makes it possible to detect places of moisture infiltration in concrete dams. But only superficial water seepages, usually associated with cracks in concrete, have been investigated. Infiltration of water through the concrete wall of the dam was not considered. This is probably explained by the need for access from two sides of the wall, which is possible only in dams with internal galleries. In addition, there is no integral criterion for assessing the intensity of infiltration, based on the information contained in the acquired thermograms.

Thus, it is appropriate to conduct a study aimed at devising a thermographic method for detecting and quantifying the degree of water infiltration in the concrete body of a dam.

3. The aim and objectives of the study

The purpose of our studies was to assess the possibilities of using thermography to control the degree of water infiltration in the concrete body of a dam. This could make it possible to practically monitor the state of concrete at various hydrotechnical structures, for example, the Dnipro HPP.

To achieve the goal, it was necessary to perform the following tasks:

– to choose the most speed-optimized method for inspecting the concrete surface with a thermal imager;

– to conduct a natural experiment and devise a temperature criterion for assessing the degree of water infiltration;

– to devise a methodology for processing observation results;

– to qualitatively and quantitatively assess the state of water infiltration along a dam.

4. The study materials and methods

A historical hydraulic structure was chosen as the research object – the dam of the Dnipro Hydroelectric Power Plant, the body of which incorporates internal viewing galleries that provide access to the opposite surface from the water (Fig. 1).

The Dnipro HPP dam has the shape of an arc with a radius of 690 m and a length of 766 m. The above-water part has 48 supports forming 47 spans of the spillway.

According to the scheme for conducting a thermographic study, shown in Fig. 1, thermal imager 5 was located in gallery 4, due to which it was possible to register the infiltration of water 3 through concrete body 2 of the dam.

It was assumed that in those areas of the inner surface of concrete where water infiltration 3 is observed, the temperature would differ from the average value, which could be an informative sign of the presence of concrete density violations.

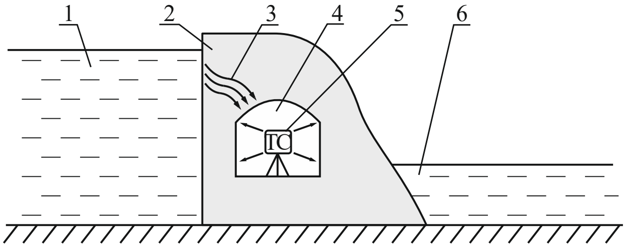


Fig. 1. Schematic showing the thermographic monitoring of the dam body: 1 — river in front of the dam; 2 — dam body; 3 — place of water infiltration; 4 — internal gallery; 5 — thermal imager; 6 — the river behind the dam

From a practical point of view, the choice of the Dnipro HPP dam is based on the fact of its historical uniqueness. Construction of the Dnipro HPP began in 1927, the first hydro units were put into operation in 1932, and its construction was completed in 1939. The dam was the largest such structure in Europe for a long time and is still considered a masterpiece of world engineering thought. However, the historical events of the past could not help but affect the technical condition of this grandiose facility. During World War II, the dam was blown up twice [9]. The first time was during the withdrawal of Soviet military units on September 18, 1941; it was restored in 1943, but it was again destroyed by the retreating German troops on October 20, 1944. After the war, over a short time of 1947–1950, the dam was restored. In the 1970s, changes were made to the structure of the bridge crossing on the dam, which affected the overall distribution of its load. Many years of operation, multiple updates and structural changes have affected the technical condition of the facility.

Therefore, conducting a thermographic survey of the Dnipro HPP dam and evaluating the condition of the concrete base of the dam on its basis can be considered a relevant practical task.

Thermal images were acquired using an IRTIS-200 thermal imager. The limit of long-wave sensitivity of the IR sensor is 6.4 μm. Table 1 gives basic characteristics of IRTIS-200.

Table 1

Basic characteristics of the thermal imager IRTIS-200

Sensitivity to temperature changes at the level of 30 °C	0.05 °C
Field of vision	25×20 degrees
Instant field of vision	2×2 μrad
Range of controlled temperatures	−20...+1200 °C

The radiation perceived by the thermal imager has two main sources:

1) radiation emitted by the surfaces of the gallery and directly related to its temperature;

2) radiation emitted by heat-emitting devices (lighting lamps, electrical distribution equipment).

Because the goal of our study was to obtain relative temperature characteristics for different areas of the gallery, the emissivity of the object was set on one of the areas, named the reference one.

