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# MODELLING EVENTS OCCURRING IN THE CORE OF A FLOOD BANK AND INITIATED BY CHANGES IN THE GROUNDWATER LEVEL, INCLUDING THE EFFECT OF SEEPAGE

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K e y w o r d s: flood banks, changes in groundwater levels, water seepage, FEM modelling.

A b s t r a c t

The paper presents results of numerical modelling of the response of a flood bank to the rising or lowering water table. The modelling was performed with the finite element method (FEM) in two variants: excluding the effect of groundwater seepage through the flood bank (PLAXIS v. 8) and including groundwater seepage during intervals between increments in the height of the groundwater table (PLAXIS 2D 2010 with a FLOW model).

## MODELOWANIE ZJAWISK ZACHODZĄCYCH W KORPUSIE WAŁU PRZECIWPOWODZIOWEGO POD WPŁYWEM ZMIAN POZIOMU WÓD GRUNTOWYCH Z UWZGLĘDNIENIEM FILTRACJI

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S ł o w a k l u c z o w e: wały przeciwpowodziowe, zmiany poziomu wód gruntowych, przepływ wody w gruncie, modelowanie MES.

A b s t r a k t

W pracy przedstawiono wyniki modelowania numerycznego zachowania się wału przeciwpowodziowego w trakcie podnoszenia i obniżania zwierciadła wody. Modelowanie przeprowadzono metodą elementów skończonych (MES) w dwóch wariantach: bez uwzględnienia przepływu wody w gruncie (PLAXIS wersja 8) oraz z uwzględnieniem przepływu wód gruntowych w okresach między przyrostami wysokości zwierciadła wody (PLAXIS 2D 2010 z modułem FLOW).

## Introduction

Understanding and modelling events which occur in the core of a flood bank caused by fluctuations in the groundwater level is the first step towards predicting changes inside flood banks due to different hydrometeorological conditions. In 2008, under the framework of the Scientific Network called *Transport of sediments and contaminants and degradation of environment in rivers, river mouths and marine coastal areas* (TROIAnet) and in collaboration with the Institute of Hydroengineering of the Polish Academy of Sciences in Gdańsk, experimental tests on a physical model of the riverward slope of a levee were carried out, including studies on changes in the core of the flood bank caused by rising and lowering the groundwater table level (KACZMAREK, LEŚNIEWSKA 2010, LEŚNIEWSKA, KACZMAREK 2010). These studies were a continuation of some earlier research, completed under the EU 6th Framework Research Project FLOODsite, carried out in 2006–2009 (LEŚNIEWSKA et al. 2007, KACZMAREK et al. 2009), which demonstrated that changes in the groundwater table level could lead to alterations in the structure of a levee, which in extreme cases – alongside other modifications due to such external events as atmospheric precipitation, changing water levels in rivers and water reservoirs protected by flood embankments, might cause levee failure or damage. The current physical experiments on a model of a flood bank are carried out at the Institute of Hydroengineering in Gdańsk under the research project NN 506317039 called *Studies on changes in the microstructure of ground and its influence on processes of water flow and contamination transport in flood banks*.

The preliminary results of the numerical modelling of deformations in a flood embankment under the effect of changing groundwater levels have been presented in the papers by KACZMAREK, LEŚNIEWSKA (2010) and LEŚNIEWSKA, KACZMAREK (2010).

## The analysed case

The numerical analysis was carried out for the conditions transferred from one of the experimental tests, in which an incremental rise and fall in the groundwater level were investigated. A change in the groundwater level was constant and equalled ±20 cm. This case was discussed in some earlier articles, e.g. KACZMAREK, LEŚNIEWSKA 2010, LEŚNIEWSKA, KACZMAREK 2010, except that the previous numerical modelling executed with the software package PLAXIS (version 8) could not take into account the fact that as the water table outside the flood bank rises, it begins to flow through the ground (seepage). This flow occurs in a finite time and does not stop until the new level of groundwater, which corresponds to the set level of water inside the core of the flood bank, stabilises.

