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Monika Chuchro*, Anna Franczyk*, Barbara Bukowska-Belniak*, Andrzej Leśniak*

Reducing Flood Risk using Computer System for Monitoring River Embankments

Wykorzystanie Informatycznego Systemu Monitorowania Obwałowań Przeciwpowodziowych w ograniczaniu zagrożeń powodziowych

*AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection, al. A. Mickiewicza 30, 30-059 Kraków, Poland,chuchro@agh.edu.pl

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Słowa kluczowe: flood embankment, flood risk, numerical models, flood embankment stability assessment, time series, anomaly detection

Abstract
In order to learn about the phenomena occurring in flood embankment under the influence of external factors, including the increasing water level in the river during floods, a Computer System for Monitoring River Embankment (ISMOP) was developed using an experimental flood embankment. The project was carried out by a consortium consisting of AGH University of Science and Technology departments (Computer Science, Hydrogeology and Engineering Geology, Geoinformatics and Applied Computer Science and two companies (NEOSENTIO and SWECO Hydroprojekt Kraków) in co-operation with the Czernichów Community Council.
An experimental flood embankment was built with two parallel sections with a length of 150 m and a height of 4.5 m, connected by a meandering, creating a reservoir that can be filled with water. For the construction of the embankment, different types of soils were used in all the five sections. Inside the flood embankment 1300 sensors are placed, including sensors for temperature, pore pressure, vertical displacements, as well as inclinometers. Also fiber optic strands, capable of measuring the temperature of the flood embankment on the upstream side, are located inside the experimental embankment [ismop.pl].
Together with the real experiments, numerical modelling using the Itasca Flac 2D 7.0 was performed in order to describe the impact of water pressing on the flood embankment and the impact of increasing and decreasing reservoir water level on the phenomena that occur within the embankment.
The results of modelling compared with the real sensor data allowed the evaluation of the current and future state of the embankment. Based on the data measured by the sensors and data received during the numerical modelling, a group of algorithms that allowed detection of anomaly phenomena was developed.

Streszczenie
W celu zbadania zjawisk zachodzących w wale przeciwpowodziowym pod wpływem czynników zewnętrznych w trakcie powodzi, w tym rosnącego poziomu wody w rzece, powstał Informatyczny System Monitorowania Obwałowań Przeciwpowodziowych (ISMOP). W ramach projektu ISMOP wykonany został eksperymentalny wał przeciwpowodziowy, znajdujący się w Czernichowie. Projekt realizowany jest przez konsorcjum składające się z AGH Akademii Górniczo-Hutniczej reprezentowanej przez katedry: Informatyki, Hydrogeologii i Geologii Inżynierskiej oraz Geoinformatyki i Informatyki Stosowanej oraz firm: NEOSENTIO i SWECO Hydroprojekt Kraków.
Ziemny wał eksperymentalny naturalnej wielkości został zbudowany został z dwóch równoległych do siebie odcinków, połączonych zakolami. Wewnątrz korpusu wału zostało umieszczonych ponad 1300 czujników mierzących temperaturę, ciśnienie porowe, przemieszczenia pionowe, wychylenie od pionu (inklinometr) oraz dwie nitki światłowodu, umożliwiającego pomiar temperatury wzdłuż wału po stronie odwodnej [ismop.pl].
W celu poznania wpływu wody napierającej na wał oraz tempa wypełniania i opróżniania zbiornika na kształtowanie się zjawisk zachodzących w obrębie wałów przeciwpowodziowych prócz eksperymentów polowych wykonywano modelowania numeryczne w programie Itasca Flac 2D v. 7.0. Wyniki modelowań porównane z danymi rzeczywistymi pozwoliły na bieżącą ocenę stanu wału przeciwpowodziowego, a także mogą pozwolić na predykcję jego stanu. Na podstawie danych napływających z czujników opracowano także metody pozwalające na detekcję zjawisk anomalnych, związanych z zaburzeniem stateczności wału przeciwpowodziowego.