To increase the temperature contrast of the registered thermal fields, the survey was conducted at the beginning of September, taking into account the annual changes in water temperature in the Dnipro River (Fig. 2), which corresponds to the recommendations in [7].

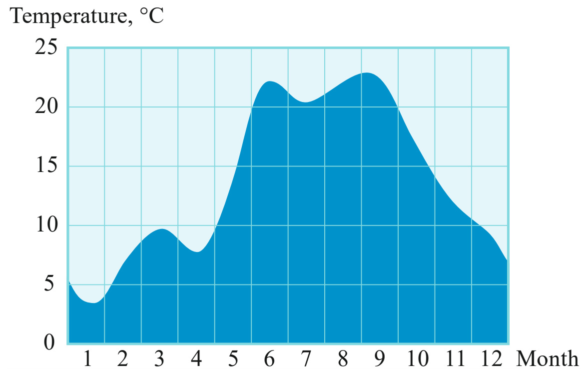


Fig. 2. Annual changes in water temperature in the Dnipro River

The surfaces of the walls and ceiling along the length of the viewing gallery were heterogeneous and areas with different conditions were observed:

– smooth dry concrete;

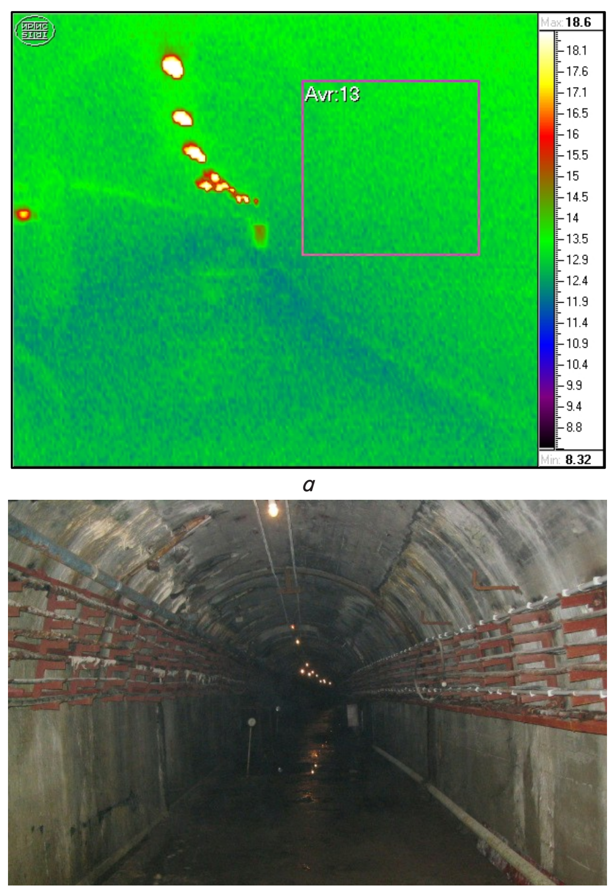
– smooth concrete of varying degrees of humidity;

– concrete covered with a coating of plant origin;

– concrete with traces of carbonation.

The research was carried out using the methods of comparative thermography. In particular, the integrated criterion for assessing the state of the gallery surface was applied to assess water infiltration through the concrete of the dam massif.

A surface with smooth and dry concrete with a temperature of 13 °C, close to the average temperature inside the gallery, was chosen as the reference area (Fig. 3).



a

b

Fig. 3. Reference surface of the dry section of the gallery: *a* — thermogram; *b* — visible image

The examination of the observation gallery of the dam was carried out from the right bank, and a reference site was also chosen there.

Along the length of the gallery, on the head-free wall, pointers with the numbers of the supports were installed on the outer upper part of the dam. The distances between the pointers corresponded to the length of the spans of the spillway. They served as landmarks when setting up the camera in the center of the gallery.

5. Results of the dam study

5. 1. Choosing a method for thermal imager inspection of the surface of concrete that is optimal in terms of speed

The dimensions of the gallery were 3×4 m, the length was 766 m, with a radius of curvature of 690 m. The dimensions and geometry of the gallery did not allow the use of the building thermography method, in which the optical axis of the thermal imager was perpendicular to the plane of the control object. Under the conditions of limited internal space and the curvature of the gallery walls, the survey of the internal surfaces and the accurate linking of the results to the state of the structural elements of the external surface of the upper part of the facility is a difficult task. The method of frame-by-frame shooting while moving the camera along the gallery was chosen. The duration of work using this method was 2 hours, which turned out to be 22 times faster than temperature registration of surfaces as in building thermography.

