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REVIEW OF THE CONCEPT OF SMART LEVEES

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Abstract

Monitoring of structures during construction and their exploitation is a common practice, often required by investors and/or national standards, to ensure that the performance of the structure is satisfactory with regards to the specified limit states. For this purpose, various quantities are measured, all related and most indicative of problems arising from approaching a specified limit state. In geotechnical practice, these usually include pore-water pressures, deformations, stresses, and temperatures. All the mentioned measurements can be either conducted and collected manually at discrete time intervals, or automatically such that data is collected remotely almost continuously. When equipment to measure and collect these quantities automatically is installed into a levee, a so-called Smart Levee is established. Its purpose should be to provide real time data to existing prediction models which can then predict any critical behaviour of the levee before failure occurs. Since most of commonly used the equipment for gathering the mentioned quantities is designed to collect data in a single point along the levee, the monitored sections should be spaced such that each is representative of a longer reach. Alternatively, equipment that allows for gathering data along a line should be used, to be placed along the whole stretch of levees which need to be monitored. Examples of such equipment mostly include fibre optic cables for strain and temperature measurements, and stationary or UAV-mounted terrain surveying equipment. This paper gives a review of the practices in constructing Smart Levees throughout the world, discussing the most commonly used equipment and monitored quantities, with the expected results and their application.

Key words

monitoring, smart levee, real-time data, early warning system (EWS)

1 Introduction

Monitoring of levees as flood protection structures is an activity of repeated and frequent measurements, used for early detection of potential failure to avoid fatal consequences. The terms “frequent” and “early” are relative terms – they can be conducted multiple time across the span of multiple hazardous events (floods) or be practically continuous within a single event. In the first case, the results could indicate a slow degradation of the levee, which can be used to detect sections that need to be strengthened before the next floods. In the second case the data is searching for the initiation of failure mechanisms during a single event, which require immediate action to prevent complete failure, meaning they must be detected as soon as possible by ensuring continuous measurements in time. The commonly used term for detection of potential failure from the sensor data is “anomaly detection”, and is usually done by statistical analysis of time series or machine learning procedures (Balis et al., 2017). In the realm of possible failures of levees, we can identify several mechanisms, as described by Wolff (2008) to be overtopping, slope stability, external erosion, underseepage and through-seepage, with the latter two being also collectively called internal erosion mechanisms. To detect the correct failure mode/mechanism that is initiating, the appropriate quantities must be measured. Traditionally, though, regular assessments are done by visual inspection (Hopman et al., 2011), which offers only very limited type of data to work with, and only at the levee surface without much insight into the physical state of the soil within the levee. The state of the interior can be inferred from what is seen on the surface, but only qualitatively, which may be good for sensitivity type of analyses. Visual inspection, if frequent enough, can help detect anomalies due to long-term degradation of materials. Measurements with instruments offer what visual inspection cannot and can be categorized according to various criteria. The broadest division is made by local/in-situ or remote/ex-situ measurements (van Vliet et al., 2012). The former refers to the measurement of a quantity at any point on or inside the levee with a sensor placed at the exact location of measurement, while the latter refers to any measurement taken away from the sensor, regardless of whether the instrument is on land, airborne or in space (e.g. geophysics, LiDAR, satellite). Measurements can further be categorized by being used to measure a property directly or indirectly, by their spatial coverage (single point, along a line or over a surface), and by their frequency/density (spatial). Due to the scale of the various failure mechanisms, it is advised to keep the frequency/density within 1-30 m (Cundill, 2016). In that sense, “continuous” measurements in the longitudinal direction can be considered as having any density that could detect the relevant failure mode. Such categorizations offer a useful tool for selecting the appropriate instruments for the specific case, during the design phase of the monitoring system.

When any combination of sensors on/in a levee is incorporated into an automated system for collecting data, the result is called a “smart levee”. Technological advances offer development of smaller, lighter, cheaper and more energy-efficient sensors in the form of micro electro-mechanical systems (MEMS), such as piezometers, thermal sensors, inclinometers and accelerometers (Cundill, 2016), which make smart levees more viable in practice. Such sensors can also become smart sensors themselves, by including individual information processing functions that can perform various calculations and make decisions. This functionality is not a requirement for smart levees, as the data can still be collected in its entirety and analysed by a separate computer. However, the aspiration for all smart levees is to not only collect data, but also implement an automatic data processing structure that combines data from multiple sensors, and which detects anomalies, calculates risks, and alarms the competent authorities. This, however, requires that the development time of the failure modes is long enough, and that the failure initiation is detected early enough, to leave enough time for reaction – otherwise the effort may be in vain. Nevertheless, even without immediate processing, the data collected is useful, especially in newly monitored levees, to investigate their behaviour after one or more hazardous events, to then improve the understanding and employ more efficient management measures and improved design of future levees. When enough data is collected, the system can then be extended with models that automatically perform all the necessary calculations, to become a functioning part of an early warning system.

