Slope stability of the Włocławek Dam frontal earth dam in the light of the modernisation works carried out in the period 2000-2011

Stabilité de la pente du barrage en terre de Włocławek à la lumière des travaux de modernisation exécutés dans la période 2000-2011

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The authors of this paper carried out an analysis of archival data associated with the more than 40 years of Włocławek Dam exploitation for the needs of new dam design within the lower section of the Vistula River. The analysis was aimed at the issue of the existing dam safety and covered all its elements including the frontal earth dam. Archival geotechnical investigation were analysed as well as the monitoring results and all the modernisation and improvement works executed since the year 2000. As part of the task slope stability analyses were carried out for the frontal earth dam for various filtration conditions accounting for changes resulting from the modernisation works and improvements. The calculations were realised for variable sets of geotechnical parameters as a result of the interpretation of available archival geotechnical data in form of a sensitivity analysis in order to facilitate the comparison of the analysis outcome with the results of archival analyses done by others during the exploitation period of the structure. Within this paper the background for performing the analysis has been described as to explain the safety issues related with the existing structure in the light of the ongoing design of the new dam structure downstream.

Les auteurs de cet article ont conduit l'analyse des données concernant 40 ans d'exploitation du barrage de Włocławek, nécessaires pour élaborer le projet de construction d'un nouveau barrage situé en aval sur la Vistule. L'analyse a pris en considération avant tout la sécurité du barrage existant et tous ses éléments, y compris le barrage frontal en terre. On a analysé les informations géotechniques, les résultats d'observation et tous les travaux de la modernisation exécutés après l'année 2000. On a exécuté les calculs de la stabilité de la pente du barrage pour des conditions d'infiltration différentes. Les calculs étaient faits pour divers jeux de paramètres géotechniques (obtenus par interprétation de données géotechniques d'archives), sous forme d'analyse de sensibilité. Ce type de calcul a facilité la comparaison de nos résultats avec ceux d'analyses exécutées par d'autres pendant l'exploitation de l'ouvrage. L'article contient la description de la base de calcul et l'explicitation des problèmes de la sécurité du barrage à la lumière du projet de construction du barrage nouvel situé plus bas en cours du fleuve.

KEYWORDS: earth dam safety, seepage, piping effect, suffusion, internal erosion,

1 INTRODUCTION.

The analysed Dam structure is located at 674+500km chainage of the Vistula River in Poland. It consists of earth frontal dam (length of approximately 635m), 10 bay weir, fishpass, hydropower plant and navigation lock.

The soil profile beneath the dam and weir foundation level is formed by alluvial sands and partially by Tertiary deposits in form of clays, high plasticity clays and sands. The hydropower plant and navigation lock are founded on approximately 6 – 8m thick Pliocene clays and high plasticity clays overlying Miocene sands with lignite interbeddings. The earth dam body was formed partially as hydraulic fill (its centre and bank side) and partially as traditional fill (within the former river island zone).

The structure was originally designed as first of eight similar dams working in a cascade, however originally assumed system was never constructed, which basically resulted, in lack of downstream support to the analysed structure as assumed in the design process. In turn the structure has been operational since its construction in 1970 under unfavourable conditions compared to the design.

The key condition for establishment of cascade of dams along the Vistula River was, that downstream water level for each of the proposed dams to be formed by backwater from the downstream structure.

2 STUDY

Lack of the next structure downstream from Włocławek as discussed above induced major changes to the bottom of river valley immediately below and further downstream from the existing dam. Downstream erosion caused significant lowering of the river bottom within 40km distance from Włocławek, with obviously the most significant effect immediately below the dam cross-section. The observed effects of downstream water level lowering comprised among others:

- Abasement of the phreatic level within the earth dam,
- Increase of the hydraulic gradients below the weir and hydropower plant,
- Impact on hydropower plant blocks overall stability.

The induced areas of threats, to which Włocławek Dam has been exposed within passing years are the following:

- Decreasing density of the material within earth dam body,
- Hydraulic contact between up- and downstream levels within 6 of weir bays.

Since 1970s, when Włocławek Dam became operational, it was subject of continuous documentary, investigation, observations and modernisation works.

Within years of exploitation number of ground investigation campaigns and technical condition assessments was undertaken, starting from 1986, when first dynamic soundings through the earth dam were executed, supplemented by CPTs and georadar surveys in following years. Underwater observations and examinations were also carried out.

