Life cycle monitoring of dikes

Surveillance du cycle de vie des digues

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ABSTRACT: Dikes as a permanent measure for flood protection are often characterized by a perpetual life cycle of designing improvements, reconstruction, management and maintenance operations with periodic safety assessments, and a post-rejection phase during which funds need to be acquired for a new cycle. Monitoring, performed via measurements and inspections followed by appropriate action if required, can help significantly to reduce the uncertainties in the dike's behaviour. A method is presented to evaluate and improve monitoring systems for dikes and illustrated for two cases at different phases of the life cycle.

RÉSUMÉ : Digues comme une mesure permanente pour la protection contre les inondations sont souvent caractérisées par un cycle de vie perpétuelle de concevoir des améliorations, de la reconstruction, la gestion et les opérations de maintenance avec des évaluations périodiques de la sûreté, et une phase post-rejet au cours de laquelle les fonds doivent être acquis pour un nouveau cycle. Surveillance, effectuée par des mesures et des inspections suivies par des mesures appropriées si nécessaire, peut aider à réduire l'insécurité dans le comportement de la digue. Une méthode est présentée pour évaluer et améliorer les systèmes de surveillance des digues et illustrée pour deux cas dans des différentes phases du cycle de vie.

KEYWORDS: monitoring, dikes, asset management, life cycle, design, construction, rehabilitation, operation, maintenance, calamity

1 INTRODUCTION

Dikes as a permanent measure for flood protection are ideally characterized by a perpetual cycle of designing improvements, reconstruction, management and maintenance operations with periodic safety assessments, and a post-rejection phase during which funds need to be acquired for a new cycle. Yet, there is always a chance that the dike will fail, either because of lack of height or by geotechnical failure mechanisms, like overall stability or an internal erosion mechanism. In many countries, a certain reliability is imposed on dikes, e.g. 1/200 to 1/500 year^{-1} in the USA (Van der Meer et al. 2009) and 1/100 to 1/300,000 year^{-1} in the Netherlands, with typical values of 1/10,000 to 1/30,000 year^{-1} in the more densely populated parts (Van der Most et al. 2014). The latter is comparable to the recommendations applied to large dams (ANCOLD 2003). However, the approach is fundamentally different, as the Dutch residual risk levels are based on a consideration of what risk level is accepted by society, while the ANCOLD guidelines are based on the ALARP principle: "reducing risks as low as reasonably practicable," thereby accepting exceptional cases where the desired risk level is not reached.

For both approaches, monitoring provides a means to reduce uncertainties related to a structure or its environment, including its foundation. Monitoring is defined here as the whole of time-dependent, where necessary repeated, measurements at or in a structure, and the processing thereof, to enable, if necessary substantiated modifications to the structure, to the management and maintenance of the structure or to the monitoring itself (Koelewijn and Van den Berg 2015). Monitoring should lead to increased efficiency and knowledge of the behaviour of the structure over its lifetime. This article presents a method to evaluate monitoring solutions including aspects related to the life cycle of the structure.

2 PHASES IN THE LIFE CYCLE OF A DIKE

The life cycle of a dike comprises the design, construction, regular operation and maintenance with regular evaluation of the safety, and a period after rejection in the safety assessment during which funds need to be acquired to enter the cycle again with the design of rehabilitation works. Demolition of a dike hardly ever occurs and is therefore not considered here. In Figure 1 the life cycle is visualised, including the role of monitoring in each phase and an extra condition which may occur at any phase and which should not lead to the end of the cycle: a calamity (e.g. a flood).

The different phases constitute an interconnected chain of events, as is well known in the realm of asset management.. However, the approach in current practice is often different: each phase is regarded on its own, creating problems which could easily have been avoided by sufficient anticipation in an earlier phase (or multiple phases), for example employing pore pressure meters right after rejection to obtain a reliable time series, instead of the need to make assumptions during the often short design phase. The lack of an integral approach often leads to an unnecessary increase in costs and delays. Lack of monitor-

Figure 1. Life cycle of a dike indicating the role of monitoring in each phase

ing in the past cannot be undone, but towards the future this can be avoided.

3 EVALUATING MONITORING SOLUTIONS

Considerations for site investigations and the selection of instruments for levee monitoring are given in Section 7.9 of CIRIA (2013). The method presented here primarily aims at the evaluation of a given monitoring system, to improve the current situation to arrive at a better cost/benefit ratio and to improve the general awareness of the life cycle aspects. Furthermore, it provides a means for clients to ask for a suitable quality on each aspect (i.e. low quality where possible), for designers to offer the required and requested quality and for manufacturers to modify monitoring solutions to the required needs.