The paper presents results of modelling changes occurring in the core of a levee caused by fluctuations in the level of groundwater – rising or lowering the table groundwater by 20 cm. Based on the model studies, it has been assumed that the final level of groundwater stabilises in five days. Including groundwater seepage in the numerical analysis was possible owing to the FLOW module, dedicated to studying water flow in ground. This model is compatible with the programme PLAXIS (v. 2D 2010). The analysis started with the simplest case – it was assumed that a change in the groundwater table at a given point occurred in a linear fashion, according to the formula:

$$y(t) = y_0 + \Delta y \cdot \frac{t}{\Delta t},$$

where,
$y_0$ – the current groundwater level for each stage of modelling, in meters,
$\Delta y$ – a rise or fall in the water level in a set time; in this paper, $\Delta y = \pm 0.2$ m and was identical for all stages of calculations,
$\Delta t$ – the time interval set for the calculations, during which the assumed change in the groundwater level occurs; in this paper $\Delta t$ is 5 days, and it was constant or all stages of the calculations.

The numerical simulation was conducted via application of a network of triangular elements with 15 nodes (3 external and 12 internal), which is generated automatically by the PLEXIS programme. The minimum value of the ground compactness was assumed as 0.1 kPA, whereas the other parameters of the materials corresponded to the actual ones, obtained in laboratory analyses of the sand sampled in Lubiatowo, which was used to construct

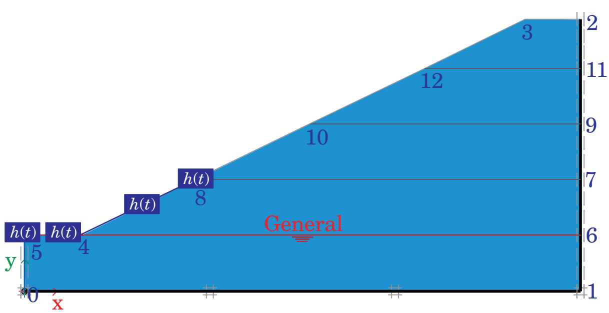


Fig. 1. Impervious boundaries taken for modelling a water flow

the physical model (KACZMAREK, LEŚNIEWSKA 2010, LEŚNIEWSKA, KACZMAREK 2010). In Fig. 1, the thick black line shows the limits of impervious ground as assumed for the modelling.

## Analysis of displacement fields

Total displacement fields and maximum values of these displacements obtained from the numerical modelling with the FLOW module and linearly time-changeable water flow in the ground are distinctly different from the ones produced by earlier analyses, in which water seepage was not included (LEŚNIEWSKA, KACZMAREK 2010).

First of all, a change in the directions of displacement resultants is visible in the first phase of the experiment, when the groundwater level was gradually raised, especially during the first stages of this phase (0–20 cm; 20–40 cm) (Fig. 2a and 2b as well as Fig. 2f and 2g). When the groundwater table was raised by steps (with no seepage in the ground), total displacements were directed vertically upwards and their maximum values were contained in the range [$2.37 \cdot 10^{-6}$ m; $40.77 \cdot 10^{-6}$ m] (Tab. 1, Fig. 2a–2e). In the analysed case, on the assumption that the water flow is changing linearly, the direction of total displacements for the first stages of groundwater rising is horizontal in the whole area (Fig. 2f and 2g), but for the other three stages (Fig. 2h, 2i and 2j) of the phase when the groundwater table is rising, directions of total displacements are comprised within the range of angles (270°, 360°). It seems that the horizontal direction of displacements is a result of the dominant horizontal water flow component, which appears in the first stages of phase I of the experiment. Inclusion of water seepage caused simultaneous increase of the maximum values of total displacements, which in this case are in the range of [$37.23 \cdot 10^{-6}$ m; $49.65 \cdot 10^{-6}$ m], and their detailed values for particular stages of our calculations have been collected in Table 1.

