The potential of using performance information in the assessment of existing quay walls

Den Adel, N.; De Gijt, J. G.; Wolters, H. J.; Schweckendiek, T.

DOI
10.1088/1757-899X/615/1/012050

Publication date
2019

Document Version
Final published version

Published in
IOP Conference Series: Materials Science and Engineering

IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

The potential of using performance information in the assessment of existing quay walls

To cite this article: N den Adel *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **615** 012050

IOP Conf. Series: Materials Science and Engineering **615** (2019) 012050 doi:10.1088/1757-899X/615/1/012050

The potential of using performance information in the assessment of existing quay walls

N den Adel[1,*], J G de Gijt[2], H J Wolters[1] and T Schweckendiek[2,3]

[1]Iv-Infra, Netherlands
[2]Delft University of Technology, Netherlands
[3]Deltares, Unit Geo-engineering, Netherlands

[*]Corresponding Author Email: N.denAdel@iv-infra.nl

Abstract. The design of new and assessment of existing quay walls is subject to large uncertainties. Dealing with these uncertainties is a crucial part of the engineering process. The way uncertainties are addressed has a large impact on construction and maintenance costs and on the reliability ultimately obtained. Especially in the assessment of existing structures the uncertainties can be large. An existing structure allows us to use actual performance information in the assessment, such as the structural response to loading. One way to obtain the structural response is test loading assisted by monitoring. In this research Bayesian updating is used to reduce uncertainties and to more effectively use the obtained measurement data. We present a case study of an existing quay structure along with fictitious measurement data to demonstrate the potential effects of test loading on the reliability of the structure. The results show that Bayesian updating successfully reduces the uncertainty (i.e. standard deviation) of the model prediction. Using monitoring data and Bayesian updating provides a more realistic model of the capacity of the existing quay structure and thus a more accurate reliability assessment. Which may lead to extension of the structure's lifetime or that higher loads can be accepted.

1. Introduction

During the lifetime of a quay wall it is likely that the user wishes to increase the functionality of the quay. For example, allowing for ships with a larger draught to moor alongside the quay or increase the surcharge load on the quay. In both cases the reliability of the quay needs to be reassessed. Another example is when the structure is nearing the end of its technical lifetime. It is then required to determine the actual reliability and to predict the remaining lifespan of the structure. Often the result of conventional assessments is that increased functionality is not possible, as the envisaged loads on the structure are higher than the design loads at the time of construction. In such cases, the quay needs to be reinforced and sometimes completely replaced.

This problem is illustrated in figure 1. In this figure the service life of quays in the port of Rotterdam is shown. While commonly quays are designed for a lifetime of at least 50 years, the experience is that the service life of quays on the Maasvlakte (indicated in red) is limited to 30 years, the main reason being the change in demands, not degradation [1].