4 EXAMPLE 1: LONG TERM IMPROVEMENT OF A RIVER DIKE

The first example concerns a large fill for the rehabilitation of a river dike. Instead of the usual time horizon of 50 years, here a ‘Climate Dike’ is constructed, with a projected life span of 200 years and allowing for new houses to be built on the landside berm (De Moel et al. 2010). The dike is built on the riverside of the present dike, next to a marina. A top view and a cross-section showing the sheet pile wall at the side of the marina are shown in Figure 2 and 3, respectively.

Vertical drainage is applied at part of the fill only. The construction process is controlled by a combination of settlement plates (3-4 in a cross-section, every 40 metres) and pore pressure meters at several depths (3-4 in a cross-section, at two sections where settlement plates are installed). The instrumentation was installed only after the first fill had been applied and the vertical drainage had been installed.

At the time of the evaluation, construction was nearing completion. Based upon the measurements so far, the compensation for settlement can be reduced by a third.

The monitoring system scores quite well in the quick evaluation (Table 3), but in the extended analysis some serious limitations appear (Table 4). These can be explained mainly from the focus on ‘getting the current job done’.

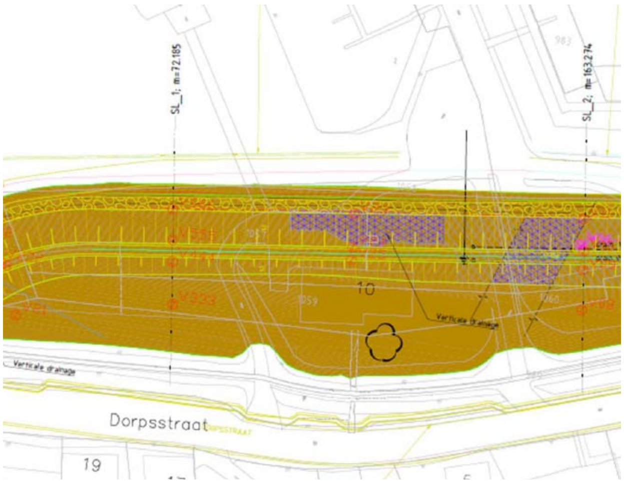

Figure 2. Top view of the evaluated section, to the riverside of the existing dike at the Dorpsstraat

Table 1. Simple matrix for quick evaluations and evaluation of parts.

Aspect/*overall score*	element	score
a. Right information?	Risks and phenomena	no / yes
- / 0 / +	Decision taking	no / yes
b. Available in time?	Initial measurement	no / yes
- / 0 / +	Lead time	no / yes
c. Reliable?	Independent cross-checks	no / yes
- / 0 / +	Robustness	no / yes
d. Cost/benefit?	Risk reduction	no / yes
- / 0 / +	Increase of opportunities	no / yes

Table 2. Extended matrix for a full system evaluation.

Aspect	element
1. Need for information	1.1 Failure mechanism / heterogeneity
	1.2 Load / geometry
	1.3 Chances of unexpected, yet useful info
	1.4 Phasing / planning (w.r.t. Life Cycle)
2. Failure indicators and data access	2.1 Failure indicator / measuring principle
	2.2 Sensitivity / measuring range
	2.3 Data processing / automated analysis
	2.4 Data presentation / visualization
3. Time aspects	3.1 Measurement time / availability
	3.2 Current status / processing time
	3.3 Alarm / measures
	3.4 Transfer of information to next LC phase
4. Reliability	4.1 Factory & Site Acceptance Tests
	4.2 Life span / replacement / availability
	4.3 Service level / reliability of data delivery
	4.4 Cross-correlation of measurements
5. Cost/benefit	5.1 Risk reduction
	5.2 Return on investment
	5.3 Enabling opportunities
	5.4 Control of project environment

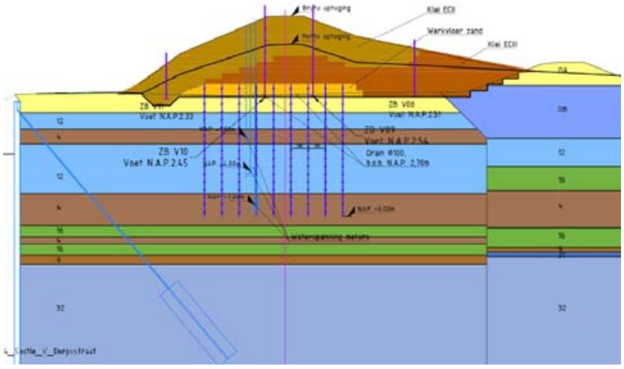

Figure 3. Cross-section of the evaluated section including vertical drainage. The river side is on the left

Table 3. Simple matrix for quick evaluations and evaluation of parts (cf. Table 1).