Table 1

Maximum total displacements $u$ calculated for the phase of groundwater table lifting

| Groundwater level [m] | Without seepage $u$ [$10^{-6}$ m] | With seepage $u$ [$10^{-6}$ m] |
|---|---|---|
| 0–0.2 | 2.37 | 37.23 |
| 0.2–0.4 | 7.40 | 37.49 |
| 0.4–0.6 | 16.19 | 39.39 |
| 0.6–0.8 | 29.06 | 45.25 |
| 0.8–1.0 | 40.77 | 49.65 |

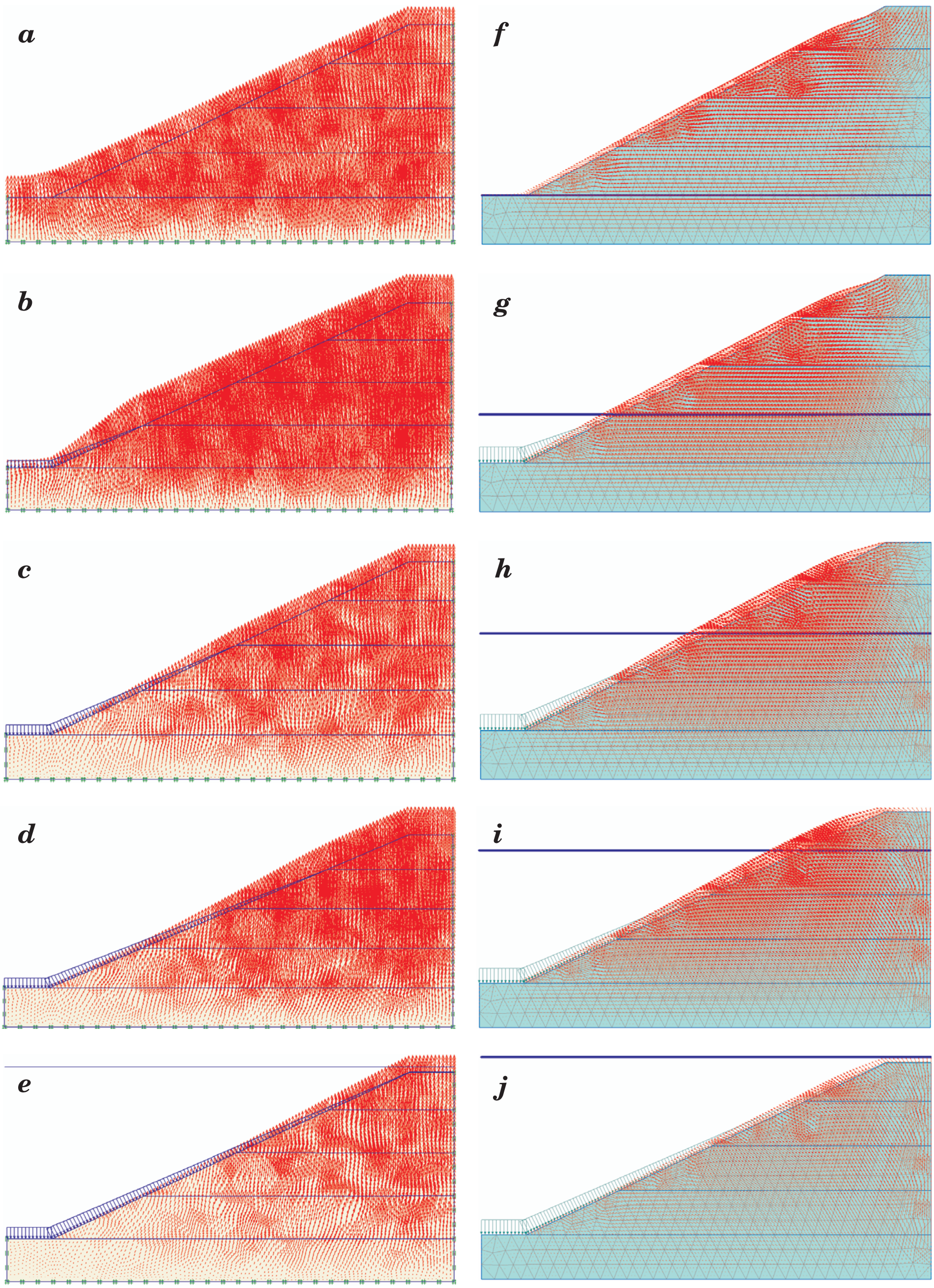


Fig. 2. Total displacements for the water level rising phase. A case of stepwise increase in water table *a–e*, displacements multiplied by 1,000. A case of linearly changing water flow *f–j*, displacements multiplied by 500