To achieve a better understanding of the failure mechanism, instruments can also be installed in experimental levees constructed only for learning and calibration purposes, just like the IJkdijk in the Netherlands (Bersan et al., 2015; de Vries et al., 2012; Koelewijn et al., 2014, 2013) or the ISMOP project in Poland (Balis et al., 2017; Sekuła et al., 2017).

2 Overview of the relevant projects

In this paper we collected and analysed several case studies involving the instrumentation of levees, to review the current best practices. A review of the available literature showed that several existing levees have been instrumented to assess their stability in real time in the Netherlands, the USA, Italy and Croatia, and some for experimental purposes in the Netherlands and Poland. When designing monitoring for experimental levees whose purpose is to deepen the understanding of the failure mechanisms and test the applicability of individual instruments, then many combinations of sensors are installed for a comprehensive and exhaustive analysis. The sensors can be of any type, depending on the goal of the experiments. When instrumenting real levees and dikes, the first obstacle is the amount of equipment that needs to be installed along the whole protected area, so only sensors that have been proven to work for specific (expected) failure mechanisms, are installed and relied upon. Studies regarding the application of individual instruments in the monitoring process with respect to one or more failure mechanisms are abundant, e.g. (Inaudi, 2019; Inaudi et al., 2013; Niederleithinger et al., 2012; Sjödahl et al., 2011), but their incorporation into an autonomous unit for levee monitoring requires more considerations.

The idea of having a functional smart levee is to monitor its state ideally along the whole structure, which may prove unfeasible due to the required amount of equipment needed to be installed to cover the whole levee while ensuring appropriate density to cover the scale of the various failure mechanisms. A compromise is thus often required, where only "weak spots" are monitored (Hopman et al., 2011). This implies that weak spots are known in advance, prior to instrumentation, which may be indicated by visual inspection. A weak spot is comprised of a specific cross-section with specific material properties, which lead to its "weak" behaviour. Rossi et al. (2023) have shown that to define a cross-section uniquely, over 100 distinct parameters are required, regarding geometry, physical, mechanical and hydraulic characteristics of the levee, the foundation soil and the immediate surroundings. However, not all of them have considerable effect on stability, so the list can be reduced while still accurately defining a cross-section. By gathering sensor data at the selected weak spots, predictive models can be created that pertain to levees with similar characteristics. Then, such models can be utilized at other sections similar to the monitored one, identified from investigation works that should be available for most existing levees from project documentation. This approach requires more time to fully implement, as it needs a period of data collection and model development, as well as exhaustive review of the available investigation works to identify the similar sections, but it also requires only one characteristic cross-section to be instrumented. Usually though, similar cross-sections are found in the vicinity of each other, within the same "reach". A reach being defined as the length of levee for which the geometry and subsurface conditions are sufficiently similar that they can be represented for analysis and design by a single two-dimensional cross-section and foundation profile (Wolff, 2008). Consider we add another condition to this definition – that a reach should also be characterized by equal consequences were the levee to fail anywhere within that reach – such that the morphology of the protected area is now also considered. This means that by carefully dividing a levee into reaches, we can instrument one cross-section within that reach, and the monitoring results would be representative of the whole thing. Of course, failure can be triggered by unforeseen circumstances at other sections, which is why special attention must be given to identifying the section with the highest probability of failure.

To evaluate local conditions on found weak spots, emphasis is often placed on monitoring of pore pressures within a levee, to assess seepage, even though recently other physical measurements have been made within and on top of levees (Hopman et al., 2011). Pore pressure measurements are conducted by piezometers which take measurements at a single point. As an indirect alternative, temperature measuring is increasingly being used to monitor seepage through dams, levees and dikes (Bersan et al., 2015), and is considered to be one of the most effective methods of assessing seepage (Sekuła et al., 2017). Temperature measurements can be conducted most efficiently by fibre optic sensors, which makes measurements continuous in the direction of installation, but can also be made by individual sensors installed together with other types of sensors, like inclinometers or piezometers. Electromagnetic methods (such as GPR – ground penetrating radar, and EMI – electromagnetic induction) have also been shown to have good application for detecting water in the soil (Santamarina et al., 2005), however they are somewhat more scarce in the practice of smart levees. Seismic methods have also been used for water detection, among other useful design parameters (Lorenzo et al., 2014). The reader is directed to Niederleithinger et al. (2012) for an insightful discussion on the various geophysical methods for dike inspection.

