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A FLOOD EMBANKMENT UNDER CHANGING WATER LEVEL CONDITIONS – A COMPARISON OF A PHYSICAL AND A NUMERICAL MODEL

***Jarosława Kaczmarek*[1], *Danuta Leśniewska*[2]**

[1] Chair of Civil Engineering and Building Constructions
University of Warmia and Mazury in Olsztyn
[2] Institute of Hydroengineering, Polish Academy of Sciences in Gdańsk
University of Technology in Koszalin

K e y w o r d s: flood embankments, changes in the water level, modeling, FEM caluclations, PIV method.

A b s t r a c t

The paper compares the results of a study on a plane physical model of a flood embankment with the outcome of a numerical modeling using the finite element method (FEM). The numerical modeling was performed with the PLAXIS software package while the empirical data were processed with the geoPIV programme. Two types of model studies were completed, consisting of alternately raising (up to complete flooding) and lowering (to complete desiccation) the water table which affected the flood embankment model. The objective of the study was to assess the applicability of the particle image velocimetry (PIV) method to analyzing deformations of a flood embankment under changeable hydrological conditions. Qualitative agreement was found between the empirical and numerical displacement fields in the body of a flood embankment.

WAŁ PRZECIWPOWODZIOWY W WARUNKACH ZMIENIAJĄCEGO SIĘ POZIOMU WODY – PORÓWNANIE MODELI FIZYCZNEGO I NUMERYCZNEGO

***Jarosława Kaczmarek*[1], *Danuta Leśniewska*[2]**

[1] Katedra Budownictwa i Konstrukcji Budowlanych
Uniwersytet Warmińsko-Mazurski w Olsztynie
[2] Instytut Budownictwa Wodnego PAN w Gdańsku,
Politechnika Koszalińska

S ł o w a k l u c z o w e: wały przeciwpowodziowe, zmiany poziomu wody, modelowanie, obliczenia MES, analiza obrazu, metoda PIV.

A b s t r a k t

W pracy przedstawiono porównanie wyników badań na płaskim fizycznym modelu wału przeciwpowodziowego z wynikami modelowania numerycznego metodą elementów skończonych (MES). Modelowanie numeryczne przeprowadzono z zastosowaniem programu PLAXIS, dane z doświadczeń opracowano za pomocą programu geoPIV. Wykonano dwa typy badań modelowych, które polegały na naprzemiennym podnoszeniu (do całkowitego zalania) i obniżaniu (do całkowitego osuszenia) zwierciadła wody oddziałującego na model wału przeciwpowodziowego. Celem pracy było stwierdzenie przydatności metody analizy obrazu (PIV) do badania deformacji wału przeciwpowodziowego w zmiennych warunkach hydrologicznych. Otrzymano jakościową zgodność między doświadczalnymi i obliczeniowymi polami przemieszczeń w korpusie wału.

Introduction

Nowadays, with predicted changes in the global climate leading to more frequent incidents of intensive hydro-meteorological events which will threaten human life and material possessions, it seems essential to analyze changes that occur in flood embankments under different ambient conditions (LEŚNIEWSKA et al. 2007, BOGACZ et al. 2008, MORRIS et al. 2008). Flood embankments are typically the first line of defence against flooding water, therefore any changes caused by a rising water level within the body of an embankment should be thoroughly analyzed (LEŚNIEWSKA et al. 2008, SCHNELLMANN et al. 2010, ZARADNY 2008).

Under the TROIAnet Science Network, financed by the Ministry of Science and Higher Education, laboratory tests were carried out in 2008 to analyze changes in a flood embankment body which appeared due to changing levels of the groundwater table.

Some preliminary results of these analyses, conducted using the geoPIV method, revealed that even minor changes in the position of the groundwater table led to measurable deformations in the body of a flood embankment (KACZMAREK et al. 2009).

This paper compares the results of tests completed on a flat physical model of a flood embankment with the results of numerical modeling using the finite element method (FEM). The numerical modeling was conducted with an aid of the PLAXIS software package while the empirical data were processed using the geoPIV programme.

The experiments

Two types of tests were performed, each consisting of alternately raising (up to complete flooding) and lowering (to complete desication) of a water table affecting a model of a flood embankment. Each test was run for 1.5 to 2 months. The types of the tests were different in the velocity of raising the water level: type I – slow changes and type II – rapid changes in the position of groundwater.