The disadvantages of the chosen thermography method included the following:

1) existence of a blind spot in front of the camera;

2) getting into the frame of a space that exceeds the length of the investigated section of the gallery (Fig. 4).

The shortcoming of the chosen thermography method was that a significant section of the gallery still entered the frame, which made it difficult to link the obtained temperature pattern to a specific spillway span (Fig. 4).

Fig. 4 demonstrates that the section of the gallery that exceeds two spans of the spillway enters the frame. For accurate installation on the front border of the studied area, the camera was installed in advance of the length of the blind zone, which was 2.5 m. The operator determined the boundaries of the areas by markings on the head-free wall. These actions made it possible to carry out thermal imaging of a part of the gallery that exactly corresponded to a certain span of the spillway. Thus, each frame of the thermogram captured a section of the gallery that corresponded to the length of the spillway span of the outer part of the dam.

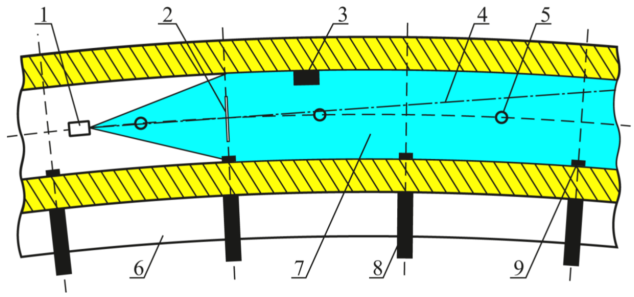


Fig. 4. Scheme of capturing the gallery space by the camera frame due to the structural curvature of the dam (top view): 1 — camera; 2 — large-scale ruler; 3 — electrical distribution equipment; 4 — optical axis of the thermal imager; 5 — lighting equipment; 6 — spans of spillways; 7 — the space captured by the camera frame; 8 — supports of spillway spans; 9 — labels with support numbers

5. 2. Field experiment and devising a temperature criterion for assessing the degree of water infiltration

As a result of the survey, water infiltration was observed in some areas of the gallery. The temperature of the water differed in the places of the leaks, which indicated the different speed of its arrival through the water-head wall and the ceiling inside the gallery (Fig. 5) [10].

Analysis of 47 acquired thermograms revealed that the temperature contrast between the leaked water and the walls of the gallery was 1.0–3.0 °C.

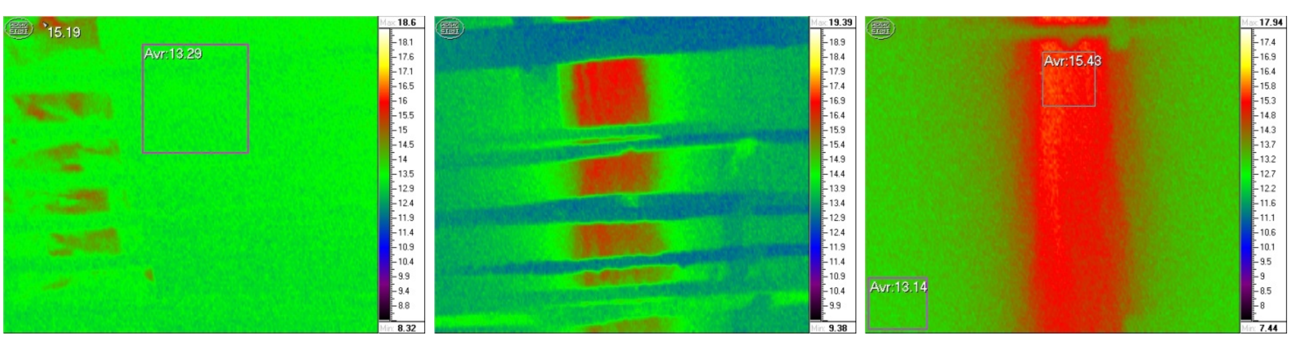
The structural features of the object and the analysis of previously acquired images made it possible to identify 3 factors that reduce the accuracy of the registration of the temperature fields of the gallery:

1) availability of heat-dissipating devices (electrical distribution equipment, lighting devices);

2) capture by the camera of a large space of the gallery, which in the projection on the above-water part corresponds to several spans of the spillway;

3) distortion of the image due to the structural curvature of the gallery walls (Fig. 4).