2.1 Experimental embankments

The IJkdijk experiments utilize various combinations of equipment to detect different failure modes on the four constructed embankments (east, west, north, south). Bersan et al. (2015) used piezometers, flow metres, fibre optics for temperature, infrared cameras with visual inspection for validation using high definition cameras, at frequency of two measurements per hour. All of these instruments are utilized to assess changes in seepage due to underseepage (piping) failure mode in the west embankment. According to the measured data, they show that the pipes during internal erosion in the initial stage have much smaller area of influence than 1 m, and that a higher density than that would be beneficial for detecting this type of failure, and that a higher data collection frequency is required for implementation of an early warning system (EWS). Koelewijn et al. (2013, 2014) performed analyses (AIO-SVT, all in one sensor validation test) on three of the four embankments (east, west, south), to their respective design failure modes – piping, micro-instability and overtopping for the east and west, and deep sliding for the south embankment. Piezometers, fibre optics for temperature and strain (installed vertically and horizontally), fast ground-based SAR (synthetic aperture radar) system (for displacement), infrared camera, flow meters, ERT (electrical resistivity tomography) system and inclinometers were used in an automated manner, while GPR has been used manually, also with visual inspection by HD cameras. The authors emphasize the performance of the infrared cameras, SAR system and the vertically installed fibre optics for strain and temperature measurements. Of note is a proposed and tested automatic prevention measure, in the form of drainage tubes which can automatically open to drain water from the levee based on measurements, whose performance was also shown to be satisfactory. de Vries et al. (2012) performed piping experiments on the IJkdijk embankments, and used plastic and glass fibre optics for deformation, vibration and temperature monitoring, acoustic sensors for dynamic imaging, self-potential to detect leakage, infrared cameras for deformations and well locations, MEMS piezometers and inclinometers with temperature sensors, and conventional piezometers for their respective uses. Even though pore pressure measurements have been shown to be quite good at predicting piping, temperature measurements within the layer of potential failure give more detailed information, and given their relative cost compared to piezometers, are a good alternative to be implemented.

As part of the ISMOP project, Balis et al. (2017) and Sekuła et al. (2017) instrumented a levee in the Lesser Poland region, using piezometers, individual temperature sensors as well as fibre optic cables for temperature measurement, weather stations, earth pressure sensors and inclinometers. Their measurement frequency adapts dynamically to the current situation, and the instruments are placed at each 2.5 m along the levee where the permeability was higher, and 5 m where it was lower. They discuss many practical considerations regarding installation and operation of the instruments during levee exploitation, as well as the architecture required for implementing an automated failure detection and warning (support) system, which includes data collection in a shared database and processing using "urgent computing" (e.g. Leong and Kranzlmüller, 2015) services, and decision making processes. The latter being divided into three phases – anomaly detection, threat estimation on section where anomalies are detected, and risk assessment when the threat exceeds a certain threshold.

2.2 Operational embankments

When instrumenting operational dikes and levees for practical implementation of an early warning system, only a fraction of the instruments is viable for monitoring of larger stretches of embankments unless a large financial commitment is possible. As part of the planned iLevee project in the USA, 10 section of the flood protection system, from I- and T-walls to earthen embankments, have been instrumented as a demonstration. Inclinometers and extensometers have been installed on all sections with interferometric SAR for monitoring, while additional fibre optics for strain measurements and tiltmeters have been installed along the walls, and additional piezometers and shape acceleration arrays

(SAA) were installed on the levee sections (Dunbar et al., 2017). In Italy, Cola et al. (2019) instrumented a 350 m long section along the Adige river affected by piping. They utilized piezometers and ERT, along with standard field and laboratory investigation techniques to identify the area most prone to piping, which has then been additionally instrumented with fiber optics for temperature measurement and traditional temperature sensors at or near the land side toe of the levee, at three depths. The sensors operate remotely while communicating data to a server every hour. It is noted that the one-hour frequency is enough to detect seepage paths, but not for the implementation of an early warning system. The fiber optics were shown to be an efficient methods of monitoring temperature variations connected with seepage through the soil. An instrumented cross-section is shown in Figure 1. In the Netherlands, as part of the UrbanFlood FP7 project, Melnikova et al. (2011) have instrumented an operating dike with piezometers and inclinometers, at four sections deemed critical. The gathered data was used to calibrate numerical and empirical models, whose performance was later compared with the actual data. The models have been implemented into an EWS for levee stability, breaching and flood propagation calculations by Krzhizhanovskaya et al. (2011), with a thorough discussion of all the constituent parts of an EWS, and considerations for its implementation at local and larger scales. For the test site with four cross-sections instrumented with piezometers and inclinometers, the simulations implemented in the EWS have been shown to perform in less than one minute with the usage of supercomputers, which would otherwise take much longer to run. If supercomputers are available through an urgent computing system, such models are a viable option. However, when instrumenting large levee stretches which require hundreds of models to run to detect failure mechanisms which are short to occur, and urgent computing is not available, machine learning models can be trained in advance on collected data, to be run within seconds or minutes when needed.