For the analysis presented in this paper, phase I of type II tests was examined, i.e. rapid raising of the water table up to complete flooding of the body of a flood embankment. Five stages of the experiment were analyzed, corresponding to the water level h_0 = 0 cm (dry embankment), h_1 = 20 cm, h_2 = 40 cm, h_3 = 60 cm, h_4 = 80 cm and h_5 = 100 cm (the embankment completely flooded). The geoPIV software package (WHITE, TAKE 2002) was used to analyze digital photographs documenting each stage of the tests in order to obtain the corresponding displacement fields and deformations.

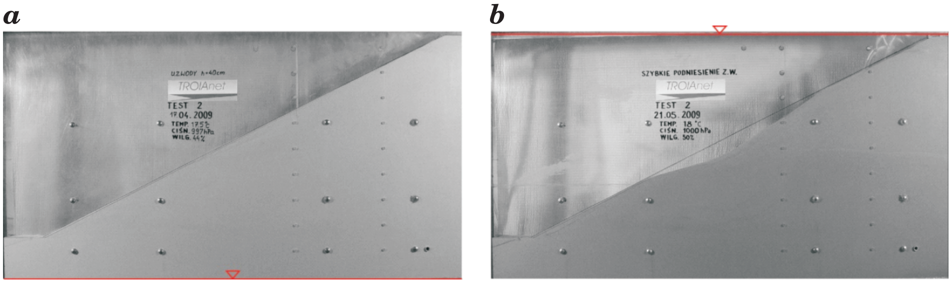

Fig. 1. The initial and final stage of phase I test II, red line – position of water table: *a*) h_0 = 0 cm, *b*) h_5 = 100 cm

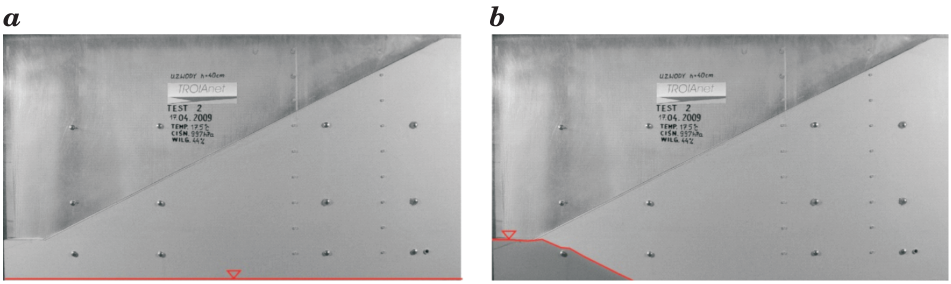

Fig. 2. Stage I of the analysis – the groundwater table at the height of: *a*) h_0 = 0 cm, *b*) h_1 = 20 cm (red lines)

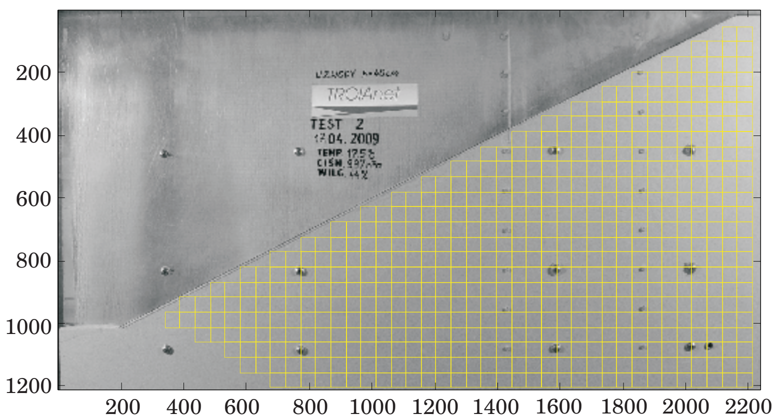

Fig. 3. geoPIV – the mesh adapted for the calculations (division of a photograph into elements)

