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Reliability-based alarm thresholds for structures analysed with the finite element method

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ABSTRACT

Civil engineering structures are commonly monitored to assess their structural behaviour, using alarm thresholds to indicate when contingency actions are needed to improve safety. However, there is a need for guidelines on how to establish thresholds that ensure sufficient safety. This paper therefore proposes a general computational algorithm for establishment of reliability-based alarm thresholds for civil engineering structures. The algorithm is based on Subset simulation with independent-component Markov chain Monte Carlo simulation and applicable with both analytical structural models and finite element models. The reliability-based alarm thresholds can straightforwardly be used in the monitoring plans that are developed in the design phase of a construction project, in particular for sequentially loaded structures such as staged construction of embankments. With the reliability-based alarm thresholds, contingency actions will only be implemented when they are needed to satisfy the target probability of failure.

1. Introduction

Observation of structural behaviour is standard practice in civil engineering, in particular for structures of high importance or high risk. As the cost for sensors and other equipment reduces, more and more structures are being monitored. Examples include large dams, bridges, nuclear power facilities, and geotechnical structures such as tunnels and excavations [1–7]. The purpose can be, for example, validation of design assumptions and evaluation of need for design alterations or remedial measures to ensure structural safety or satisfactory serviceability. Observations of structural behaviour can also be used to gain information about engineering properties of existing structures in assessments of their structural safety. Additional information generally implies that uncertainties are reduced and that the calculated structural reliability is improved; thereby, costly replacement or strengthening interventions may be avoided. This principle is widely applied in reliability-based design and reliability-based safety assessments of civil infrastructure; see e.g. [8–17].

As additional information is more favourable in terms of reliability improvement when uncertainties are large, observations of structural behaviour are particularly useful in geotechnical engineering, because its construction materials—soil and rock—are created by nature, which implies that their engineering properties are largely uncertain and, in addition, may exhibit a substantial inherent spatial variability. Consequently, geotechnical design codes particularly emphasise the need for monitoring during their construction; for example, Eurocode 7 [18] requires details of the planned monitoring to be included in the Geotechnical Design Report. Moreover, the challenge of managing large uncertainties in geotechnical engineering has spurred the development of a design method in which observation during construction is a key feature: "the observational method" [18,19].

When monitoring or other types of observation of the structural behaviour are targeting structural safety, an essential concern is how to ensure that safety-enhancing contingency actions are put into operation in time. A common method is to establish an alarm, which helps the decision maker to timely interventions based on the monitoring results, but lets the decision maker attend to other tasks most of the time [20]. When the alarm threshold is violated, the decision maker is alerted to act and failure of the monitored structure can be avoided.

Despite the crucial role of alarm thresholds to ensure structural safety and satisfactory serviceability, there is little guidance available to the designing engineer on how to establish them. For example, neither Eurocode 7 nor the available application guidelines provide any detailed advice: Frank et al. [21] point out that "it is the designer's responsibility to prepare and communicate specifications for any such monitoring". This lack of guidance causes problems especially when applying the observational method, as the alarm threshold defines when the design must be changed. This deficiency may have

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contributed to the limited use of the observational method; the need to clarify the safety aspects of its application has been discussed for decades [22–25].

In this paper, we address this lack of guidance and discuss how to establish alarm thresholds for monitored structures so that their structural safety and serviceability is continuously satisfactory. The paper builds directly on the findings of Spross and Johansson [26], who presented a reliability-based methodology that aids a decision-making engineer in choosing between the observational method and conventional design. Their methodology also showed how alarm thresholds need to be related to the acceptable probability of failure of the structure. However, Spross and Johansson [26] mainly discussed the decision-theoretical considerations regarding the application of the observational method. Therefore, we focus this paper on the more general issue of establishing alarm thresholds for civil engineering structures. While Spross and Johansson only looked at examples with analytical solutions, we here show how their methodology can be applied to a more general class of engineering problems by making use of the Finite element method and Subset simulation.

The paper is structured as follows: Chapter 2 describes the features of an alarm that ensures structural safety; Chapter 3 provides the structural reliability considerations in the establishment of alarm thresholds; Chapter 4 presents an algorithm for how reliability-based alarm thresholds can be set for structures that are analysed with the finite element method; Chapter 5 presents an illustrative example where the algorithm is applied to a concrete beam; Chapter 6 discusses the applicability of the proposed algorithm to civil engineering structures; and Chapter 7 summarises the major findings.