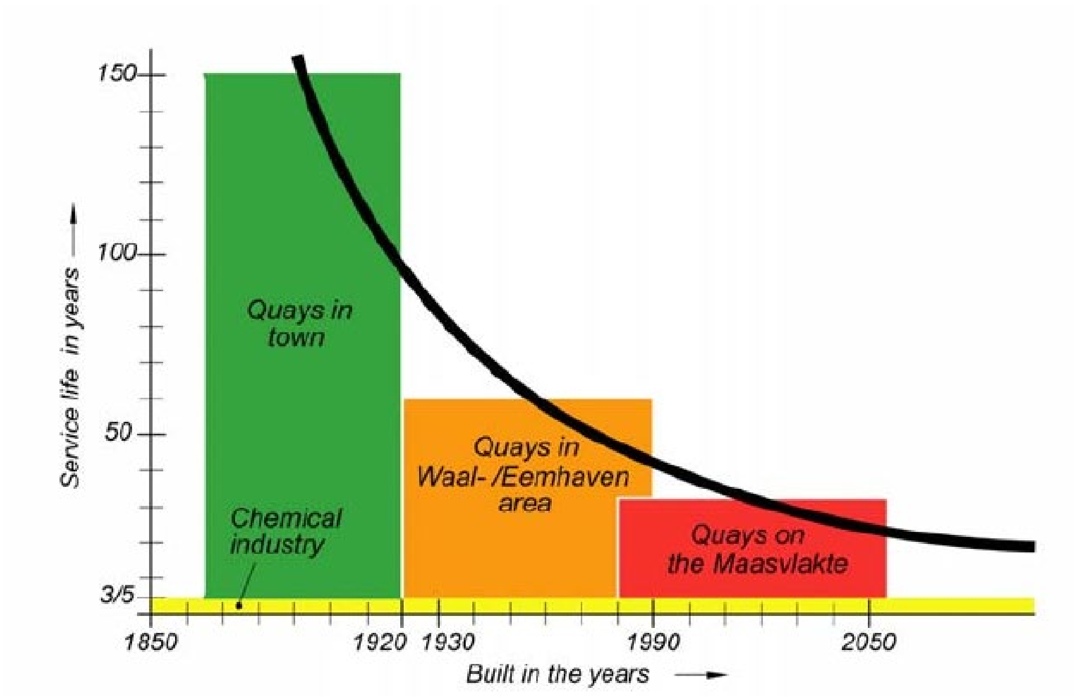

Figure 1. Service life of quay walls in Rotterdam [1].

The above illustrates that existing quay structures are replaced well before their technical lifetime ends. Often this is due to the fact that proving the reliability of a quay structure is no easy task. One of the reasons for this problem is the large uncertainty in the assessment of the existing quay structure.

An example of the uncertainty is the state of the structure. A quay wall is for the most part submerged and embedded in the subsoil, which makes it difficult to inspect the structure and thus to determine the current state of the structure. Next to the uncertainty in the structure itself, there is in many cases a large uncertainty in soil strength and stiffness properties. Furthermore, a complete site investigation to determine the soil parameters with high accuracy is not always available.

The large uncertainties lead to conservative estimates of the soil- and structural parameters. A too conservative approach can lead to expensive reinforcement measures or an entire replacement of the quay which might not be necessary from a reliability point of view. Therefore, there is a need for a method which can more accurately predict the actual strength and thus to more accurately predict the reliability of a quay wall, ideally making use of the information provided by survived load conditions and alike.

This research proposes to use performance information in the assessment of existing quay structures. This performance information can, for example, be the structural response of the structure to an applied load. This response can be obtained from a test loading of the quay structure. How to perform a test load on a quay wall is not part of the scope of this research. As a first step towards actual performing a test load, in this research a case study is performed on an existing quay structure along with fictitious measurement data to demonstrate the potential effects of using performance information on the reliability of the structure.

2. Case Study

The proposed method of using performance information is demonstrated with a case study. The method consists of the steps shown in figure 2.

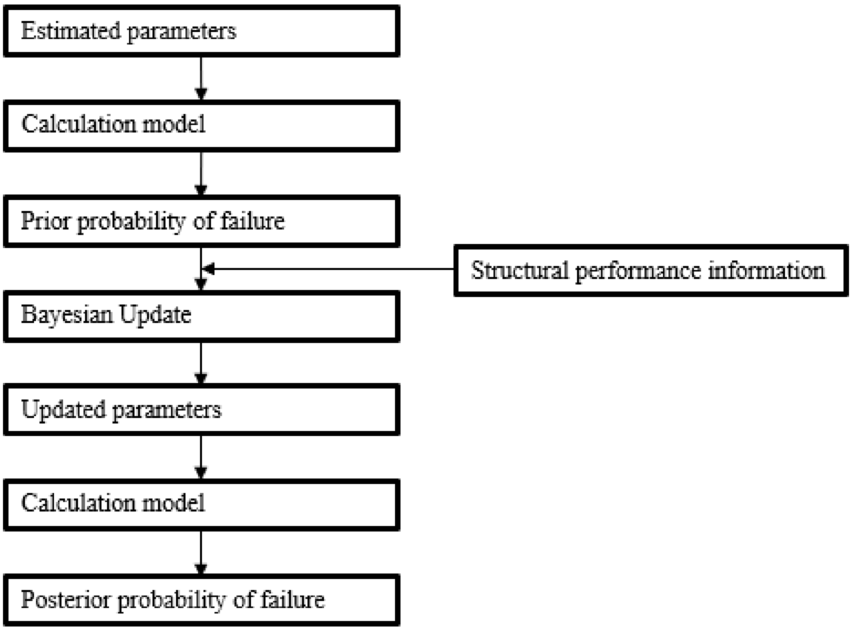

Figure 2. Flowchart of Bayesian updating and using performance information.