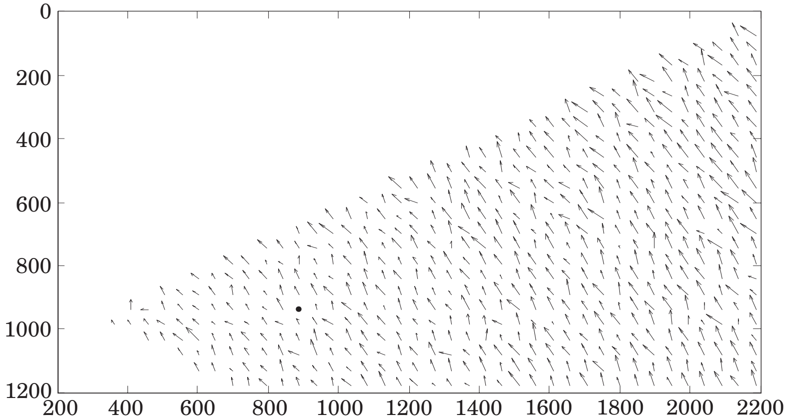

Fig. 4. Experimental fields of displacements (scaled 50 times)

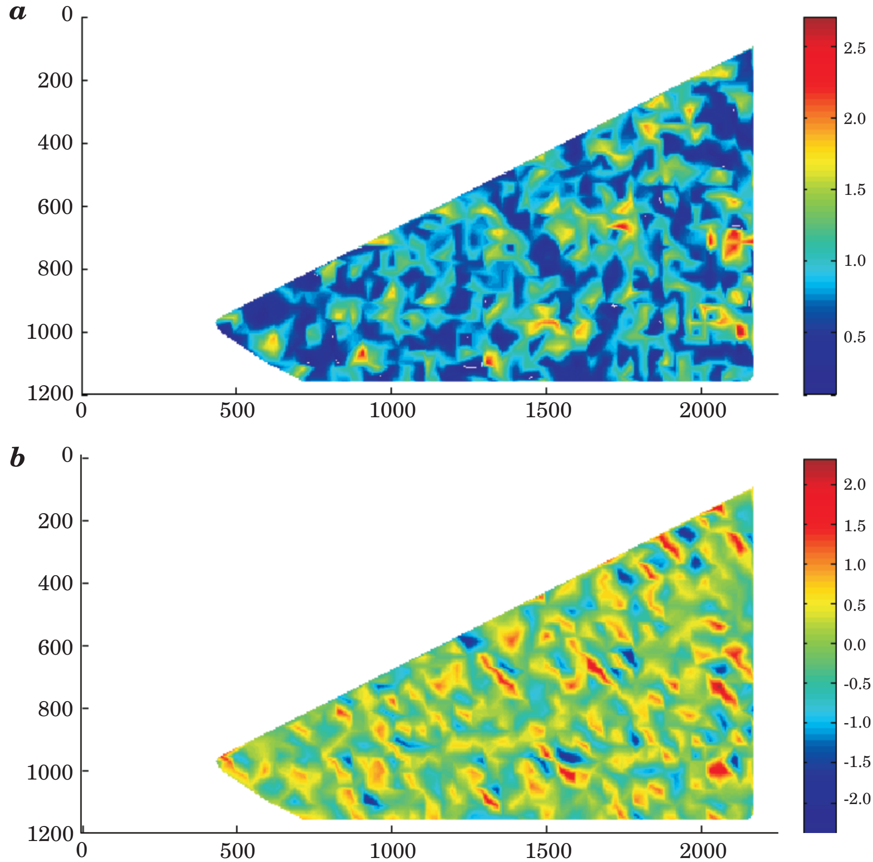

Fig. 5. shear (*a*), volumetric strains [%] (*b*) obtained from experimental field of displacements

Modeling with the finite element method (FEM)

The modeling of deformations in the body of a flood embankment caused by changes in the position of the water table based on the finite element method (FEM) was run with the PLAXIS (v. 8) software programme.