1. INTRODUCTION

One of the purposes of constructing flood embankment is to limit the damage caused by an increased flow in the river bed, which may result in flooding of the adjacent areas. There are many types of flood embankments based on design and materials used [Borys, 2007, Żbikowski, 1982, PN-B-12095]. The most common flood embankment in Poland is a trapezoidal form of construction made of the material in the vicinity of the river. According to Polish standard (PN-B-12095) in an embankment

construction could be used mineral, organic or anthropogenic soil.
A scientific and industrial consortium came together to develop a Computer System for Monitoring River Embankment (ISMOP) project with the aim of carrying out research related to a complex system for monitoring embankments and forecasting development of failure. The research includes, among others, continuous collection of data that is measured, optimized data transmission, interpretation and analysis of collected data with the use of numerical simulation and reporting of the visualized results to the appropriate authorities.
The general information about the project was presented by J. Stanisz et al. [2015] in the publication named ISMOP Project (IT system of levee monitoring) as an example of an integrated monitoring of the levee. Additional information can be found in the publication of Chuchro et al. [2016] and on the ISMOP webpage.
As an important part of the project was building the real-size flood embankment in Czernichow, near Krakow. Experimental flood embankment was built with two parallel sections with a length of 150 m and a height of 4.5 m, connected by meandering, creating a reservoir that can be filled with water (Fig. 1). For the construction of the embankment, different types of soils were used in five sections. Inside the flood embankment, 1300 temperature sensors, 40 pore pressure sensors, 18 piezometers (sensor EPKO 4, Budokop, www.budokop.com), 6 vertical displacement sensors (sensor from NeoStrain, type 4800, www.neostrain.pl) and 6 inclinometers were placed. Fibre optic strands (1200 m in length) capable of measuring the temperature of the flood embankment on the upstream side were also inserted inside the embankment. More information about sensors used in the embankment are presented in Stanisz et al. [2014]. Additionally, measurement of weather conditions in the two meteorological stations were made. Apart from the measurement system installed permanently, additional measurements such as surface monitoring using geodetic grid for the registration of vertical displacement and deformations, based on the classical method will be carried out (TC, GPS). Additionally, measurements were made using terrestrial long-distance interferometer radar (Image By Interferometric Survey-IBIS-L) and thermography camera (FLIR T620) [Stanisz et al. 2014].
The main aim of the article is presenting the details of the ISMOP project. The research methodology is also presented, allowing a comprehensive assessment of the stability state of the flood embankment together with visualization of the obtained results. Using the presented method, an assessment of the stability state of the embankment at the current time and with the future state of the embankment with a certain amount of probability can be performed. The assessment of stability state is done using the time series analysis of two parameters: the water pore pressure and temperature. Information from other measured parameters such as, for example, weather conditions are used in the analysis.

2. METHODOLOGY

One of the tasks of the ISMOP project was to create a module for assessing the state of the flood embankment expressed in terms of normal, abnormal behaviour and failure. The proposed research method of data interpretation is a method based on the analysis and comparison data from the sensors with the previously created numerical models (model-driven method). Additionally, an analysis of anomalies detection for pore pressure and temperature sensors is performed in the model. The analysis is performed for each sensor in a section separately. Stability evaluation is performed for each sensor and then expanded to cross-section and across the whole flood embankment. The general course of the assessment of flood embankment stability is presented in the scheme below and will be discussed further in this article (Fig. 2.) [Habrat et al. 2015].

Figure 1. Experimental flood embankment (fot. Sonia Bazan, http://losa.tech).