The processes of internal erosion of the dam body has been observed and degradation of its structure notified. These processes were described by W.Wolski and M.J.Lipiński, A.Furstenberg and T.Barański in "Influence of internal erosion on safety of old dams" 2000 and they generally consists of movements of soil particles within soil layers, form one soil to another, along boundaries of the layers or along the soil contact with rigid surfaces such as concrete etc.

"These movements of soil grains, irrespective of the aforementioned situations, are strongly dependent on the force of seeping water, characterized by the hydraulic gradient. The bigger the force of seeping water, the coarser the grains which can be moved. The movement of the soil particles is controlled by the geometry of the pores in the soil, particularly any constrictions the particles encounter during their movement. Certainly, if a particie is bigger than a constriction, the constriction will prevent its further movement (Kenney & Lan, 1985).

Nevertheless, whichever type of internal erosion takes place, the effect of the process is to increase the porosity of the soil zone thus influenced (Lafleur et al., 1993).

The effects of internal erosion most often detected are those located close to the drainage zones, which are characterised by higher gradients, particularly where the filters are not efficient. In these zones a large volume of particles may be washed out of the dam body or its foundation, thus creating sinkholes or caverns, often followed by regressive erosion - piping (Wolski, 1987).

Much more hazardous for dam safety, because more difficult to detect, are the internal erosion "Loose zones", which are characterized by increased (with respect to initial) porosity of the soil, which may develop without visible symptoms on the ground surface or the slopes of the dam. The internally eroded soil in the loose zones may be contractive during undrained shearing and therefore it has a high liquefaction potential. The phenomenon of liquefaction initiated in such loose zones "hidden" in the foundation or dam body can be triggered by any dynamic loading, e.g. during flood discharge, thus causing a flow slide usually with catastrophic consequences"

One of the elements being the subject of consistent observation and recording is the shape of phreatic level within the earth dam of Włocławek. This is supported by dense network of piezometers installed and automatically observed during the years of operation.

It has been identified that the observed phreatic level within the earth dam significantly differs from the designed one, calculated for stable downstream level (W.Wolski & others; 2000). Based on archival data analysis the scheme of low density material extent has been prepared (W.Wolski., J.Mirecki. 2011) within cross-section V – see Drawing 1. Drawing 2 presents the zones of loose material within dam body (with D_R<0,33). Based on the scheme of material zones the numerical model of the dam has been generated, taking into account the zones of low density material. Calculations have been performed using Z_SOIL2011v.11.13 software, the commonly used software based on final elements analysis method used for geotechnical, hydrotechnical and environmental engineering calculations (Data Preparation & Tutorials Z_SOIL PCv2010).

4 variants were considered for calculation purposes:

Variant 1 – the zones of low density material as shown on Drawing 3. The academic assumption (based on expert's recommendation) was, that low phreatic level within the dam is being induced by proper work of surface insulation of upstream slope. The watertight facing adopted within zone of known upstream slope surface strengthening. The scheme of material zones as shown on Drawing 3.

Variant 2 – assumptions as per Variant 1. The watertight screen adopted within zone of known concrete panels location at upstream slope surface.

Variant 3 – the zones of low density material considered as per Drawing 3. The upstream slope surface insulation not considered, due to poor condition of the slope strengthening elements, qualified for repairs. The piping effect considered within dam base, as per expert's recommendations (W.Wolski, J.Mirecki.2011). Location of the piping effect has been indicated within area, which was the subject of temporary partition during construction stage and where strong water flow was observed (K.Fanti, K.Fiedler, J.Kowalewski, S.Wójcicki, 1972)(page 352 drawing 5-5). Based on this assumption the zone of loose alluvium has been introduced within the model, that such effect has not been considered at design stage as induced during dam erection. This area has been prescribed for piping effect occurrence. Similarly, another zone of piping effect may take place in location of oxbow beyond the earth dam. Material zones scheme for Variant 3 as per Drawing 5.

Variant 4 – all assumptions as for Variant 3. Additionally, the watertight facing has been adopted within zone of known concrete panels location at upstream slope surface. Variant 4 assumes necessary repairs of concrete panels made.

At calculation stage, the different up- and downstream water level configurations were considered. Flooding conditions were modelled as per water states dated 23.05.2010, and normal working conditions dated 01.04.2012.

Boundary conditions were established based on both of records from existing piezometers and up- and downstream water levels. Two calculation cases were taken into consideration: normal working conditions and flooding conditions.

The piezometers network has been modelled, and after analysis completion, the results were compared with values observed in real. The seepages at upstream slope were also analysed, however only the ones having place above the existing downstream water level were considered. The above comparison was used for back analysis of the ground parameters and adequate modifications were made to meet the best matching to the real situation. The leading case for parameters verification was the normal working conditions of the dam.