A geometrical model of the problem

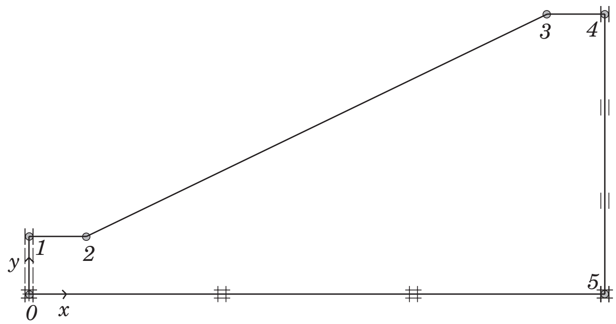

Fig. 6. The geometrical model of a flood embankment

The dimensions of the model were taken like in the experimental tests: 200 cm × 97.5 cm. The distances between the points marked in Fig. 6 are 0–1: 20 cm, 1–2: 20 cm, 3–4: 20 cm, 4–5: 97.5 cm and 0–5: 200 cm, respectively.

Computational parameters of the soil

The laboratory model of a flood embankment was made of fine-grain (d_{50} = 0.25 mm), very well sorted, natural beach sand collected from a beach lying on the open coast of the Baltic Sea near the IBW PAN Seashore Laboratory in Lubiatowo, situated about 70 km west of Gdańsk.

For the mathematical modeling, parameters of Lubiatowo sand in a moderate density state were chosen: Young module E = 50 000 kN m^{-2}, Poisson's ratio υ = 0.3, internal friction angle φ = 26° and cohesion c = 0.1 kPa m^{-2}.

Calculation mesh

For the calculations, 15 triangular node elements offered in PLAXIS programme were chosen. Finite elements mesh was generated using a fine mesh option available in the package.

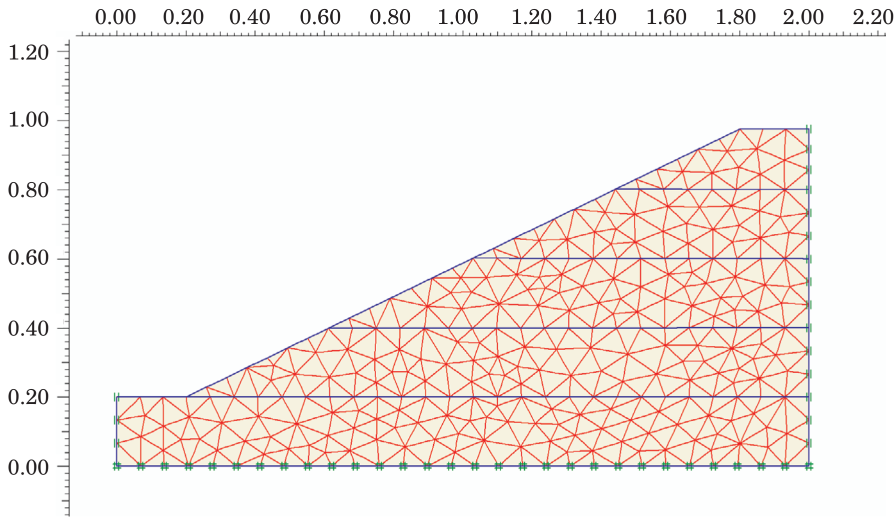

Fig. 7. The FEM calculation mesh

Soil model

For the soil (Lubiatowo sand) model, the classical Coulomb-Mohr model was selected with the associated flow law. The Coulomb-Mohr plasticity condition is an extension of Coulomb's law of friction which involves the general state of tension. This condition ensures that Coulomb;s law of friction is fulfilled in every external plane of the element of the material. The full Coulomb-Mohr border condition can be defined via three border functions representing the principal stresses:

$$f_1 = \frac{1}{2} | \sigma'_2 - \sigma'_3 | + \frac{1}{2} (\sigma'_2 - \sigma'_3) \sin\varphi - c \cdot \cos\varphi \le 0 \tag{1a}$$

$$f_2 = \frac{1}{2} | \sigma'_3 - \sigma'_1 | + \frac{1}{2} (\sigma'_3 - \sigma'_1) \sin\varphi - c \cdot \cos\varphi \le 0 \tag{1b}$$

$$f_3 = \frac{1}{2} | \sigma'_1 - \sigma'_2 | + \frac{1}{2} (\sigma'_1 - \sigma'_2) \sin\varphi - c \cdot \cos\varphi \le 0 \tag{1c}$$

The two parameters of the model are internal friction angle φ and cohesion c.

