Monitoring strategy: a rational approach to measuring and processing data

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Introduction

Monitoring can play an important role in the risk management of geotechnical projects, as it may help reduce initial uncertainties regarding the heterogeneity and behaviour of the soil. In order to maximise the benefits of a monitoring programme, it should be set up in a systematic and rational manner, providing answers to the questions ‘Why, What, Where, When, and Which degree of monitoring?’ In combination with the quantitative processing of data measured during both the construction phase and operation phase of a project, monitoring can help optimise risk management during a project’s lifetime.

A rational monitoring strategy is presented here, comprising a systematic approach to setting up a monitoring program and incorporating measured data in the decision process. This strategy has been developed within the Delft Cluster project ‘Monitoring Philosophy HerMes’, carried out by GeoDelft and TNO (Koelewijn, 2000). Inspired by the name of the messenger of the gods in Greek mythology (being an early example of monitoring), HerMes stands for tHE Rational Monitor Evaluation System. The purpose of this Delft Cluster project is to develop a method by which monitoring data can contribute quantitatively to assessing the reliability of a construction, and to the decision process regarding further construction and maintenance. In the pilot stage of the project, a preliminary version of the method was applied to the river embankment stability test to be carried out at Bergambacht and a railway embankment settlement test performed at 's-Gravendeel (both near to Rotterdam). The results of this pilot study proved very useful in the design of the river embankment stability test.

A treatise on rational monitoring is first presented, followed by guidelines for the systematic establishment of a monitoring program and a method to incorporate measured data in updated predictions to assist in the decision process.

Rational monitoring

Monitoring is defined here as the process of repeatedly carrying out measurements at a construction, *and* the processing of measured data to facilitate decisions regarding further construction and maintenance.

Monitoring may contribute essential information on the reliability of a construction. Thus, the answer to the question 'Why monitoring?' is usually related to reducing the probability of failure, which may be either actual failure of the construction (i.e. exceeding the ultimate limit state) or failure to meet the functional requirements of the construction (i.e. exceeding the serviceability limit state).

Monitoring may be carried out in an operational, scientific or a legal context. In this article, the emphasis lies on the first two aspects: information obtained by monitoring is either used to support further decisions regarding construction and maintenance, or to validate and improve the models used in the design process.

Figure 1 presents a flow chart for rational monitoring, which may help provide answers to the remaining questions stated in the introduction, namely ‘What, Where, When, and Which degree of monitoring?’