Aspect/*overall score*	element	score
a. Right information?	Clear limit value to increase in pore pressure under fill	yes
+	Clear when next layer of fill can be applied	yes
b. Available in time?	Initial measurement not taken	no
0	Sufficient lead time to take appropriate action	yes
c. Reliable?	Independent cross-checks from settlement and pore pressure changes	yes
+	Robustness seems limited, but very little loss of instruments	yes
d. Cost/benefit?	Unclear horizontal deformations	no
0	Optimised fill scheme, reduced total amount of fill	yes

Table 4. Extended matrix for a full system evaluation (cf. Table 2).

Element	score
1.1 Main mechanism covered, loss of instruments fatal	**
1.2 Variation in geometry is generally covered	***
1.3 Other mechanisms may be detected	**
1.4 Current situation only,even not suited for current phase	*
2.1 Relevant mechanism is measured in limited sections	***
2.2 Inaccuracy of measurements up to 35 cm (rather bad)	*
2.3 Highly automated process, can be used also in case of a flood to decide on measures (including excavation of fill)	****
2.4 Data is presented visually, including physical limits	****
3.1 Time series started to late, yet flexible availability	***
3.2 Near real-time insight in processed data	*****
3.3 Alarming is irrelevant here (controlled, cautious fill)	*
3.4 No consideration of next life cycle phase	*
4.1 FAT+SAT OK, documents available, but no spares	***
4.2 Life time neglected, replacement troublesome	*
4.3 Daily communication, but repairs take several days	**
4.4 Different types of instruments at same location	***
5.1 Beyond main goal, measures possible in case of flood	*****
5.2 Limited, proven technology yields very useful info	****
5.3 System allows for flexible filling in time and amount	****
5.4 Little consideration of external influences	**

5 EXAMPLE 2: OPERATIONAL PHASE OF A RIVER DIKE STRENGHTENED BY RELIEF WELLS

In the vicinity of a weir in one of the smaller branches of the Rhine river, bed erosion caused by weir operations exposed an intermediate sand layer underneath the river to the direct influence of the water level. This led to landside instability of the dike, of which the top view and the cross-section are shown in Figure 4 and 5, respectively.

Stabilisation of the dike during flood conditions has been achieved by installing relief wells, on average one every 18 metres and connected by a drainage collector, as indicated in Figure 4. The monitoring system basically consists of a head pressuremeter in every second well (with the possibility to quickly add additional meters in any of the other wells) and several head pressuremeters halfway between two wells. All meters are roughly on a long line, parallel to the river. The data is transferred to a central command centre: normally twice a day but immediately in case pre-set warning or alarm levels are exceeded. In case of partial clogging during a flood, each well can easily be equipped with a pump. However, the total number of pumps available will be limited.

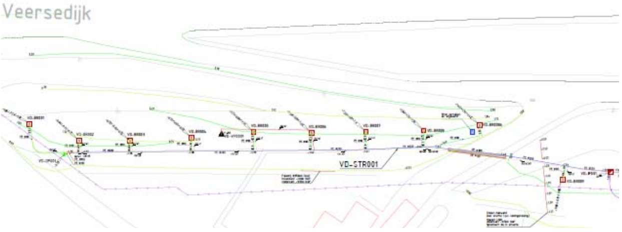

Figure 4. Plan view of a section of approx.. 100 m of the Veersedijk, indicating 10 relief wells (9 on a row) by small squares.

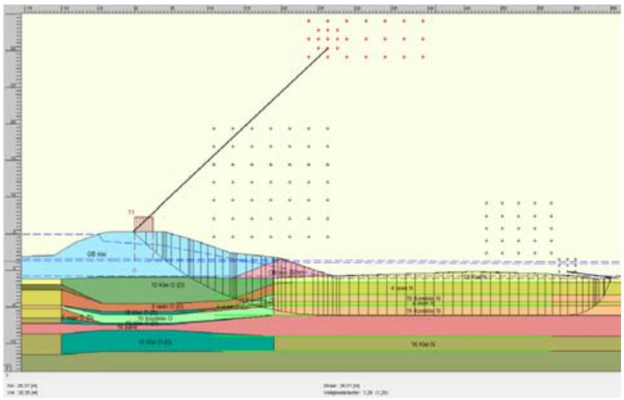

Figure 5. Cross-section of the Veersedijk with the intermediate sand layer right below the calculated inner slope sliding plane

At the time of the evaluation, the system had been completed and was running for a full year. In the meantime, no serious flood levels had occurred, although the weir had been operated a few times during higher run-offs.