Results of the FEM modeling

The phenomenon of raising a water table (every 20 cm higher until complete flooding of the flood embankment body) was modeled mathematically in order to compare the resultant failure mechanisms and the experimental fields of displacement with the actual behaviour of a physical model

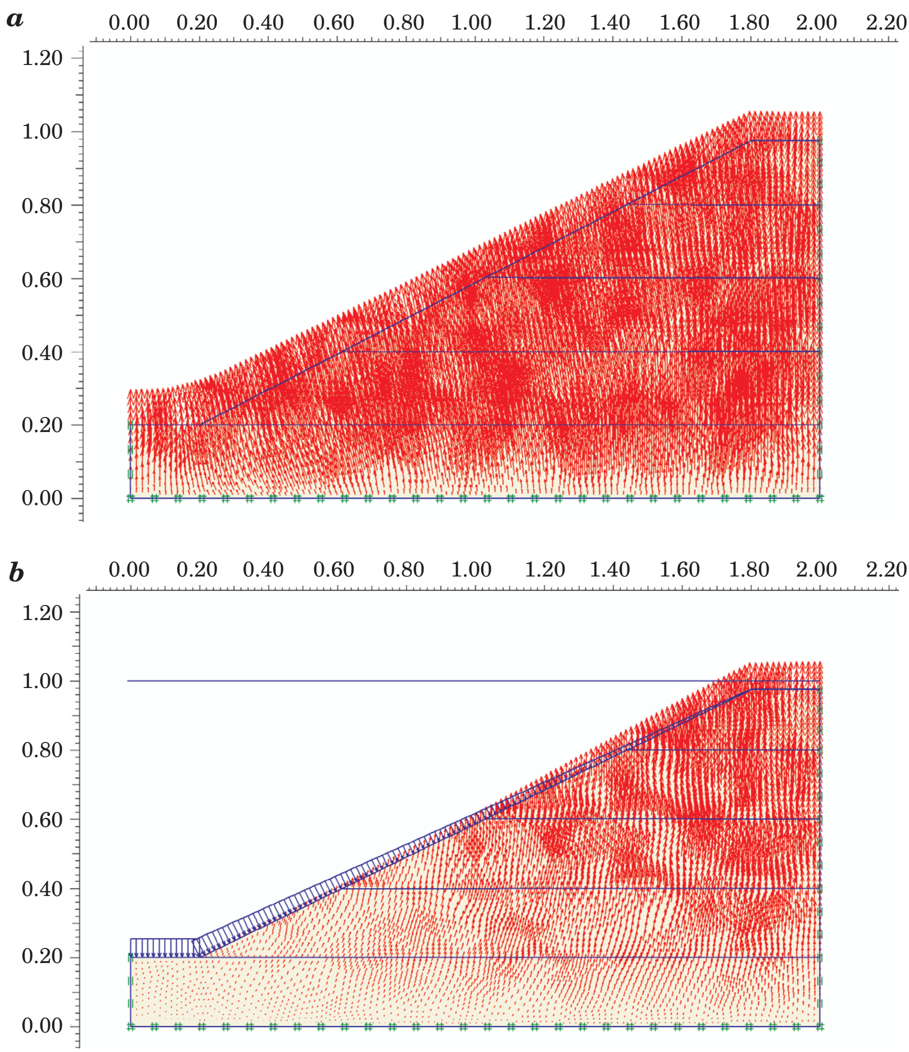

Fig. 8. Calculated fields of total displacements: *a*) h_0 = 20 cm, extreme calculated displacement $2{,}37 \cdot 10^{-6}$ m (scaled 50 000 times), *b*) h_5 = 100 cm extreme calculated displacement $40{,}77 \cdot 10^{-6}$ m, (scaled 2000 times)

of a flood embankment. The experimental (obtained by the image analysis method) and calculated fields of displacement were compared qualitatively. The results of the numerical calculations are presented in Figs. 8–10.