Analysis of the thermograms acquired as a result of our field experiment revealed differences in the average temperature in different parts of the gallery. Since this is a consequence of concrete deterioration, the average temperature was chosen as an integrated evaluation criterion.



a *b* *c*

Fig. 5. Temperature contrast ΔT of the infiltrated water on the water-head wall: *a* — ΔT=1.9 °C; *b* — ΔT=2.8 °C; *c* — ΔT=2.3 °C

5. 3. Devising a methodology for processing observation results

To reduce the influence of factors that compromise the accuracy of temperature field registration, a methodology for processing thermograms was devised, which took into account the features of the object of thermography.

To reduce the impact of the shooting angle on the research results, the acquired thermograms were integrally normalized according to the expression:

$$T(s,t)=\Upsilon\left\{\frac{F_T(s,t,\alpha)}{F_{TE}(s,t,\alpha)}\right\}=$$

$$=\Upsilon\left\{\frac{F_T(s,t)\Phi(\alpha)}{F_{TE}(s,t)\Phi(\alpha)}\right\}=\Upsilon\left\{\frac{F_T(s,t)}{F_{TE}(s,t)}\right\}, \quad (1)$$

where $T(s, t)$ is a function characterizing the temperature of the dam section after processing; $F_T(s, t)$ is a function that characterizes the temperature of the dam section before processing and does not depend on the viewing angle; $F_T(s, t, \alpha)$ is a function that characterizes the temperature of the dam area before treatment and depends on the viewing angle; $F_{TE}(s, t, \alpha)$ is a function that characterizes the temperature of the reference section of the dam before treatment and depends on the viewing angle; $F_{TE}(s, t)$ is a function that characterizes the temperature of the reference section of the dam before processing and does not depend on the viewing angle; $\Phi(\alpha)$ is a function characterizing the dependence of the functions $F_T(s, t, \alpha)$ and $F_{TE}(s, t, \alpha)$ on the viewing angle, and obtained from them using Lambert's law; $\Upsilon\{F_T(s, t), F_{TE}(s, t)\}$ is an operator that characterizes the sequence of applying filters and processing methods to the functions $F_T(s, t, a)$ and $F_{TE}(s, t, \alpha)$ in order to eliminate noise, obstacles, and elements that do not belong to the investigated section of the wall [11, 12].

Applying the variable separation method made it possible to identify a multiplier that takes into account, according to Lambert's law, the influence of the observation angle on the recorded heat flow. And since this is also true for the reference section, the influence of the resulting dependence on the resulting integrated function is leveled off. Given this, the speed and efficiency of the performed shooting increases.

The influence of external heat-emitting sources was reduced by software. Analysis of the elements of the temperature operator $T_{i,j}(x, y, t)$ revealed that the contrasts $dT_{i,j}$ of external heat-emitting sources introduce distortion into the usable signal. Therefore, to suppress this spatial obstacle, the method of computer processing of thermograms using dependences $dT_{i,j}(x,y,t)/dx$ and $dT_{i,j}(x,y,t)/dy$ was used. The map of partial derivatives of the temperature operator, constructed from the thermographic image of a frame of a part of the dam, is shown in Fig. 6.

The essence of this method is to calculate a two-dimensional matrix, the elements of which are the corresponding partial derivatives:

$$dT_{i,j}=\frac{\partial T_{i,j}(x,y,t)}{\partial x}dx+\frac{\partial T_{i,j}(x,y,t)}{\partial y}dy, \quad (2)$$

where $dT_{i,j}$ – thermal contrast.

All elements of the temperature operator $T(i, j)$, for which the thermal contrasts $T(i, j)$ exceed the threshold values ΔT, were excluded from further calculations by replacing them with images of areas with an average temperature T_{av} of this part of the gallery.

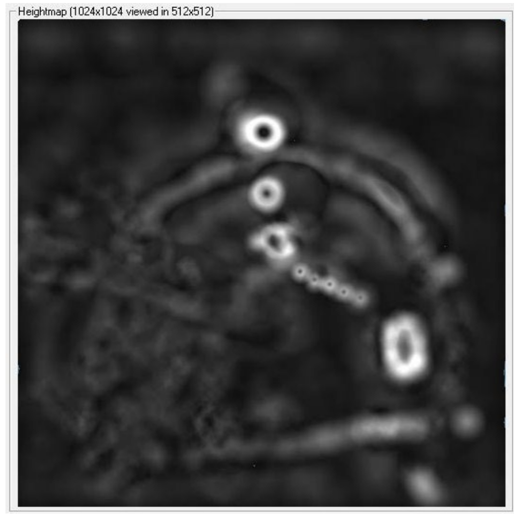


Fig. 6. Results of thermogram processing by the method of partial derivatives for the purpose of contouring heat-emitting sources

After filtering the acquired image using the dependences shown in Fig. 6, we get the final view of the thermogram after processing (Fig. 7, *b*). Comparison of the acquired thermogram with the original one (Fig. 7, *a*) confirms the fact that the influence of external heat-emitting sources has significantly decreased after processing. Quantitative assessment shows a decrease in the interference signal by more than 2.5 times [12, 13].