To perform the above steps a reference structure is selected. An existing quay located on the Maasvlakte in the Port of Rotterdam is chosen. The reference quay structure consists of a combined wall, consisting of tubular piles and sheet piles with a concrete capping beam and slab. The wall is anchored by two grout anchors in each tubular pile. A drone picture of the used quay structure is shown in figure 3. The retaining height of the structure is 14.0 m. The method is performed with different calculation models. Initially the method of Blum was used and later on a Finite Element Model (FEM) was used to verify the results. A cross section of the used model is shown in figure 4. In this paper only the results from the FEM are discussed.

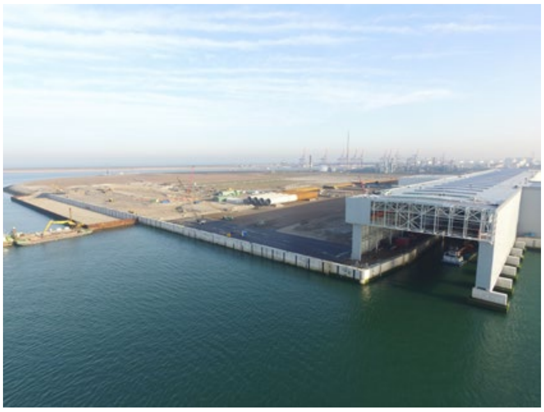

Figure 3. Reference quay structure used in the case study (Image of MUC; Alain Timmermans).

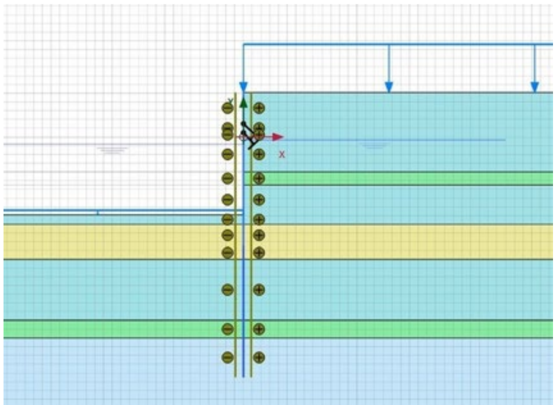

Figure 4. FEM representation used in the case study.

2.1. Prior reliability

The prior prediction of the reliability of the quay is made with a probabilistic FEM. This prediction is based on the design documents of the quay and a site investigation, consisting of CPT's, is used to determine the soil profile and soil parameters. In order to limit the calculation time of the model, a selection in which parameter is chosen stochastic is made. One of the aims of applying Bayesian updating is to reduce the uncertainty in the variables by obtaining better estimates. This will be most interesting for the most uncertain variables. It is assumed that the soil parameters are the most uncertain and therefore only these parameters are chosen stochastic. The geometrical and the structural strength and stiffness parameters are deterministic parameters.

2.2. Bayesian updating
As shortly introduced, Bayesian updating will be used to update model predictions according to measurements on site. Bayesian updating is a probabilistic method to improve the accuracy of a predictions based on additional information. This information can in general be any measured quantity or observation.

Bayesian updating is based on the conditional probability theory developed by Bayes [2]. This theorem is defined as:

$$P(A \mid B) = \frac{P(B \mid A) * P(A)}{P(B)} \quad (1)$$

Bayes' theorem can in principle be solved analytically for any kind of problem. However, to determine the analytical solution for a Bayesian updating problem with a large number of variables is difficult. In order to solve the formula, it must be integrated over all included variables. The result is a multi-dimensional integral which in general cannot be solved easily. Therefore, a different approach is required. A commonly applied method to approximate the solution of the equation is using sampling methods. The most well-known are the Markov Chain Monte Carlo (MCMC) methods.