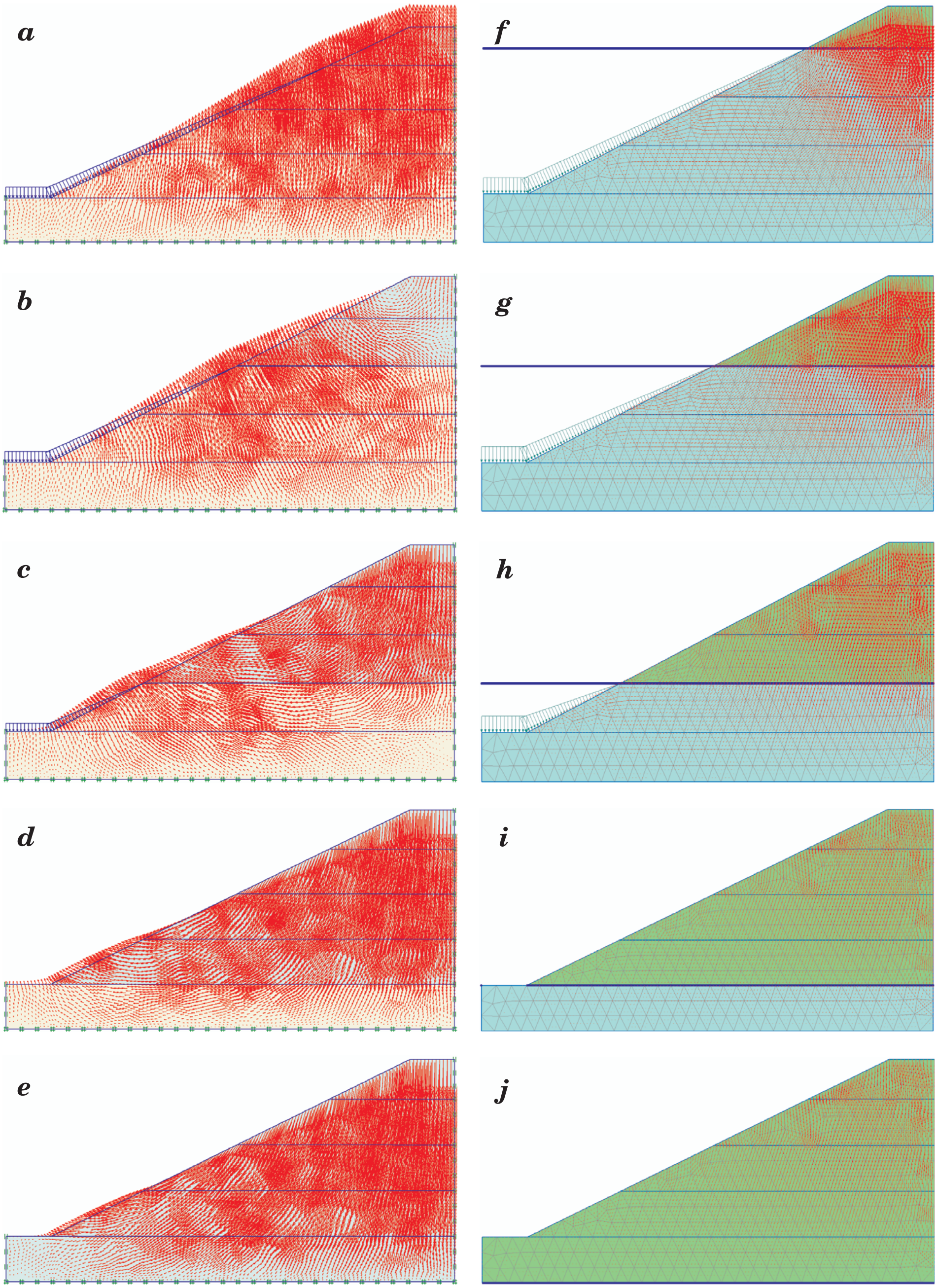


Fig. 3. Total displacements for the water level rising phase. A case of stepwise increase in the water table level *a–e*, displacements multiplied by 1,000. A case of linearly changing water flow *f–j*, displacements multiplied by 500

In the second phase of the experiment, in which the groundwater table was lowered for five days, by 20 cm each time, and the linearly time-dependent changeable water seepage through the ground was included, total displacement fields (Fig. 3f–3j) attained a similar pattern of distribution as when water seepage was not considered in the calculations (Fig. 3a–3e). Both cases, however, are considerably different from each other in the values of maximum displacements, which are in the range of $[20.66 \cdot 10^{-6}$ m; $71.52 \cdot 10^{-6}$ m] (Table 2) for the scenario without water seepage through the ground.

Table 2

Maximum total displacements $u$ calculated for the phase of groundwater level lowering

| Groundwater level [m] | Without seepage $u$ $[10^{-6}$ m] | With seepage $u$ $[10^{-6}$ m] |
|---|---|---|
| 1.0–0.8 | 25.10 | 20.66 |
| 0.8–0.6 | 16.35 | 43.61 |
| 0.6–0.4 | 19.41 | 59.47 |
| 0.4–0.2 | 28.48 | 68.55 |
| 0.2–0 | 31.44 | 71.52 |

It is evident that the inclusion of the simplest scenario of water flow through the ground (stationary in space with linear changeability in time) causes bigger strains inside the flood bank (dislocation of ground) during the phase of both groundwater rising and falling.