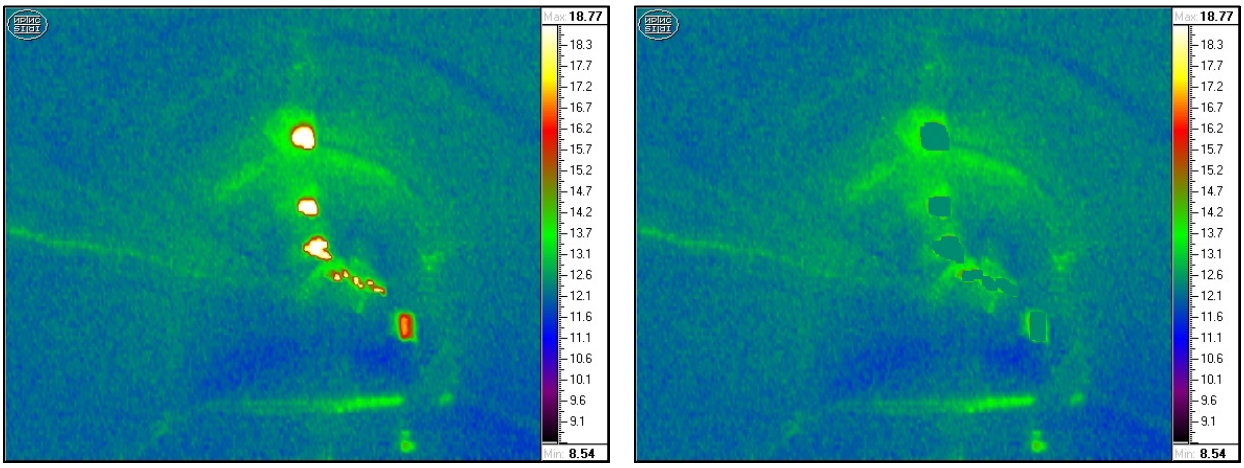
Having decoded $T_{i,j}(x, y, t)$ using the $dT_{i,j}$ dependences shown in Fig. 6, we build a map of derivatives that indirectly characterizes the position of external heat sources (Fig. 5).

During thermal imaging, a part of the gallery that did not belong to the surveyed area was captured in the frame (Fig. 3, 5). In order to eliminate other parts of the gallery from entering the frame and perspective distortion due to the curvature of the structure, a procedure was devised and used, which made it possible to exclude an unnecessary part of the thermal image. Based on the dimensions of the cross-section of the gallery and the position of the borders of the following sections, the dimensions of the mask were calculated, which hid the part of the image related to the continuation of the gallery. As a result, only the investigated section of the gallery entered the camera frame, and the following were screened and were not taken into account in the calculations

Exclusion of a part of the gallery that does not belong to the corresponding section was carried out in several stages. First, on the reference (undamaged) space of the gallery, the recalculation of the frame scale to the real dimensions of the gallery was performed for equipment elements of a known size that entered the frame.

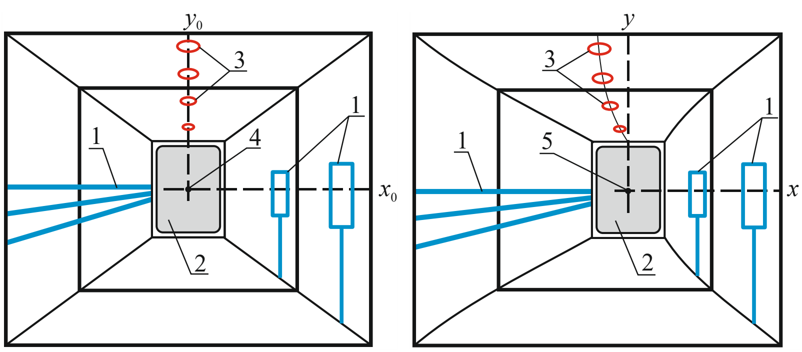
The next stage was the collection of additional a priori information about the geometry of the corridor through measurements and calculations of the sizes and positions of periodically located equipment elements: cables, switchboards, lighting elements (Fig. 8, *a*).