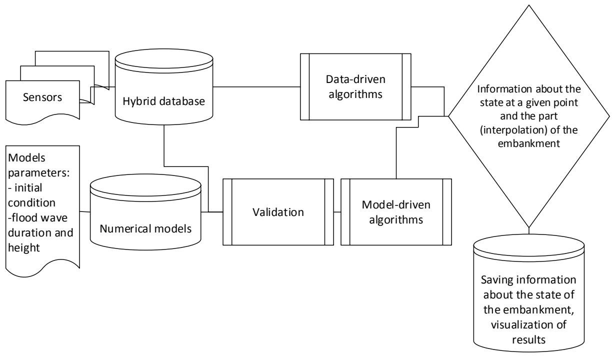

Figure 2. Flood embankment stability assessment.

a. Sensors

The experimental embankment is built making use of two parallel levees with a length of 150 m connected with curves at the north and south directions. A reservoir was created in the construction of the embankment using which a simulation of the impact of high water level can be done on the embankment during floods. So the embankment forms a reservoir, which can be filled with water. A high inflow of water can be used to simulate flood.
The embankment is made of five types of soils characterised by variable filtration coefficients in the range 10^{-5} m/s to 10^{-8} m/s [Borecka et al. 2017]. The slopes on the western embankment are symmetrical in the eastern embankment water, the side slope is less inclined than the air-side slope. Western embankment is entirely built using one type of material (filtration coefficient 10^{-7} m/s), whereas the eastern embankment was built using three types of material (Fig. 3b). The bends of the embankment are built from the least permeable material (filtration coefficient 10^{-8} m/s). Inside the embankment, the reference sensor network is mounted

Table 1. The values of geotechnical parameters of the flood embankment material [Mościcki et al. 2014, Borecka et al. 2017].

	A	B	C	D	Subsurface	Silty	Sands
Density [g/cm³]	1.90	2.07	1.96	1.94	2.10	1.89	1.85
Cohesion [kPa]	12.50	12.75	15.43	16.11	10.30	13.70	10.00
Friction [°]	30.04	30.50	35.20	31.42	32.90	22.50	36.20
Bulk Module [MPa]	8.53	8.53	7.25	7.25	7.25	16.20	36.30
Shear Module [MPa]	3.27	3.57	3.35	3.35	3.43	6.63	21.80
Porosity [%]	37	30	32	32	27	40	35
Filtration factor [m/s]	1.83E-5	3.57E-6	5.24E-5	3.86E-5	1.52E-5	1.35E-5	5.60E-6

[details in Borecka et al. 2017], which consists of three cross-sections – north, central and south (Fig. 3a, red lines) – and two fiber optic strands surrounding the reservoir from the air side (Fig. 3b).
Location of the cross-sections with reference sensors is done to measure the physical parameters of each type of the soil at the base of the embankment. Sensors mounted in these cross-sections are temperature and the pore pressure sensors [details in Borecka et al. 2017].
An additionally mounted test network of over a thousand temperature sensors is located in 74 cross-sections (Fig. 3a,c,e, blue lines). These sensors are located in the cross-section at various depths, with fourteen sensors in each cross-section (Fig. 3d). Figure 3e shows the locations of sensors in different sectors. The red lines correspond to reference cross-sections, and the blue lines correspond to additional measurement test sections. The blue dots show temperature points and pore pressure measurements. The red dots show points of temperature measurement on the optical fibre. The measurement is in every metre along the fiber.

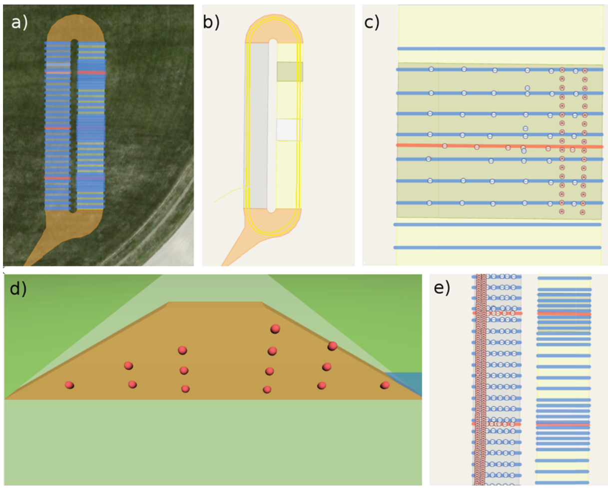

Figure 3. Experimental embankment: (a) whole embankment view with all cross-sections, (b) soil types with two fibre optics loops (yellow lines), (c) sensors in the NE sector, (d) 14 temperature sensors in the test system cross-section, (e) sensors in the western part of embankment (dots) and cross-sections in the eastern part (lines) [http://ui.ismop.edu.pl].