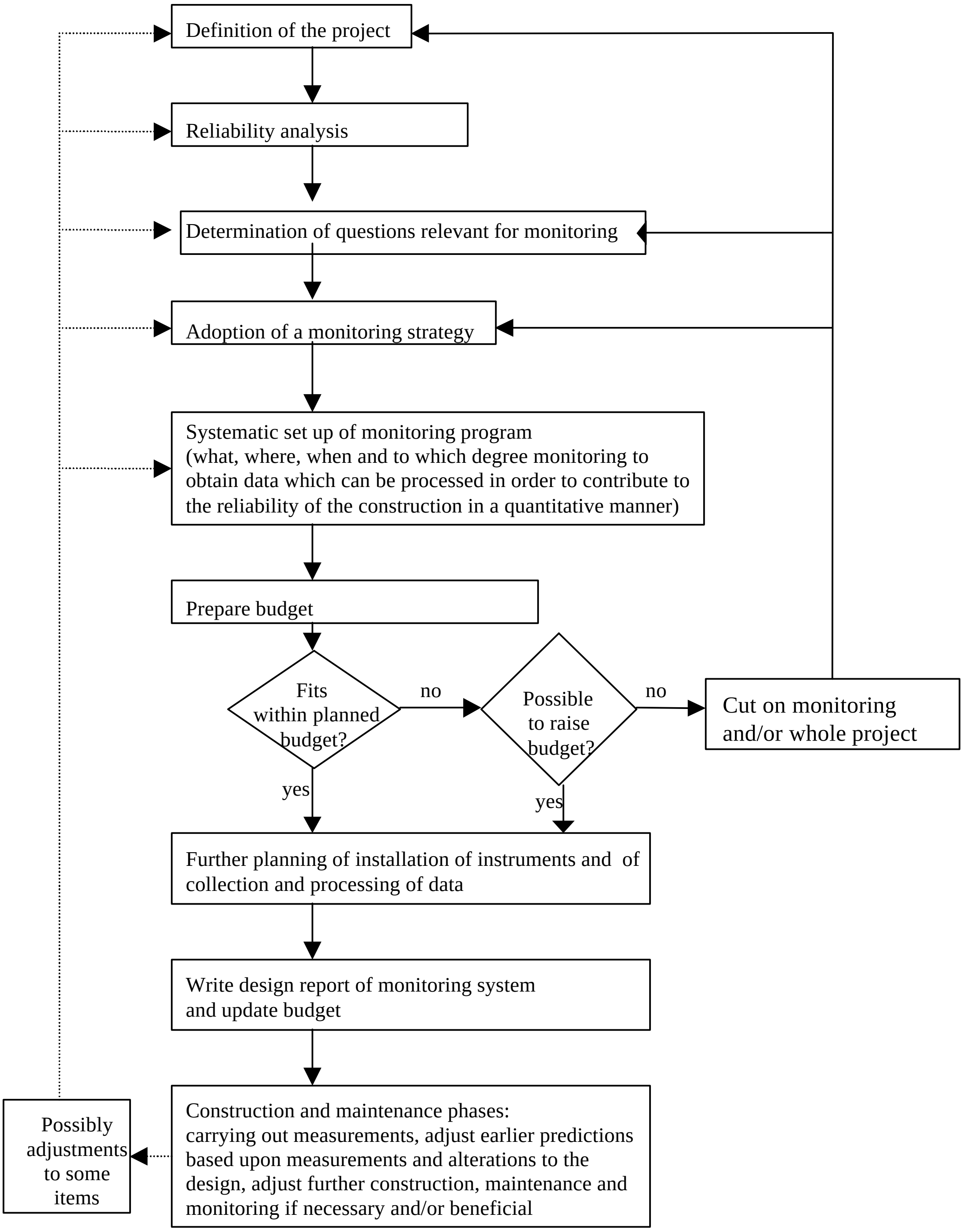

Figure 1 Flow chart for rational monitoring

First of all, a clear definition of the project is required. For those already involved in the project, this can be useful for understanding what is relevant to the project and in acquiring a broad view of all influencing factors. For those who become involved at a later stage, it will be helpful in understanding the project quickly. Personnel responsible for a project (including the monitoring programme) are often replaced by others, especially during transition from one stage of a project's life cycle to another (e.g. from the construction phase to the operation & maintenance phase). During such transitions, alterations may be carried out too easily and this may lead to serious problems later on. Two items which should be included in this step are, for instance, a description of the project's functional requirements and a description of the design models used, including the (often implicit) assumptions and limitations of these models and the simplifications made therein.
Once the first step has been completed, a reliability analysis should be made. A quantified reliability analysis is vital for a rational monitoring programme set-up which focuses on the most important mechanisms controlling behaviour. The monitoring programme may otherwise focus on insignificant parameters. A sound, quantified reliability analysis will reveal which parameters at which locations are the most significant to monitor. The reliability analysis may start with a Failure Mode Effect Analysis (FMEA), which identifies mechanisms in a qualitative manner. This should be followed by a quantitative, (semi-) probabilistic analysis of those mechanisms which (by engineering judgment) are expected most likely to occur. Those mechanisms with a disastrous impact may also be investigated more carefully. Furthermore, the reliability analysis might indicate that reducing the uncertainty of some of the input parameters will significantly improve the overall reliability of the construction. In this case, a limited amount of money spent on extra soil investigations, for example, may prove very economical.