The correction for the curvature of the gallery was accounted for based on the location of the lighting lamps on the ceiling. The use of a priori information made it possible to calculate corrections dx and dy to the coordinates of the center of the filtering mask (Fig. 8, *b*).



a *b*

Fig. 7. Eliminating the influence of external sources of radiation: *a* – initial thermogram; *b* – processed thermogram



a *b*

Fig. 8. Schematic showing the frame of the thermal imager in perspective: 1 – elements of the gallery equipment; 2 – filter mask; 3 – lighting lamps; 4 – coordinates of the center without taking into account the curvature of the gallery; 5 – coordinates of the center, taking into account the curvature of the gallery; *a* – without taking into account a priori information; *b* – taking into account a priori information

Given the magnitude of the curvature of the dam body with a radius R and the length of the gallery span studied in one frame L, we can say that $R \gg L$, namely, that the radius of curvature of the dam is much greater than the length of the studied span [14, 15]. Then the dx value, namely the correction to the x coordinate of the center in the frame due to the curvature of the dam, can be calculated using the formula:

$$dx = \frac{R}{M}\left(\sqrt{1+\frac{L^2}{R^2}}-1\right), \quad (3)$$

where M is the scale determined by the size of one pixel of the image in meters in the plane of mask placement. The scale is calculated based on the size of the reference object located in the same plane.

Also, taking into account the error of the angle of camera location with respect the floor (90±2°), the vertical correction dy was calculated based on the expression:

$$dy = \left(\frac{y_2' - y_1'}{2} + y_1'\right) - \left(\frac{y_2 - y_1}{2} + y_1\right) = \frac{y_2' + y_1'}{2} - \frac{y_2 + y_1}{2}, \quad (4)$$

where y_2' is the vertical coordinate of the center of the gallery ceiling on the processed frame in the mask placement plane; y_1' – vertical coordinate of the center of the gallery floor on the processed frame in the mask placement plane; y_2 is the vertical coordinate of the center of the gallery ceiling on the reference frame in the plane of the mask placement; y_1 is the vertical coordinate of the center of the gallery floor on the reference frame in the mask placement plane.

Processing of the acquired thermograms was carried out in four stages:

1. Analysis of the visible image, which included:

– selection on the visible image of zones of interest (zones with a sharp brightness gradient) and zones that do not belong to the investigated section of the corridor;

– obtaining contours from the map of partial derivatives according to the intensity of the selected object of a technological nature on the visible image;

– transfer of the contours of the zones of interest to the thermogram;

– detection of zones with average emissivity on the investigated surface of the gallery.

2. The thermogram of each part of the gallery was prepared using the following methods:

– normalization of the image (redistribution and matching of coordinate values and intensity values of the corresponding pixels in the image);

– combined filtering with differentiated smoothing of areas with different information value [13];

– median method [16, 17];

– linear and non-linear filtering [18];

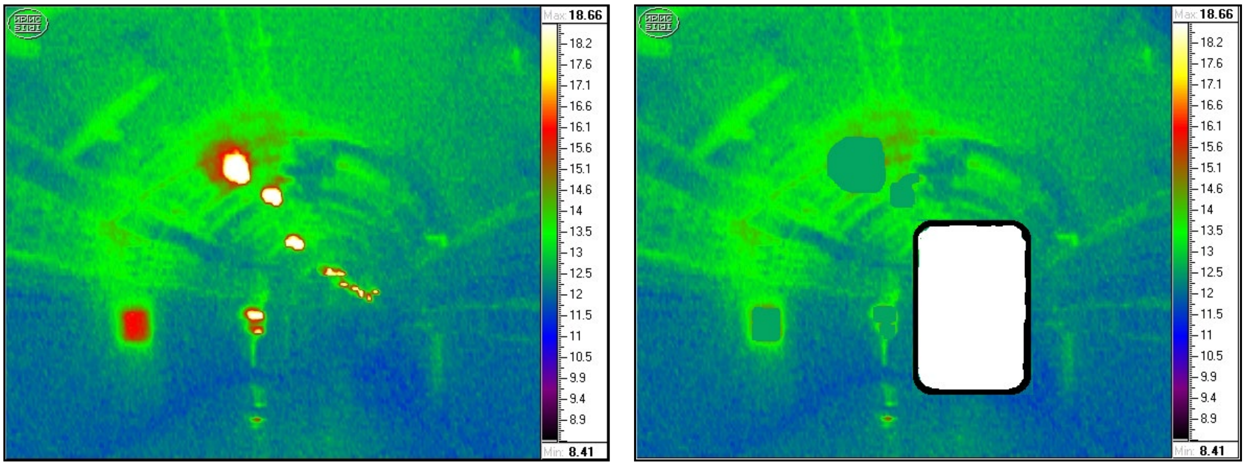
– the SUSAN method [19, 20];

– convolution [15].