b. Numerical modelling

Numerical modelling is carried out simultaneously with the real experiments of the flooding process. They are primarily used to investigate the effect of the assumed flooding wave scenario in the embankment area when there are no sensors. They are also used to simulate tests of the physical phenomena occurring in the embankments during the flooding process in conditions other than those existing at present. Finally, they allow for multiple simulations of the process, such as destruction of the embankment, which in real experiment may happen only once.
Numerical modelling is carried out using the FLAC 2D software [Itasca Consulting Group, 2011] for 2D horizontal cross-section set across the experimental flood embankment. In Figure 4, the location of all three profiles together with geometry, geology and location of sensors is presented. All three cross-sections are perpendicular to the embankment axis so they have the same geometry. Therefore only an example cross-section, called the 'North Profile', is presented.
Cross-sections are established in the embankment areas built with materials having different geotechnical parameters. The material of the embankment crown (materials A–D) has been chosen to obtain a high filtration rate variability. Numerical modelling carried out for this range of filtration values allow to compute the impact of the flooding waves on the different types of flood embankments. The geotechnical parameters of the material used for the experimental construction are presented in Table 1.

c. Example of the numerical modelling results

Fully coupled thermal-flow mechanical simulations were conducted. The combination of all processes required a restrictive assumption for the adopted computational grid at each time step. The numerical stability of the calculation was achieved only for square rectangular computational grid with 0.1 m length. Also time steps were significantly reduced. The calculation performed for the coupled simulation was carried out with the smallest time step, in the order of tens of seconds, that provide stability of the flow process. As a result of numerical modelling, distributions of parameters describing the embankment state were obtained for each point in the assumed computational grid. The values of parameters computed during the simulation were collected with the assumed two-hour time step. This allows to analyse the changes over time of selected parameters crucial for the stability of the embankments (Fig. 5).
Modelling was conducted for assumed scenarios of the flooding process. The results of numerical modelling concerning flood scenarios for both single flood wave and consecutive successive flood waves were analysed [Franczyk et al. 2016]. The scenarios were created on the basis of an analysis of historical floods occurring in the Vistula river [Kret 2015]. They were also adopted with regards to the technical documentation of experimental flood

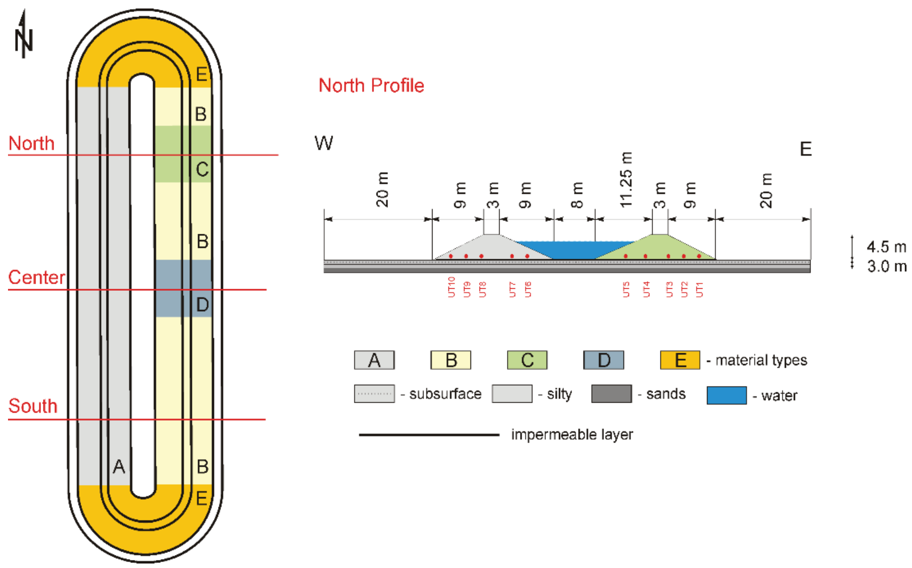

Figure 4. On the left side of the picture the location of the all three cross-sections through the experimental embankment designed in the area of different type of materials used for embankment construction (A–E) is presented. On the right side the geometry of cross-sections and location of the pore pressure sensors is also presented.

embankment irrigation system that forced certain restrictions on the pace of increasing and decreasing water level and on the maximum height of the water level.