The next step is to determine the questions relevant for monitoring. As formulated by John Dunnicliff (1988, 1999), 'Every instrument on a project should be selected and placed to assist in answering a specific question: if there is no question, there should be no instrumentation'. Most of the questions relevant for monitoring will usually follow directly from the reliability analysis. In addition, some questions may be posed to determine the validity of the assumptions and simplifications made in the design models used.

Once the questions relevant for monitoring have been determined, a monitoring strategy can be formulated. Some general aspects will first be discussed, followed by a less abstract 'recipe' describing how to systematically set up a monitoring programme.

Essentially, formulation of a monitoring strategy is a decision problem. As illustrated in Figure 2, the first decision to be taken is whether a measurement will take place or not. Even without any observation, the next decision is whether to carry out some kind of maintenance (a repair) or not. This decision may, for instance, be based on the original design in which regular maintenance intervals were foreseen. Although the likelihood of failure will differ, failure is still possible in each scenario during the next time interval. The intensity of the monitoring programme should be such that the total project costs (including, for example, monitoring costs and direct and indirect failure costs) can be expected to be as small as possible. Bayesian decision theory (see e.g. French [1993] or French & Smith [1997]) can be used for a thorough analysis, so that a rational choice can be made between the various possibilities concerning the intensity of both monitoring and maintenance.