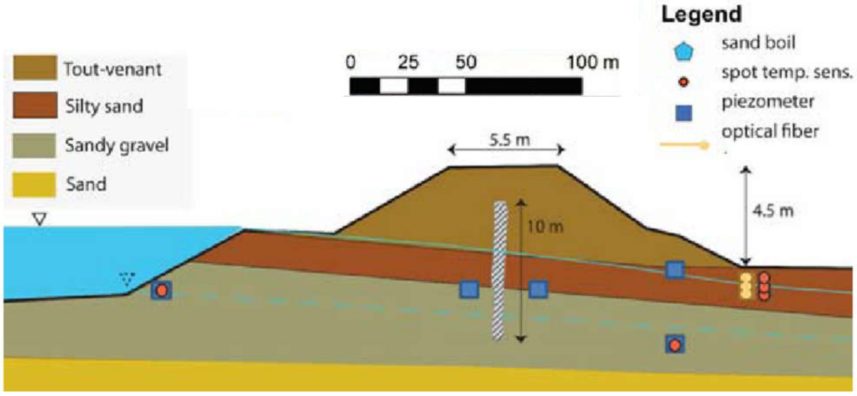

Figure 1. Instrumented cross-section along the Adige river, from (Cola et al., 2019).

In Croatia, the VEPAR project (Grget et al., 2023) instrumented a levee on one cross-section next to the Sava river. As part of the project, a suitable location is found, ground investigation performed, a numerical model established, instruments installed and a system for automatic data gathering and transfer employed, and the response of the system is tested. The used instruments included inclinometers with MEMS technology and piezometers with thermal sensor at three cross section in a stretch of 100 m of levee, and linear thermal sensors along the stretch with sensors every ~9m. The cross-sections consists of levees 4-5 meters high, with a high and wide land-side berm for the service road, only approx. 1 m from the crest height (Figure 2). Due to such geometry, the berm height was not exceeded in either of the two recorded flood events, even though one of them was the second highest event ever recorded. For this reason, most of the inclinometers located near the crown did not register any displacements. One inclinometer installed on the slope within the inundation of the river showed lateral movements in both directions, during the increasing phase of the water wave and the receding phase respectively. This location has been previously known for soil creep, and some parts have been subjected to reinforcement measures (Mihaljević and Gagro, 2010). Still, the inclinometer shows that the displacements continue to increase slightly as the water wave recedes. The registered pore pressures corresponded nicely with the incoming water wave with a time delay of one day, therefore the smaller fluctuations in water height were not registered, but only the main events. The thermal sensors within the inclinometers and piezometers did not manage to detect the water waves per se, except for some variations in some of them, but the linear sensors placed at the toe showed a continuous increase in temperature from their installation, with much more fluctuations during the measurements. These fluctuations are not evidently correlated with the water wave, but information from the weather station could be used to analyse the data more deeply.