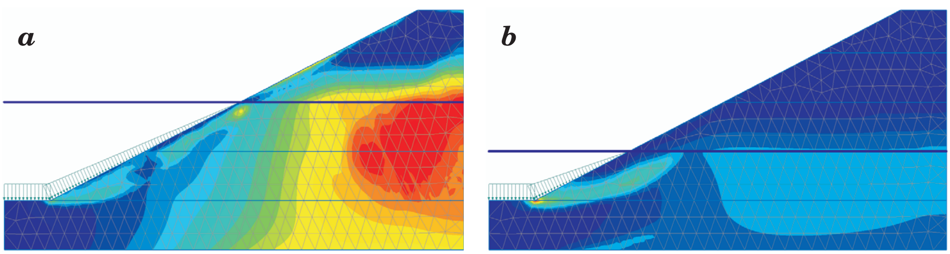


Fig. 4. Increments of non-dilatational strains corresponding to the water level: *a* – decreasing the water level from 0.8 m to 0.6 m, *b* – decreasing the water level from 0.6 m to 0.4 m

Besides, in both stages of the groundwater falling phase, we can observe some residual, not fully developed slip lines. In the first stage (decrease from 0.8 to 0.6 m) we can observe localisation of strains, practically running along the borderline of the slope (Fig. 4a – maximum values of increments of strains appear in the area delineated by points (1,5; 0,6), (2,0; 0,65), (2,0; 0,25), (1,45; 0,25)). In the second stage (decrease from 0.6 to 0.4 m) – localisation begins at the toe of the slope and reaches the height of 40 cm (Fig. 4b). The highest values of strain increments are found in the area at the toe of the slope. The biggest changes in increments of non-dilatational strains were recorded for the stage of lowering the water table from 0.8 to 0.6 versus the stage from 0.6 to 0.4 m – between these stages, the above values changed from $1.7 \cdot 10^{-3}$ % do $7.42 \cdot 10^{-3}$ %. This is more than double versus the case when no groundwater seepage through a levee is included in the analysis.