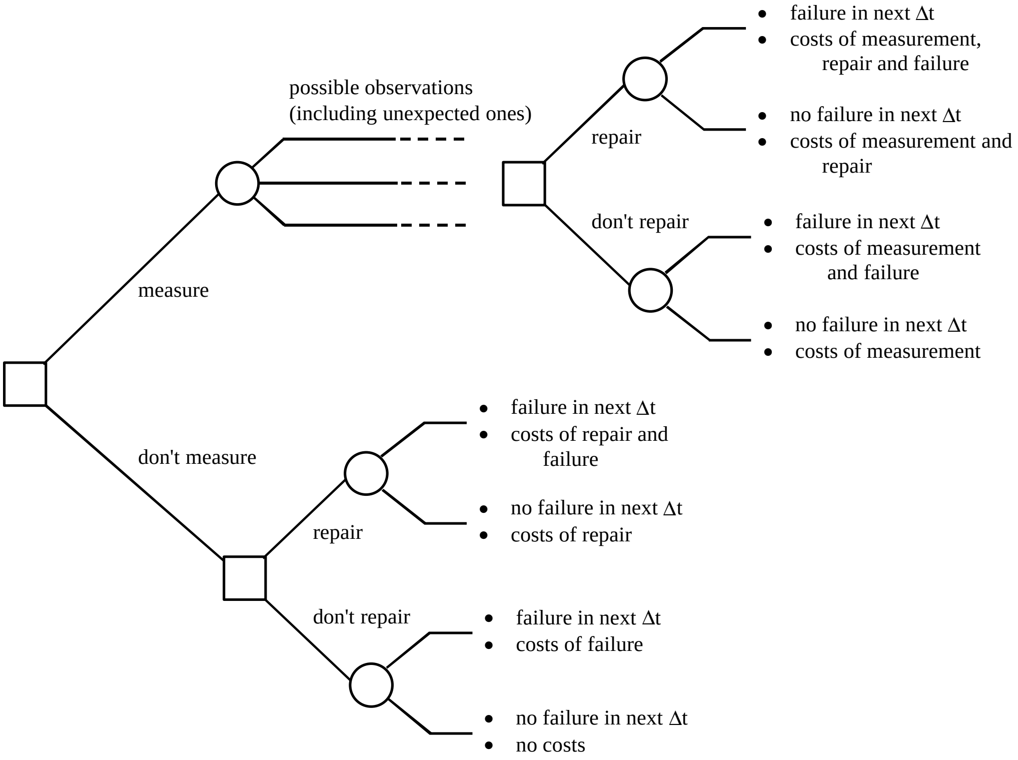

Figure 2 Illustration of the decision problem related to a monitoring strategy

In practice, such analysis will be further complicated by discrepancy between the behaviour of the construction expected during the design phase and actual behaviour. This is illustrated in Figure 3, where the reliability index against time is given for a hypothetical case, assuming a high degree of linearity. The thick line indicates the decrease in the value of the reliability index against time according to the design calculation (i.e. the initial prediction). Once this index is expected to reach a certain warning level, an inspection is carried out. This might reveal that the actual reliability index is still (much) higher (case a, b and c) or (slightly) worse (case d). In the latter case, repair will be required. In all cases, a decision has to be made concerning the next moment of inspection. In some cases, this may be far in the future. The numerous possibilities regarding actual behaviour of a construction will always necessitate making some short-cuts in the decision process. Nevertheless, performing analyses as indicated here may help reduce the total costs of a project and increase knowledge about the actual reliability of a construction.

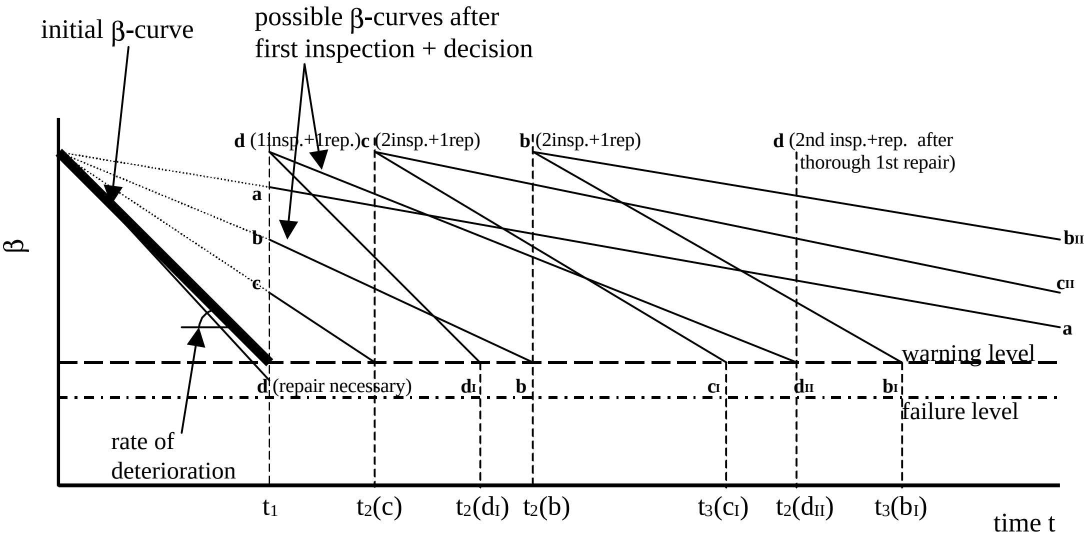

Figure 3 Example of a monitoring strategy in which measurements are carried out whenever the reliability index is expected to fall below a certain warning level

Systematic set-up of a monitoring programme during design

Despite the complexity of rational monitoring from a theoretical point of view, a more rational approach to monitoring is not impossible in practice.

First of all, it is important to note that design of a monitoring programme will never really be finished. This can be because of changes to the project during design, construction and maintenance, for instance caused by more detailed engineering, practical problems, a general increase in knowledge on certain mechanisms controlling behaviour, a change in attitude towards environmental issues, or data provided by the monitoring itself. Nevertheless, this should not prevent a professional engineer from setting up a monitoring programme during the design phase of a project. It should be borne in mind that the purpose of monitoring is not the collection of data, but to facilitate decisions on further construction and maintenance based upon the actual state of the construction.