3. Based on the scheme of the frame (Fig. 5) and the visible image (Fig. 3, *b*), the effective distances (in pixels) were calculated according to the x and y coordinates of the frame, which relate to the studied area. The dimensions of zone masks or "windows" that do not apply to the investigated part of the gallery were also defined. The specified masks were removed from the frame when window filtering was applied.

4. The specified zones were excluded from the frame and were not taken into account in the calculation. The average temperature T_{av} was calculated for each processed frame.

The results of algorithm application when processing a sequence of thermograms according to the specified methodology are shown in Fig. 9.

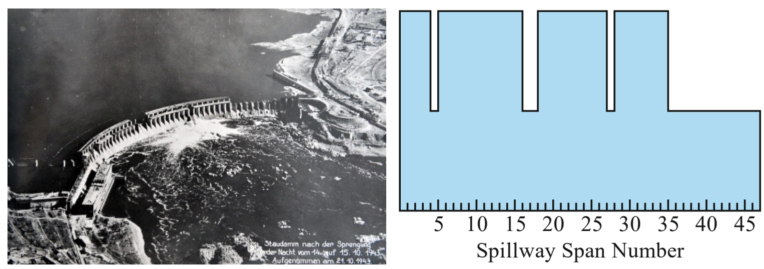


a *b*

Fig. 9. Thermogram of the section of the upper gallery with angular displacement:
a — untreated, T_{av}= 13.6 °C; *b* — after processing, T_{av}= 12.7 °C

At the same time, the angular perspective obtained from a priori information according to the scheme shown in Fig. 5 was taken into account.

Fig. 9 demonstrates that as a result of thermogram processing, the integrated temperature criterion T_{av} turned out to be less than that on the unprocessed one because of the exclusion of influence of lighting lamps and electrical distribution equipment, as well as taking into account the mask. After processing the entire sequence of thermograms, the difference between the average temperatures of treated and untreated ones was 0.7–2.8 °C.



a *b*

Fig. 11. Dnipro HPP Dam:
a — after the explosion on October 15, 1943; *b* — diagram of destruction of the above-water part of the dam

5. 4. Qualitative and quantitative assessment of the state of water infiltration along the dam

Based on the results of the processed thermograms, the dependence of the integrated temperature criterion T_{av} of the gallery on the number of a spillway span was obtained (Fig. 10).

According to Fig. 10, the temperature distribution in the gallery is uneven, which is an indicator of the intensity of infiltration processes. Sections of the gallery adjacent to the left bank of the river (No. 27–45) stand out. They have a temperature criterion higher than the areas adjacent to the right bank. This difference sometimes reaches 1.8 °C. A noticeable anomaly is observed in the area of section No. 17. A comparison of the results of frame-by-frame processing of the temperature field of the gallery (Fig. 10) with the image of the destroyed part of the Dnipro HPP dam (Fig. 11) revealed the coincidence of abnormally warm areas with restored wartime destruction of the surface part.

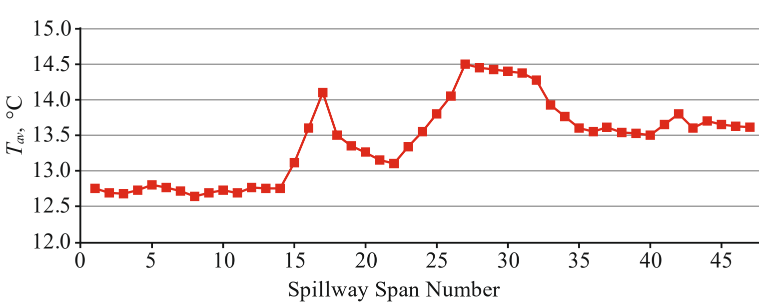


Fig. 10. Dependence of the integrated temperature criterion T_{av} of the gallery surface on the number of spillway span

According to Fig. 11, the following piers of spillway spans were destroyed:

1) No. 4, 5;
2) No. 16–18;
3) No. 27;
4) No. 35–47.