2. What is an alarm?

Alarm as a concept may be differently defined depending on the discipline. Wallin [27] identifies three different definitions (Fig. 1). In civil engineering, the stimuli-based model is normally used, as it allows a technical definition of the alarm based on the state of the monitored object. In contrast, the response-based model implies that the observer defines what constitutes as an alarm based on the incoming information, such as when an operator at a public-safety answering point decides on whether to send the rescue service or not to the caller. The message-based model refers to cases where the term "alarm" is used for the alarm *notification* exchanged by systems; this is common in the telecom industry. In the context of structural safety, the stimuli-based alarm model implies that structural behaviour is monitored and when some predefined threshold is violated, the alarm goes off, requesting the decision maker to act.

A crucial aspect is the establishment of the alarm threshold. The threshold should neither be too conservative, nor be too allowing: while the former may lead to costly false alarms that reduce the credibility of the alarm in the long run (known as the "cry-wolf effect") [28–30], the latter may make the alarm go off too late, resulting in a failed structure.

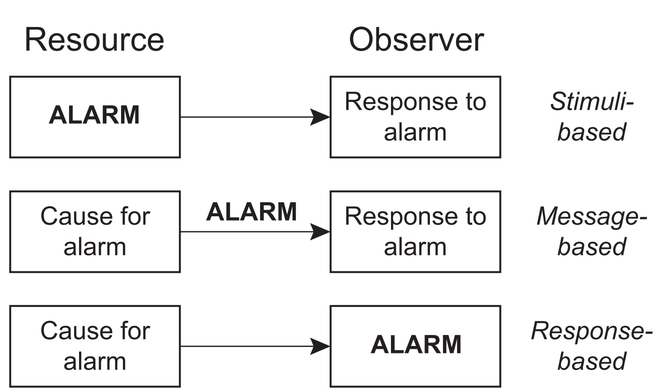

Fig. 1. Alarm definitions, extended from [59]. We use the stimuli-based definition, which is common in engineering. (© 2017. Wallin [27]. With permission of Springer.)

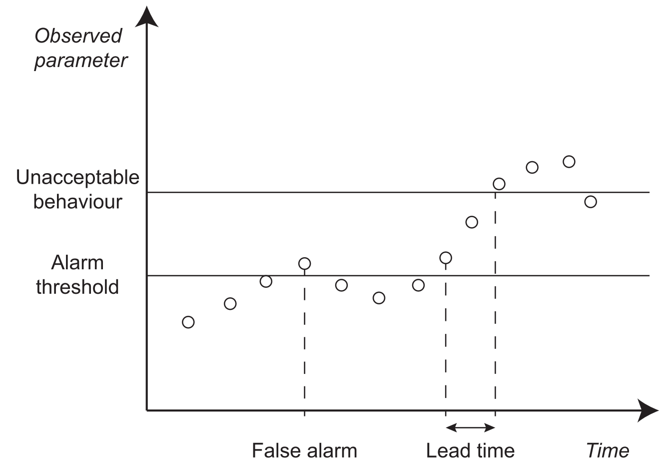

Fig. 2. False alarm and lead-time.

The alarm threshold must be clearly distinguished from the point where unacceptable behaviour is expected to occur. The time in between the alarm threshold and the point of unacceptable behaviour is defined as the "lead-time" of the alarm (Fig. 2) [31]. This timeframe must be large enough to allow for contingency actions to be put into operation. Consequently, the required lead-time depends on the type of intervention, equipment availability, and—not to forget—the efficiency of the project organisation [32]. In a complete analysis of the lead-time, the expected failure type also needs to be considered, as the failure type will affect the available timeframe; in principle, the potential situation can be considered either time variant or time invariant. Time-variant loads either follow a more or less predictable pattern or occur as a completely unpredictable (e.g. accidental) event. For predictable load variations, the concept of lead-time is relevant; however, for completely unpredictable load increasing events, the required lead-time is by definition not possible to define. Deterioration is similar to time-variant loads, but implies instead a decrease in capacity with time. For time-invariant loads, on the other hand, any load increase is under human control and there is no restriction in time when putting contingency actions into operation. A typical example of a time-invariant load increase under human control is the decision to raise the embankment height during staged construction of road or railway embankments; additional examples are discussed in Section 6.1. Thus, in principle, the alarm threshold should be selected based on the following two aspects:

- The critical limit, where unacceptable behaviour occurs with too high probability.
- The lead-time that is required to allow for contingency actions to be put into operation.

Consequently, if a required lead-time is to be assessed accurately, the designer of the alarm system needs to consider also the possible contingency actions. This implies that all monitoring plans that involve alarm thresholds must be accompanied by a contingency action plan. The need to directly link the monitoring result to contingency actions is emphasised by Olsson and Stille [32], who suggest the following general definition of an alarm threshold in a report aiming at improving the design of the monitoring system for the construction of the Swedish nuclear waste repository:

> "The alarm threshold is a predetermined value of one or a combination of several monitor parameters which, if exceeded, *will trigger predetermined measures* in order to prevent damage." [Authors' italicization]

This principle is also a key aspect of the observational method in