Another important issue that can be solved by numerical modelling is an estimation of the stability of the embankment in conditions other than the actual. The validation was preceded by sensitivity analysis. The analysis was carried out to evaluate how the uncertainty of geotechnical parameter values and the assumed boundary condition influence the model output [Pięta, Krawiec 2015, Pięta, Dwornik 2014].

An important factor that has been analysed in the process of the validation of numerical modelling was the problem of non-zero saturation in the experimental embankment [Dwornik, et al. 2017]. Saturation was examined as related to the consecutive flood waves and external conditions such as snow, rain and temperature changes. The validation was performed by a repeated simulation of the flooding process carried out for different values of initial saturation that were assumed within the embankment. Then the degree of adjustment of the computed values and values obtained from the sensors located within the embankment during real experiment was analysed. The comparison of the measured values and those obtained during numerical modelling are presented in Figure 6. The measured waves were recorded during the real experiment with a height of 3 m.

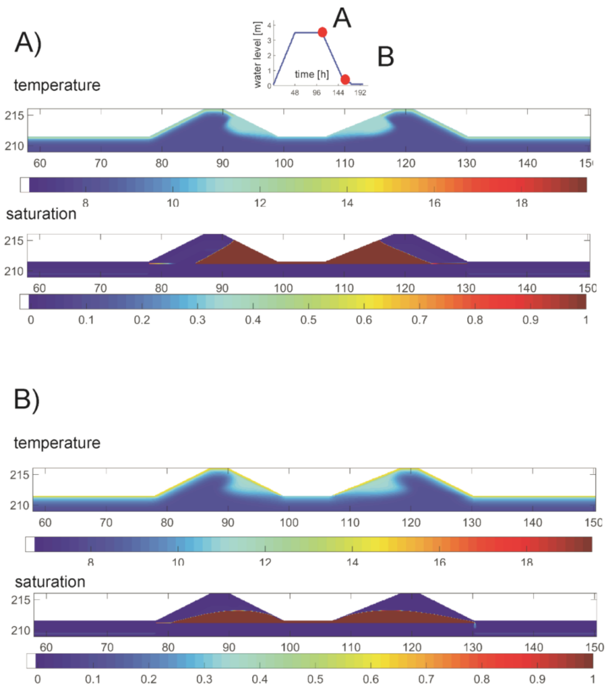

Figure 5. Distribution of temperature and saturation values within flood embankments obtained with the assumption of average daily temperature variation adopted by ICM weather forecast for spring months (http://www.meteo.pl/). The temperature and saturation distributions were presented for the maximum water level (A) and the low water level (B) of the assumed scenario of the flooding process.

d. Failure detection

Usually data-driven (model-free methods) and model-based (numerical or physical modelling) approaches are applied in order to detect failure development or flood embankment stability loss [Pyayt et al. 2015]. Both these methods are used in the ISMOP project. Detailed descriptions of the modules can be found in works of Chuchro et al. [2014, 2016] and Habrat et al. [2015].

Analysis of the model-driven module is based on a comparison of data coming from one of the cross-sections (the 100 newest observations) in flood embankment with data from numerical