The analysis results were presented in form of phreatic level projection across the dam body cross-section. Variant 1 is shown on Drawing 7. This drawing presents the low arrangement of groundwater level, which closely reproduces the one observed at the dam.

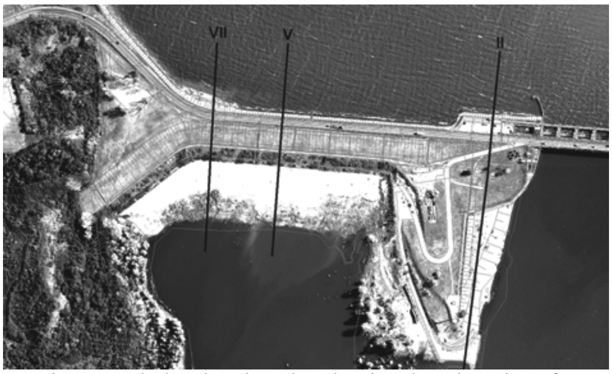
The arrangement of phreatic level is due from calculation based on the assumption that there is an impermeable facing on upstream slope. The aim of variant one of calculations was to demonstrate whether it is possible to achieve the low level of phreatic level as described in professional literature. Despite the convergence of a solution obtained from the calculations and the observed in nature above mentioned situation does not occur in the area of Wloclawek Dam. Structures situated on upstream slope were qualified to repair and do not meet conditions made in the calculations for Variant 1.

The results of phreatic level calculation in Variant 2 are presented on Drawing 8. This variant of calculations was based on the assumption that there is a watertight facing in the area of slope with reinforcing concrete panels. The results of numerical analysis for Variant 2 were not in the compliance with the position of phreatic level observed in nature.

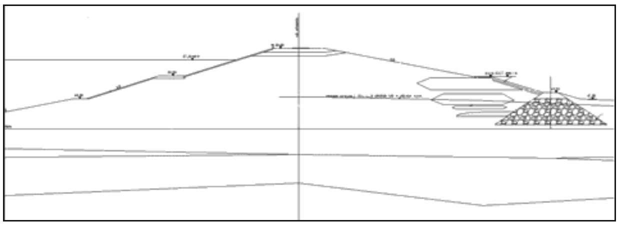
The calculation results of phreatic level in Variant 3 are presented on Drawing 9. The appearance of piping effect in the base of the dam was considered in this variant. The position of phreatic level obtained in the calculations is the most consistent with the conditions observed in nature comparing to other variants. The differences relate to the initial filtration section where soil loosening effect may occur. It can cause the change of filtration factor and flow of water perpendicular to the surface of the model which is impossible to capture in 2D modelling.

The calculation results of phreatic level in Variant 4 are presented on Drawing 10. This variant was based on the assumption that there is piping effect and hypothetically watertight facing in the area of slope with reinforcing concrete panels. In calculations the position of phreatic level is different from what was observed in nature.

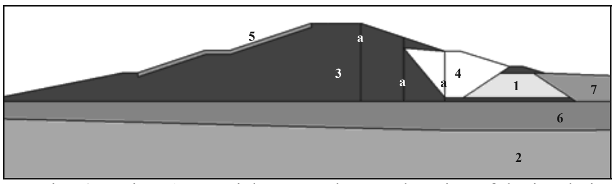
3 DRAWINGS



Drawing 1 Earth dam location plan showing the orientation of cross-section taken for calculations

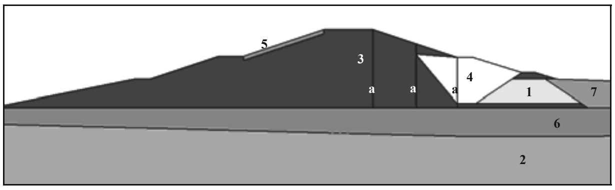


Drawing 2 Cross-section V with low density material zones marked

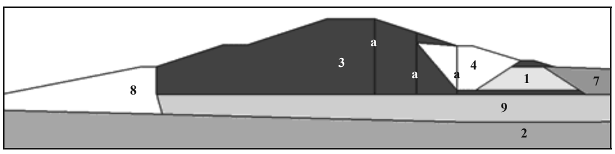


Drawing 3 Variant 1 Material zones scheme – location of the insulation at upstream slope

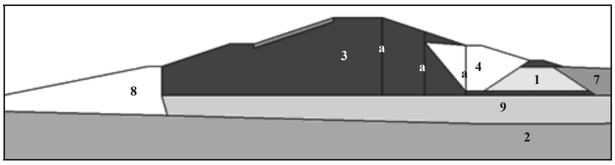
Material description – 1) dam drainage 2) impermeable layer 3) dam body – fine sand 4) loose zone within dam body 5) concrete panels/facing covering upstream slope of the dam 6) sands 7) berm 8)vertical piping – see drawings 5&6. 9)horizontal piping – see drawings 5&6 a) locations of piezometers taken into account for model establishment.