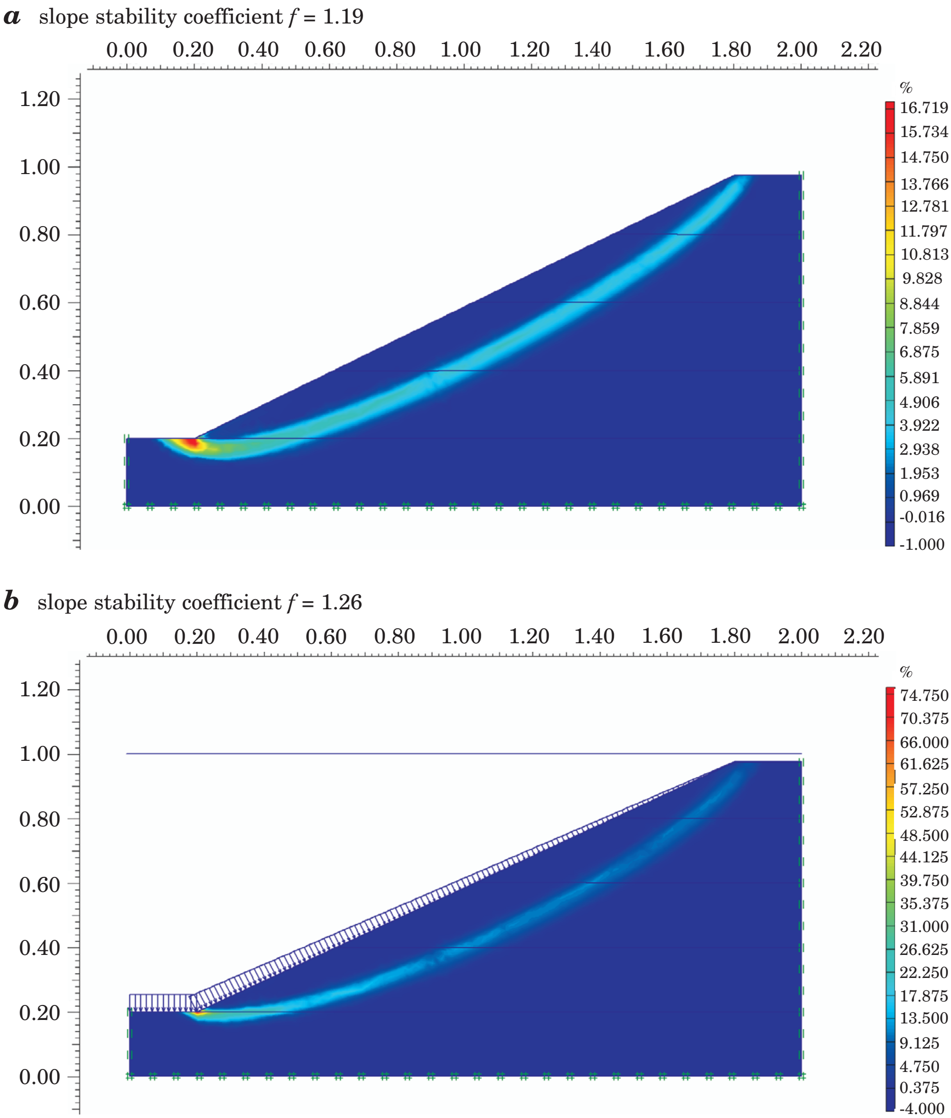

Fig. 9. Incremental shear strains (potential failure mechanism): *a*) h_0 = 20 cm, *b*) h_5 = 100 cm