The applied monitoring system scores rather well, both in the quick evaluation (Table 5) and in the extended evaluation (Table 6). It appears that the system is very well designed and dedicated to its purpose. But as a result, the probability of measuring other phenomena is small. An intermediate score is obtained regarding the transfer of information to the next phase(s) of the life cycle (element 3.4). In any other phase, the score with this system would have been higher, but now the time horizon is too far to include the next design phase already. A low score is obtained on the reliability of data delivery (element 4.3): the chain of activities to deliver the data to the (single!) command centre is considered unbreakable. Any questions to that appeared to be rather confronting, although at the same time it must be remarked that the whole chain is rather robust indeed.

6 GENERAL APPLICABILITY

The presented method can be applied to any monitoring system at a dike, in any phase of the life cycle as presented in Section 2. In fact, by considering the impact over the whole life cycle, the importance of short-term goals is diminished.

In fact, the method can also be applied to monitoring systems which still need to be devised and when monitoring systems are requested. It may even be used to develop new sensors and to improve protocols for installation of equipment,

Table 5. Simple matrix for quick evaluations and evaluation of parts (cf. Table 1).

Aspect/*overall score*	element	score
a. Right information? +	Performance of wells and alarm Warnings and appropriate actions pre-set and clear	yes yes
b. Available in time? +	Initial measurement when well is not running or closed, can be enforced Warning levels are set at a level that appropriate action is still possible	yes mainly
c. Reliable? 0	Cross-checks were assumed to be possible, but possible placement of filters in different formations was overlooked Robustness is ensured by the possibility of hand readings in combination with the inspection squads present during flood conditions	partly yes
d. Cost/benefit? 0	Cost reduced in operations and emergency measures can be designed better System is helpful for validation, but a single measurement point in a cross-section means too few points for a proper geohydrological analysis	yes partly

based on the functional requirements. As such, it can serve as a mode of communication. Possible applications by different groups include:

* For clients: specify the requirements for each element in Table 2 (the optimal score does not need to be the highest possible score) and use this to evaluate tenders

* For designers: to substantiate the choices made for the development, specification and optimisation of a monitoring solution

* For manufacturers: to develop solutions fitting to the different quality levels demanded by the clients ('fit for purpose')

* For users: for feedback and improvement of their monitoring systems

The method has recently been developed and tested at various dikes in the Netherlands in each phase of the life cycle and will become available as a technical guideline.

7 CONCLUSIONS

A method to evaluate monitoring systems for dikes in each phase of the life cycle has been presented, on both a simple level and a more elaborate level. The application of the method has been presented for two cases of river dikes in the Netherlands, one being rehabilitated, the other recently improved by a system of relief wells.

The method appears to be suitable to qualify a variety of monitoring systems and to find its strengths and weaknesses, enabling targeted improvements where required. The method can also be applied to establish the requirements of a monitoring system and to modify sensor specifications to the needs of clients.

Table 6. Extended matrix for a full system evaluation (cf. Table 2)

Element	score
1.1 Prime failure mechanism well covered, including heterogeneity of the subsoil	*****
1.2 Flexible, local measurement of hydraulic load along dike	*****
1.3 System is very dedicated to its purpose, chances of detecting and recognizing unexpected things is small	*
1.4 System covers the full life cycle	*****
2.1 Direct measurement of head, stability is then derived	****
2.2 Accuracy is very high compared to model uncertainty	****
2.3 Highly automated process with an accepted chance of false positives (regarded as unplanned, useful exercises)	****
2.4 Data is presented visually, including terrain levels	*****
3.1 High frequent, continuous measurements, additional check before floods,no periodic maintenance during floods	*****
3.2 Warning and alarm values are near real-time available	*****
3.3 Warning levels are given in time to allow for timely and adequate response	*****
3.4 Only the next phase (post-rejection) is accounted for. Note: this is likely to be nearly 50 years ahead	***
4.1 FAT and SAT tests are passed well	****
4.2 Timely replacement is taken care of, most parts are readily available	****
4.3 No guarantees – within own organisation, however	*
4.4 Pore pressures are measured close enough to each other	***
5.1 Few risks, therefore also little (not all) is covered with the system	**
5.2 Good value for money obtained	***
5.3 Poor, the system is very dedicated to a single purpose	*
5.4 System does allow for detection of further erosion, blocking of wells, etc.	***

8 ACKNOWLEDGEMENT

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