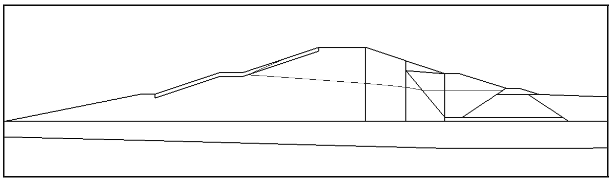
Drawing 4 – Variant 2 Material zones scheme – location of the insulation at upstream slope, within zone of concrete panels



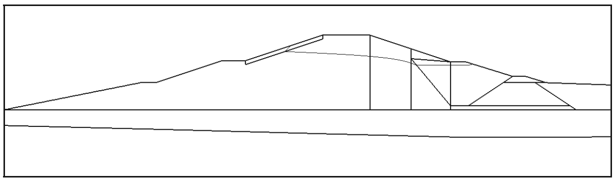
Drawing 5 Variant 3 Material zones scheme – piping effect at dam base



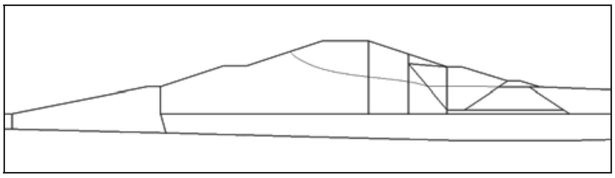
Drawing 6 Variant 4 Material zones scheme – piping effect at dam base plus watertight facing within zone of concrete panels installation



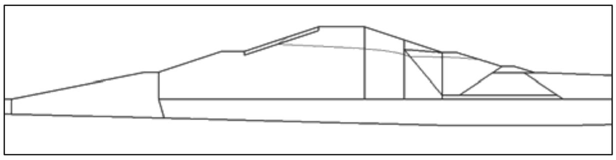
Drawing 7 Variant 1 Phreatic level across earth dam and material zones



Drawing 8 Varian 2 Phreatic level across earth dam and material zones.



Drawing 9 Variant 3 Phreatic level across earth dam and material zones



Drawing 10 Variant 4 Phreatic level across earth dam and material zones

4 CONCLUSIONS

The observed phreatic level course within the earth dam body differs significantly from the design values, which were assumed based on specified, stable downstream water level.

In Variant 3 the location of piping failure has been assumed based on known oxbow presence or base loosening indicated during the last phase of earth dam construction. These locations are hypothetical, however low phreatic level within dam body proves that phenomenon hazardous to Włocławek Dam exists.

In Variant 4, both of piping failure existence and parallel reinforcing of concrete panels at upstream slope induce deterioration of earth dam working conditions within the drainage zone (where interface between drainage and dam material not exists). It causes flow concentration and rising of the phreatic level and thus further development of suffusion phenomenon within ends of filtration paths through the dam.

Further, the seepage deformation might develop without strictly and immediately visible symptoms, and therefore might not be noticed during the operational activity of the entire structure.

This shall be also concluded, that construction of new dam, below the existing Włocławek Dam should improve its working conditions by reducing the differences between up- and downstream water levels, and thus pressure gradients which cause the suffusion within and below dam body.

Protection of the object against suffusion phenomenon development and piping effects shall be treated as the main element securing safety of Włocławek Dam.

For further observations of the loose zones and determination of the density change, periodic density control tests shall be introduced in the area of a site particularly exposed to high hydraulic gradients, as discussed above.

It is necessary to ensure that control tests are done with the use of equipment of internationally recognized standards in order to obtain the required accuracy of the density change determination and comparable results across worldwide known cases.

5 REFERENCES

Wolski W., Mirecki J. 2011. *Technical condition of Włocławek Dam assessment.* Warsaw.

Design documentation for establishment of geological conditions under Włocławek Dam.

Fanti K., Fiedler K., Kowalewski J., Wójcicki S. 1972. *Weirs*, Warsaw.

Data Preparation & Tutorials Z_SOILPCv2010. 2010. Lausanne

Wolski W., Lipiński M.J., Furstenberg A., Barański T. 2000*k*