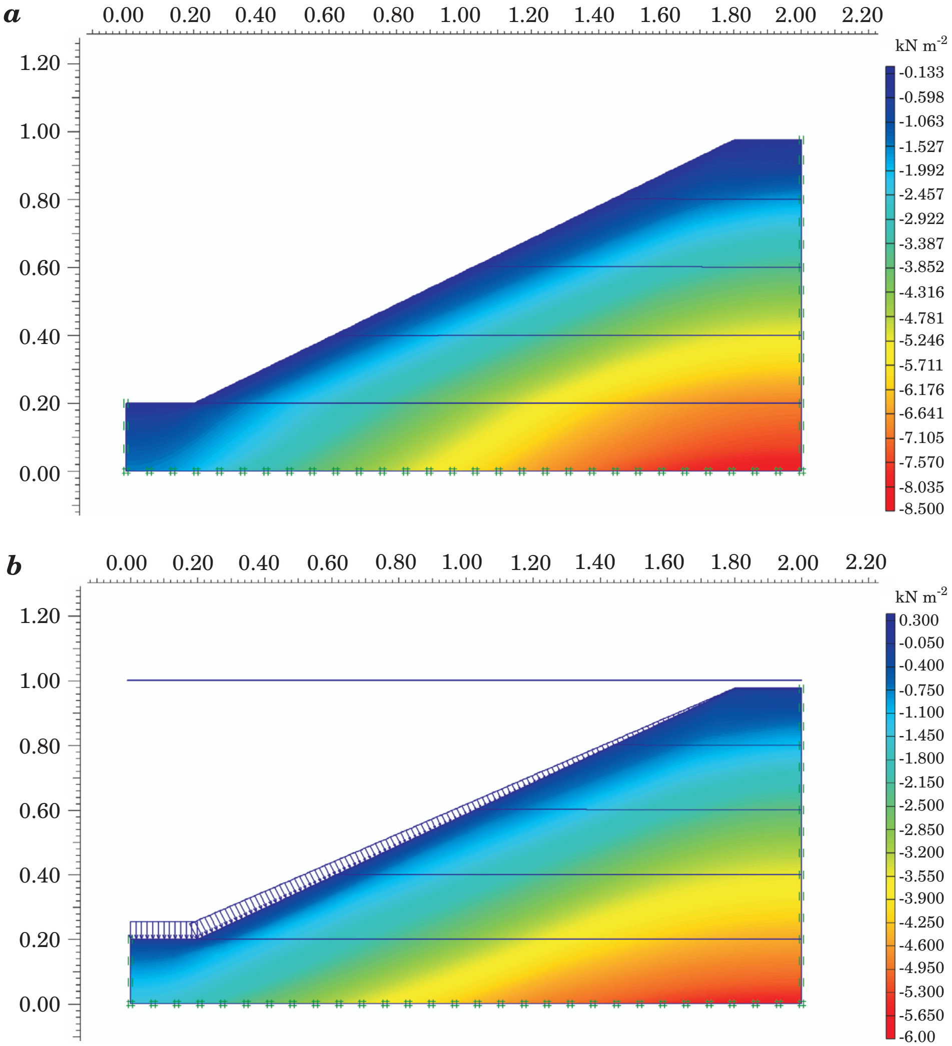

Fig. 10. Effective mean stresses in the body of a flood embankment: *a*) h_0 = 20 cm, *b*) h_5 = 100 cm

Comparison of the results of the geoPIV analyses and FEM modeling

The objective of the paper has been to examine the applicability of the image analysis method (Particle Image Velocimetry, PIV) to analyzing deformations in a flood embankment under changing hydrological conditions. Figures 4 and 5 illustrate that it is possible to read, under the conditions adapted for the experiment, a full experimental field of displacement for dry areas in a physical model. At the moment, the authors are trying to analyze areas below the groundwater table, which is difficult due to insufficient variety of the photographs taken in these areas. Vectors of displacement which make up this field are directed upwards when the water level is rising, which is in accord, qualitatively, with the results of our calculations (Fig. 8). The values of displacements, both calculated and empirical ones, are very small (in the order of 10^{-6} m). The empirical and calculated displacements show a small horizontal component.

The experimental fields of displacement, as shown in Fig. 5, demonstrate the presence of local heterogeneity of the density of the physical model, which obviously does not occur in the FEM calculations, where the soil was assumed to be homogenous. The FEM calculations generated the course of a potential mechanism of destruction of a flood embankment at every stage of the calculations, and the corresponding value of the stability coefficient. The stability coefficient for a dry flood embankment was 1.20, reaching the minimum of 1.14 for h = 40 cm, and then rising up to 1.26 for h = 100 cm. The fact that the minimum value of the stability coefficient exists explains cases of sudden loss of stability of an embankment when the water table is lowering, an event also observed in actual flood embankments.

Summary

The purpose of this study has been to test the applicability of the particle image velocimetry (PIV) method to studying deformations in a flood embankment under changing hydrological conditions. Until the present day, the authors have been successful in applying the method successfully to dry areas of a model embankment, which provides us with a useful tool for recognizing phenomena which occur in flood embankments, also under conditions which are more difficult than presented hereby.

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