The higher temperature of the specified sections of the gallery is the result of water infiltration into the body of the dam. Comparing the results of frame-by-frame processing of the temperature field of the upper observation gallery (Fig. 10) with the image of the destroyed dam of the Dnipro HPP (Fig. 11) proved the coincidence of abnormally warm areas with restored wartime destruction of the upper surface part.

6. Discussion of results of the dam study

The main result of our work relates to devising an express method for detecting places of water infiltration through the concrete of the dam by thermographic examination. This is possible only for dams with internal galleries, which makes it possible to place the thermal imager inside the concrete body and thus record the temperature fields from inside the dam (Fig. 1).

It has been confirmed that the choice of time for monitoring is related to the condition of the largest temperature difference of the water in the reservoir (Fig. 2) and the concrete of the dam. It was found that under such conditions, temperature drops caused by infiltration reach 0.7–2.8 °C (Fig. 5), i.e., values sufficient for recording by a thermal imager.

The features of the proposed method in comparison with those reported in [4–8] are as follows:

– when registering temperature fields inside the gallery, the field of view of the thermal imager is oriented not perpendicular to the surface but along the gallery, which gives a 22-fold increase in control speed;

– to assess the degree of water infiltration, we use the integrated temperature criterion in the form of the temperature averaged over the area of the frame, due to which the reliability of the method increases, and the interpretation of control results is simplified;

– the obtained observation results in the form of thermograms are subject to processing according to the developed algorithm for the purpose of correcting thermal images, excluding redundant areas with the help of a mask (Fig. 9), reducing the influence of various interferences (Fig. 7).

The validity of provisions underlying the method devised has been confirmed by the results obtained when it was applied to monitor the condition of the concrete dam of the Dnipro HPP in Ukraine (Fig. 10). Their comparison with previous destruction of the dam (Fig. 11) shows that the greatest infiltration of water was recorded precisely on the disturbed and subsequently restored spans, where the condition of the concrete is probably worse.

The limitation in applying the proposed thermographic method for surveying moisture infiltration through the thickness of concrete is that it is suitable only for structures where access to the surface opposite to the one washed by water is possible. These are, for example, dams with internal galleries.

The second limitation is related to the condition that the temperature of the water, the infiltration of which is controlled, would be several degrees higher than the temperature of the concrete.

When conducting surveys, there should be some coordinate markings in the internal gallery, for example, span numbers, which are needed to link the results of thermography to the location of infiltration sites.

The limits of adequacy of the theoretical provisions, which are the basis of our research, do not go beyond the scope of the tasks set for its implementation.

The main drawback of our research is the lack of comparative tests with normative construction methods of concrete quality control. Therefore, it is possible that in the future, after conducting such tests, some corrections will have to be made to the method of conducting a thermographic survey of the surface and the algorithm for processing the results.

The evaluation of possibilities for using thermography to control the degree of water infiltration in the concrete body of the dam showed that the devised method could become an effective supplement to existing standards as an indicative express method for monitoring the state of concrete in dams.

7. Conclusions

1. A method for conducting a thermographic examination of the state of concrete in dams has been chosen, which involves the registration of temperature fields on the surface of concrete inside the internal gallery of the dam using a thermal imager.

2. An approach has been proposed to increase the speed of examination (monitoring) through the choice of thermography angle aimed along the gallery. It was established that the temperature field could serve as an informative sign of the presence of moisture infiltration sites in the concrete body of the dam.

3. A methodology for processing the results of thermography (thermograms) has been devised, which ensures the elimination of the influence of various obstacles, restoration of the thermal image and its binding to certain coordinates of the dam. A special feature of our procedure is that, firstly, it makes it possible to correct the distortion of thermographic images caused by the selected shooting angle by computer. Secondly, it ensures the determination of the integrated criterion of the state of infiltration (the average temperature of the thermogram) and filters thermal images from extraneous heat sources. As a result, it makes it possible to distinguish a usable signal against the background of interference at a high speed of information capture.

4. It has been established that the selected criterion at the qualitative level – the average temperature of the thermogram – fully corresponds to the state of water infiltration through a concrete wall. This is confirmed by the coincidence of the detected anomalies in the distribution of concrete temperature along a specific dam (Dnipro HPP) with former damage to its body. Quantitative estimates of the value of the proposed criterion at the level of 0.7–2.8 °C compared to the sensitivity of thermal imagers of 0.05–0.2 °C indicate the sufficient sensitivity of the method. The speed of the method devised is quite high – up to 200 m of dam length per hour, which allows it to be used as an express method as a component of complex diagnostic control, analysis, and safety assessments of hydraulic structures.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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