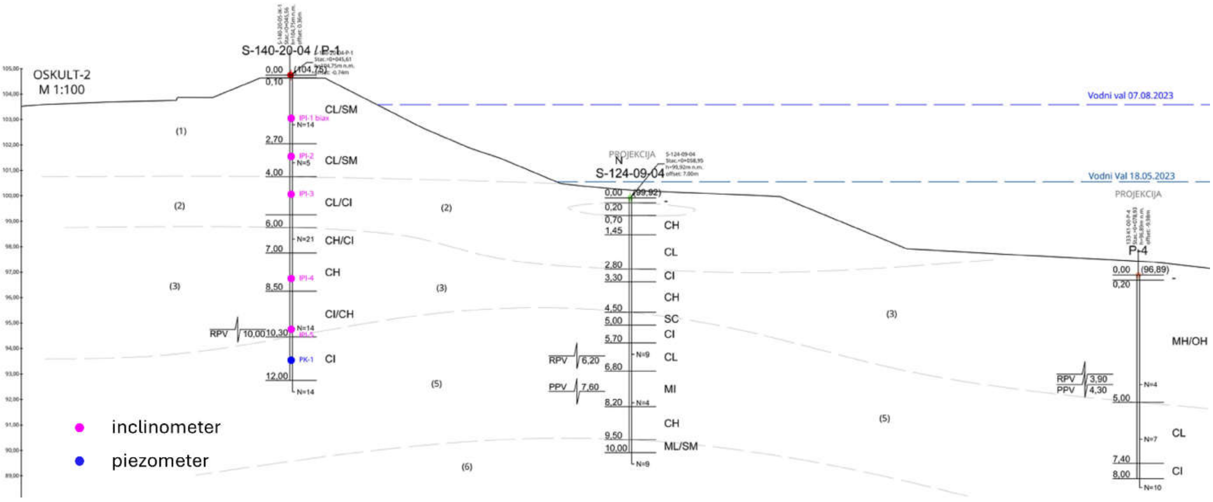

Figure 2. One of the cross-sections with installed equipment as part of the VEPAR project.

3 Analysis

Many instruments are being tested for their applicability in monitoring of embankments, either manual or autonomous, on experimental embankments as well real operational ones. However, some state-of-the-art instruments are always present and still widely used, even though there are objectively better options among the newer technologies. Such instruments include inclinometers and piezometers, with now the already widely used thermal sensors, and recently more and more of fibre optics for temperature and strain measurements. Remote sensing is also an emerging type of measurements, mostly from seismic and electromagnetic methods, as well as airborne and space measurements like SAR. To facilitate the selection of suitable methods, Table 1 divides the instruments mentioned in this paper into different categories.

4 Conclusion

Currently, visual inspection is still the most common type of monitoring for most levees, and that will likely remain the case until competent authorities are able to allocate more funds towards monitoring of levees, in order to develop early warning systems. As discussed by various authors referenced in the paper, developing such a system consists of several segments which require additional funds and personnel to maintain across the thousands of kilometres of levees under the jurisdiction of a single competent authority. In any case, advanced monitoring equipment is essential for the early prediction of failure and the assessment of the state of the embankments. Since failure prediction is mainly interested in the occurrences within the soil body, instruments for in-situ measurements have been widely used. However, most of the in-situ measurements weaken the levee by installation, by creating seepage paths, especially if they are later removed. Furthermore, by definition, in-situ methods can only measure at a single point or at several points along a line. For these reasons, remote sensing methods which do not damage the embankments and can measure continuously across areas, are becoming increasingly more interesting ways for performing geotechnical monitoring in smart levees. In-situ measurements are often direct measurements, which is more favourable than indirect ones, while remote sensing mostly relies on indirect measurements which requires correlations with the desired quantities.

Table 1. Commonly used instruments in smart levees with their categorization and typical usage

Instrument	in-situ / remote	spatial coverage	direct / indirect	measured params.	indirect quantity
piezometer	IS	point	D	water pressure	
thermal sensor	IS	point	I	temperature	water content
fibre optics	IS	line	D/I	temperature, strain, vibration	water content
inclinometer	IS	line	D	inclination (deformations)	
GPR	R	area	I	backscatter of electromagnetic waves	soil layers, structures
EMI	R	area	I	electrical conductivity	soil layers, water content
seismic methods	R	area	I	seismic waves velocity	soil layers, mechanical properties
flow meter	IS	point	D	discharge	
infrared camera	R	area	I	temperature	water content
SAR	R	area	I	backscatter of electromagnetic waves	deformations
ERT	R	area	I	electrical resistivity	soil layers, water content
HD camera	R	area	I		
acoustic sensors	R	point	I	acoustic signal	soil layers, mechanical properties
self potential	R	area	I	electric potential	water velocity, salinity, water content
weather station	IS	point	D	weather conditions	
earth pressure sensor	IS	point	D	pressure	
extensometer	IS	point	D	strains	
tiltmeter	IS	point	D	inclination	
SSA	IS	line	D	inclination (deformations)	

Of the geotechnical monitoring methods available, MEMS inclinometers play an important role in smart levees, as they provide lateral displacements in a line usually installed vertically inside the levee. Alternatives include SAA and vertically places fibre optics. However, these are all in-situ measurements that provide deformation data from within the levee, which cannot be obtained by other remote sensing methods. Instead, remote sensing methods, like the commonly used SAR, are able to cover large areas, but take measurements only at the embankments. Regarding seepage, various methods of temperature measurement are the most popular, but electromagnetic and even seismic methods have been shown to have applications in that regard. Still, one of the most used methods of water detection are piezometers, even though they are in-situ instruments which take measurements only at a single point. When designing a monitoring plan for a smart levee, it is important that adequate instruments are selected in accordance with the expected failure modes at each cross-section/reach, such that a combination of their data can detect the onset of each failure mode early enough.

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