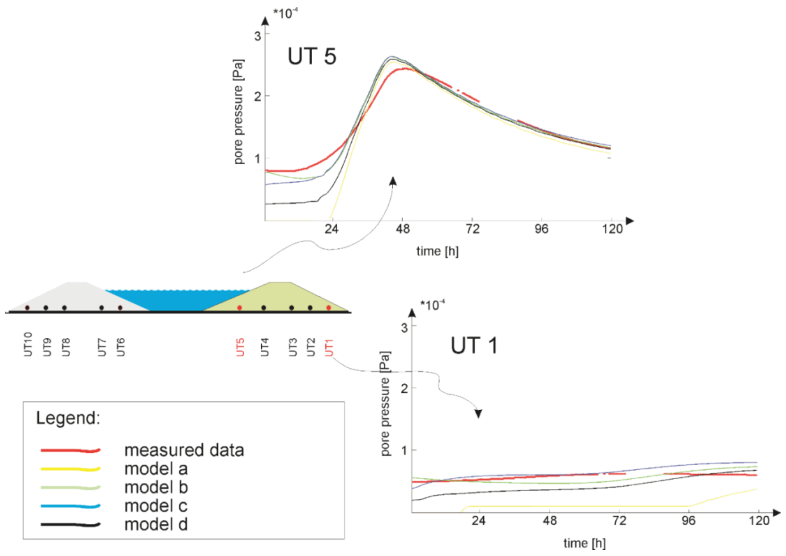

Figure 6. Comparison of modelling results obtained for different values of initial saturation and values measured during the experiment by the sensors UT5 and UT1 [Dwornik et al. 2016]. The initial saturation assumed during numerical modelling was adopted as follows: no saturation (model a), saturation obtained from the piezometers located in the embankment (model b), saturation to the 1/3 (model c) and 1/6 (model d) of the embankment height.

modelling. A time series was collected from all numerical models using the Synthetic Database for nodes corresponding to the position of the chosen sensors (from the analysed section). The most important stage of this module is to compare the time series from numerical models with the real time series registered by the sensors. The comparison is carried out in a moving time window using L1-Norm distance measure and Mean Square Error (MSE). Among the calculated values of distance, the smallest value with an amount of offset for numerical modelling is recorded. For each sensor in the section, the 10 best numerical models are selected with the smallest distance values that suit the comparable time series from the section based on the L1-Norm and MSE. According to the information of the completion of numerical modelling, *n* best-fit numerical modelling is used to calculate the probability of maintaining the stability (normal, abnormal behaviour, failure) of the embankment in the vicinity of the analysed sensors.

The modules in data-driven analyse only the data from the sensors. They are used to detect extreme variations or short time changes in the trend. The analysis was performed for time series lasting up to 12 hours for each sensor separately. Such methods as short-time Fourier transform, regression models, ARIMA, first and second derivatives and analysis of residues were used in the time series analysis. As a result, slow changes relatively over time were detected. With first derivatives single outliers and short-term changes in trends were detected. Fast Fourier transform (FFT), performed in a moving window of 192 observations, was used for the identification of anomalies, such as the increase of the amplitude of some frequencies in time, high deviations of amplitudes at base frequencies that differ significantly from the deviation measured for a 'normal' mode and rapid changes in the trend (outliers), which are usually displayed as a rapid increase and subsequent decrease of amplitudes at high frequencies.

Information about the parameter (pore pressure or temperature) and sensor in which anomalies are detected is known from the output of the module. The results obtained from the data-driven and model-driven module are then used by two other modules of the ISMOP system: decision support system and visualization module.

3. CONCLUSIONS

The article presents a comprehensive method for assessing the state of flood embankments. The proposed method is based on sensors mounted on an experimentally constructed flood embankment that allow periodic and continuous monitoring of its condition. This method is suitable for the assessment of new or existing flood embankments.

The methodology presented in this article allows to obtain information about the state of the flood embankment using two types of methods (model-driven and data-driven). The assessment results can be utilised in the decision support system, visualization of point data, information about the occurrence of the anomaly (the module data-driven) and information about the *n* best-fit numerical models with their closure (module model-driven). Use of numerical modelling with a 0.1 m long grid allows the interpolation of the assessment of flood embankment stability between the sensors.

Estimation of abnormal behaviour or failure state could allow to take preventive actions in flood embankment and nearest area protection.

What is more, based on numerical modelling and their comparison with experiments carried out on the experimental flood embankment, knowledge of the phenomena occurring in the flood embankment is widened.

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