The method used in this research is the method of 'Bayesian Update with Structural reliability methods (BUS)'[3]. BUS rewrites the formula of Bayes into a Limit State format, which can then be solved by applying the standard reliability methods. The advantage of this approach is that it can be applied relatively simple and gives flexibility, as theoretically every already available structural reliability method can be applied [3]. Results have been obtained by using BUS with Monte Carlo simulation. Applying BUS using a Monte Carlo Simulation is a relatively straightforward method. The principle is based on a simple-rejection filter [3]. The samples which should be in the posterior are filtered based on their likelihood of occurring.

2.3. Fictitious measurements
In order to perform a Bayesian update evidence is required. Evidence can be all sorts of measured data for example: deformations of the structure or the soil, strains or rotations. Another possibility is knowledge about the survived load on the quay. If it is known that a certain extreme load is placed on the quay, then also this information can be used to update the probabilistic model. In the case study fictitious measurements are used. Two types of measurements are used. It is assumed that the maximum horizontal displacement of the combiwall is measured and the strain in the anchor tubes is measured. To show the possible outcomes of Bayesian updating, three different cases are defined per type of measurement. This results in a total of six cases and thus six Bayesian updates. The cases are:

- Low less displacement or strain is measured then is predicted (best estimate).
- Average equal displacement or strain is measured then is predicted.
- High more displacement or strain is measured then is predicted.

In this paper only the results found by updating based on the displacement measurements are shown. The used measurement cases are shown in table 1.

Table 1. Measurement cases [4].

Case	Measurement μ (mm)	Measurement error σ (mm)
High	75	5,00
Average	60	5,00
Low	45	5,00

In the case study it is assumed that the displacement along the height of the combi-wall is known. As input to the Bayesian update, these are also the values listed in table 1, the point of maximum horizontal displacement is used. This point is indicated in figure 5.

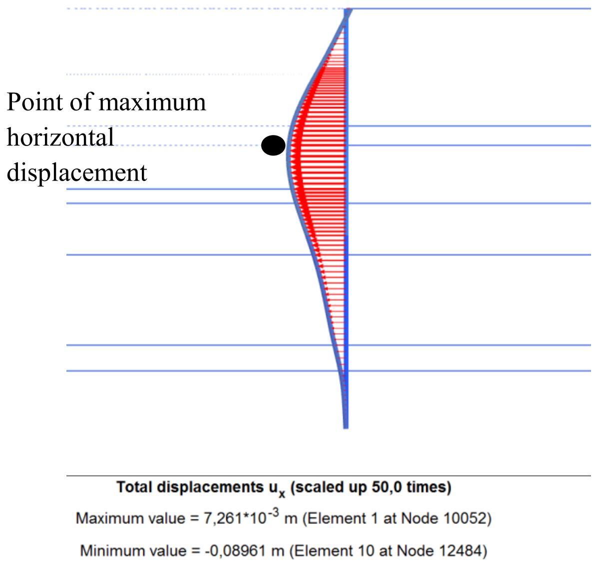

Figure 5. Fictitious measurement point used as input for Bayesian update.

3. Results

The results are described in this section. First the results for the prior prediction are shown and secondly for the posterior prediction.

3.1. Prior results

To demonstrate the potential effect of test loading, the reliability of the quay for a fictitious limit state is determined. In this case study this reliability is determined based on only one limit state function and thus only for one failure mechanism. A limit state function based on a maximum allowable horizontal deformation of 90 mm is defined. The initially found reliability index is equal to β=1,49. In addition to the calculated reliability index, the maximum horizontal displacement is predicted. Initially it is predicted that the maximum horizontal displacement can be described by a normal distribution with a mean of 59 mm and a standard deviation of 11 mm.