Based upon the reliability analysis and the questions deemed relevant for monitoring, a monitoring programme may be systematically set up using the steps described below. This ‘recipe’ is based upon a similar list of actions described by Dunnicliff (1988, 1999) which, however, focuses on the instrumentation side. Use has also been made of a comparable paper written by Matthews (2000) and a more philosophical contribution by DiBiagio (1977) on pitfalls in field instrumentation, including some lessons which are unfortunately still learnt ‘the hard way’ today.

1. Select the parameters to be monitored – these should provide answers to the questions posed previously. The measurements should be processable, and the parameters should be chosen so that the measurements provide early warning against failure.
2. Predict magnitudes of change – predictions regarding behaviour of the construction should be used to determine the required instrument ranges and sensitivities or accuracies. These predictions should also be used to determine warning and failure levels. The monitoring programme should be designed in such a way that at least the warning level(s) can be detected on time with the instruments used. Instrument reliability and workable procedures for the timely processing of monitoring data are therefore highly important.
3. Devise remedial action – if the measurements indicate that remedial action is required, this should be based on appropriate, previously anticipated plans. The Failure Mode Effect Analysis may be very useful at this point.
4. Select the locations of instruments – these should be based upon the reliability analysis. The most sensitive zones are first identified, and appropriate instrumentation is located there. If there are no such zones, or if more instrumentation is deemed necessary, one or more zones (usually cross-sections) are selected where the predicted behaviour is judged representative of the behaviour of the construction as a whole. These zones are considered as primary instrumented sections. In addition to these sections, additional secondary instrumented sections are selected where less instruments may be placed. These serve to confirm that the primary instrumented sections are indeed representative. If this assumption is not confirmed, additional instrumentation may need to be placed later on.
5. List the specific purpose of each instrument – if no viable specific purpose can be found for a planned instrument, it should be omitted.
6. Plan recording of factors that may influence measured data – for example, installation record sheets for the instruments, visual observations of expected and unusual behaviour, and environmental factors such as temperature and rainfall.
7. Describe requirements for the measurements to be carried out – i.e. range, accuracy and frequency of the measurements. The latter should be adjustable according to the (predicted) rate of change of parameters and actual readings. One important aspect is whether instruments will be read automatically or manually.
8. Establish procedures for ensuring reading correctness – some redundancy of instruments may be useful at critical locations.
9. Plan regular calibration and maintenance – this strongly depends on the instruments used.
10. Assign responsibilities for design, construction and operation phases – whichever party has the most interest in reliable data should be given most responsibility (also see Dunnicliff [1999]).
11. Select instruments – the instruments may be selected at this point. The most important feature of any instrument is reliability, which is often synonymous with simplicity. ‘Lowest cost’ should not dominate the selection procedure.
12. Write instrument procurement specifications – self-made instruments are usually not the most reliable, and instruments should therefore be purchased from established manufacturers.
13. Prepare budget – to determine whether the budget planned for monitoring within the project is sufficient. If this is not the case, it should be questioned whether the budget can be raised. If this is not possible, a cut-back on the degree to which monitoring contributes to the reliability of the construction is inevitable, even though an optimal monitoring strategy has been devised. It is doubtful whether this will be efficient for the project as a whole.
14. Plan installation of instruments – everything should be available in advance, and unforeseen changes in the planning of the construction activities should also be taken into account.

15. Plan data collection – before data becomes available, an efficient way of collecting the data should be devised to ensure that data processing can also be carried out efficiently.
16. Plan processing of data – this includes presentation, interpretation, reporting and implementation of the data in a timely manner to enable suitable action (e.g. advancing or postponing ‘regular’ maintenance) supported by recent monitoring data.
17. Update budget – possible once all planning is complete.
18. Write the monitoring design report – for future reference.

To complete the above steps successfully and thus ensure establishment of an effective monitoring programme, it will be clear that the better the mechanisms controlling behaviour are understood, the more suited monitoring will be.

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