## Analysis of stability

A possible mechanism causing damage to a flood bank was computed for particular stages of the experiment in both phases with the aid of the procedure called $c$-$\phi$ reduction, which is available in both versions of the programme PLAXIS (Fig. 5).

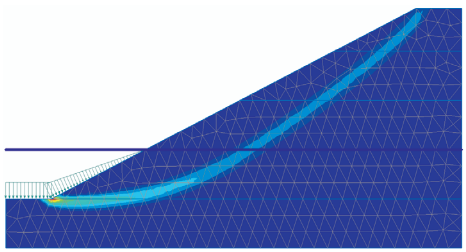

Fig. 5. A theoretical mechanism of damage to a flood bank corresponding to the stage of decreasing the water level from 0.6 m to 0.4 m

The analyses yielded identical values of stability factors for particular stages of the experiment with or without groundwater seepage (Fig. 4). This can possibly indicate that a flow of water through the levee which is relatively slow and linearly changing in time has no influence on the value of a stability factor although it affects the extent of deformation of the levee.

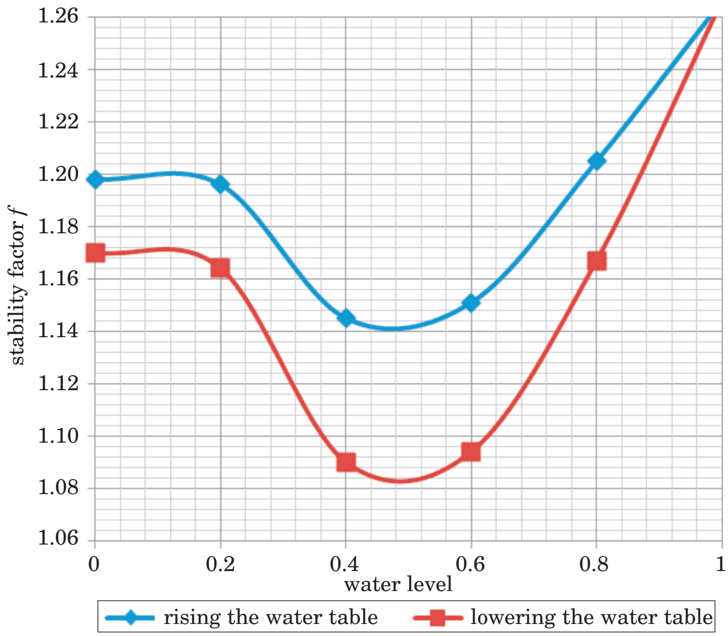


Fig. 6. The changing value of the stability factor of the levee's slope for both phases of the experiment: rising and lowering the water table

## Conclusions

The present results of numerical modelling of linearly time-dependent changeable water flow through the ground are a further step in our attempt to reproduce numerically the results of the experiments conducted under the Research Network TROIAnet and as part of the research project NN 506317039 *Studies on changes in the microstructure of ground and its influence on processes of water flow and contamination transport in flood banks.*

The paper compares results of numerical modelling with and without including a flow of water through the ground (a flow that changes linearly in time, at a constant time period assumed for establishing a stable groundwater level for all the stages). The results suggest that the adopted water flow model significantly changes directions of displacement in the first phase of water level rising, and that in all the stages of the analysed experiment it changes values of total displacements. However, the stability factors, computed for each stage of the experiment, do not change. In order to find out the best fit for the results of numerical modelling and physical experiment, it is necessary to verify more realistic water flow models and to determine which parameters are significant for the stability of a flood bank and which can be omitted.

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