3.2. Posterior results

Performing the Bayesian update based on the prior prediction and the measurement cases listed in table 1, results in figure 6 and figure 7. In figure 6 the prior and updated predictions are given for the maximum horizontal displacement. In figure 7 the changes in one of the included stochastic parameters is shown. In this figure the friction angle for the top soil layer is plotted for the different measurement cases. In addition to the figures the reliability index is calculated for the three update cases:

- Prior β=1,49
- Case high β=1,06
- Case average β=1,92
- Case low β=3,02

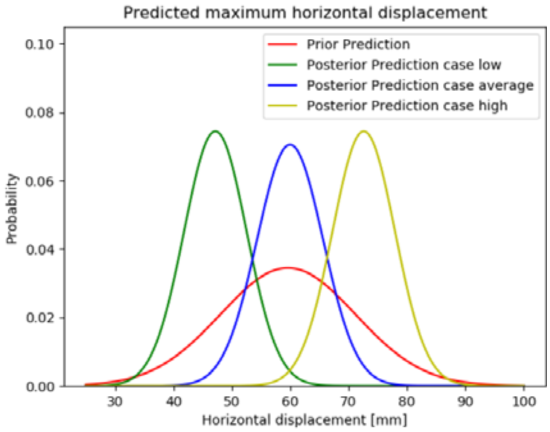

Figure 6. Predicted horizontal displacement.

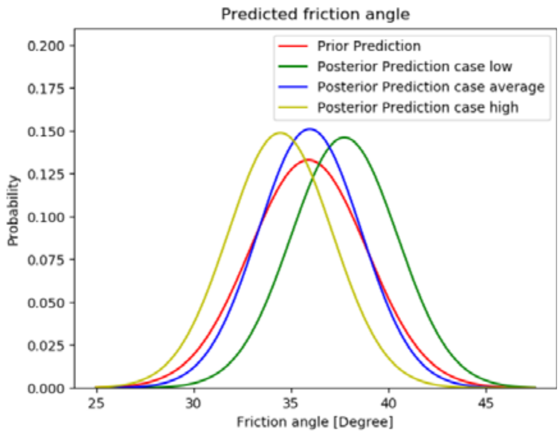

Figure 7. Prior and posterior estimates of the friction angle in the top soil layer.

Given the results in the figures and the updated reliability indices the following remarks can be made. The first and most straightforward observation is that the updated distributions tend to predict the displacement more in accordance with the provided measurement. The mean of the updated distribution approaches the mean of the measurement. The second important aspect is that all updated distributions have a significant lower standard deviation. Therefore, the updated prediction is more accurate, with respect to the initial prediction, and therewith more able to predict the 'real' behaviour of the quay. While comparing the prior reliability index with the updated indices, a logical conclusion is that the update based on 'less displacement' results in a higher index. As the limit state calculates the probability that the displacement is higher than 90 mm. Furthermore, also in the case that the measurement is almost equal to the initial best-estimate prediction an increase in reliability index is found. This can be attributed to the fact that the updated prediction shows less standard deviation.

The basis for this updated prediction is the determination of the a-priori stochastic parameters. Upon performing the Bayesian update, one receives a set of updated parameters. This updated set is based on the initially defined stochastic distribution and the measured structural response. In this case study the updated set is determined with a sample method. For each sample the likelihood of the sample is determined, based on the prior stochastic distribution of the parameters and the measured structural response. The resulting posterior set is a combination of the most likely samples. In figure 7 this is shown, for the different measurement cases the friction angle of the first soil layer is updated. For the case in which less displacement is measured then initially predicted, indicating a lower soil pressure on the wall then initially thought, the friction angle is increased. Also, the opposite is visible, the case of more measured displacement shows a reduced friction angle. Furthermore, as shown in figure 7, the updated parameter has a lower standard deviation. Here the result is presented for only a single parameter, but this can be presented for all the included stochastic parameters. Generally speaking, the less influence a parameter has on the failure probability, the less change the parameter shows in the updated probability distribution. Using this information, it is worthwhile in terms of calculation time, to reduce the number of stochastic parameters based on their influence coefficient in the initial prediction.

The next step after determining the updated parameters, is to determine the reliability of the quay with more accuracy. In the best case the updated model results in an increase in reliability. It is then possible to determine if for example the lifetime of the structure can be extended, or if higher operational loads can be accepted, e.g. by increasing the harbour depth or by increasing the surcharge load. On the other hand, if the reliability is decreased, as the resulting model is more accurate, the effect of reinforcement measures can be evaluated better or it can be decided to reduce the maximum surcharge load on the existing quay.

4. Conclusion

One of the main motives leading to the start of this research is the problem of proving that the reliability of existing quay structures is still high enough with respect to the safety requirements. The main difficulty is how to cope with the large amount of uncertainty in these kinds of predictions. An existing structure allows using actual performance information in the assessment. To demonstrate this potential a case study is performed in which Bayesian updating is applied to a probabilistic model of a quay wall. Based on fictitious measurement cases, the effect of using performance information to enhance model predictions is determined.

Based on the case study results it can be concluded that using Bayesian updating in combination with a measured structural response a significant improvement in the prediction of the reliability can be made. This improvement mainly consists of a reduced standard deviation in the updated prediction. This reduction can be explained by the fact that monitoring data can generally be obtained more accurately then using only a model to predict the behaviour of a quay.

In addition to obtaining an updated reliability estimate, Bayesian updating gives insight in to how the initially determined input parameters have changed. As the result of a Bayesian update is a statistically most likely combination of stochastic input parameters. This most likely combination is determined both on the initial stochastic definition of the parameter and the monitoring data obtained from the behaviour of the structure. Using this most likely combination it can be shown which parameters are significantly deviating from their initial estimate. Furthermore, this can based on the statistic likelihood be proven. While if one is to use a deterministically fit a model upon a for example measured displacement this is not possible. It cannot be proven, perhaps only upon expert judgement, why a certain parameter is chosen too conservative or too optimistic. Furthermore, a deterministic back analysis will result in evaluating many possible combinations while Bayesian updating determines a single combination which is most likely to occur.

5. Potential for application in practice

In the presented case study fictitious measurement data were used to demonstrate the potential of combining both Bayesian updating and using the structural performance of existing structures. For a practical case it is of course required to use real measured data. One possibility to obtain data is test loading. One option is placing a surcharge load consisting of shipping containers on top of the quay. Using shipping containers, the loads on the quay can be increased in a controlled stepwise manner. The structural response of the structure under the imposed load needs to be monitored continuously.

Another and perhaps more interesting option is to obtain the structural response of the quay during the construction stage. For example during the excavation of the soil in front of the quay wall to the required harbour depth. During this dredging operation the quay starts to deform and one could very well use this structural response to perform a Bayesian update. Using data obtained during such a construction process could be an interesting step to further evaluate the method of using structural performance data as presented in research. Furthermore, the structural response can be obtained relatively inexpensive as it is a necessary part of the construction process and for larger quay structures monitoring equipment is already installed. An additional benefit of this application of the method is that this data could directly be used to determine the ‘hidden’ safety which is included in the design and possibly if the allowable surcharge can already be increased at the start of the quay’s lifetime. If applied in combination with the observational method, the benefits can even be included during the design stage of the structure.

Acknowledgments
This research was supported by Iv-Infra b.v. and Delft University of Technology.

References

[1] De Gijt J G and Van Der Toorn A 2009 *Future trends in quay wall design* (Municipality of Rotterdam, Urban Development, The Netherlands)
[2] Bayes T and Price R 1763 An Essay towards solving a Problem in the Doctrine of Chance *By thelate Rev. Mr. Bayes, communicated by Mr. Price, in a letter to John Canton, A.M.F.R.S." Philosophical Transactions of the Royal Society of London* vol 53(0) pp 370–418
[3] Straub D and Papaioannou I 2014 Bayesian updating with structural reliability methods *J. Of Engineering* **141**
[4] den Adel N 2018 *Load testing of a quay wall* MSc Thesis