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Quality assessment of coupled partial models considering soil–structure coupling

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ABSTRACT

Integral bridges are gaining more and more interest lately because they are associated with significant cost savings in building maintenance. However, the design of these bridges makes very high demands on the planners, which have to take into account many complex phenomena for the calculation and the design of such structure. In order to assess the reliability of the model prediction and to reduce the complexity of a calculation model in a reasonable manner, this article presents an evaluation method for the prediction quality of coupled partial models. Finally, this algorithm is applied to an example of a semi-integral concrete bridge structure. The evaluation method allows for the quantification of the prediction quality and, thus, to detect optimal as well as efficient model combinations for reliable predictions.

1. Introduction

In recent years an increasing demand of the building developers according to the construction of integral and semi-integral bridges is recognisable [23]. The waiving of the non-durable bearings and joints as a result of the bearingless and jointless connections of the structural components leads to significant cost saving in structural maintenance. A lot of various complex, partially difficult to captured and challenging to modelled phenomena have to be considered in the analysis of the entire structure [4,20,30,35]. Therefore, the design of the integral bridge projects present demanding challenges for structural engineers. In particular, the assessment of the restraint effects caused by the creep, the shrinkage, the relaxation, the temperature, and their degradation forced by the cracking of the concrete and the flexibility of the soil and foundation poses high requirements on the modelling process.

The numerical analysis of the load-bearing behaviour of integral bridges requires several partial models (PM), e.g. the creep of the concrete, and the consideration of the coupling of the PM. The PM and their corresponding coupling has to be taken into account in order to establish a global numerical model (GM) of the structure. For each of the different phenomena (so-called PM), varying simplified or more sophisticated model approaches are published and available for the modelling and the design of integral bridges.

The stiffness of the soil, the foundation and the stiffness of the bridge interact together, especially in the case of the restraint sensitive integral bridges [8,12,13,21]. Therefore, the importance of the coupling between the structure and the soil (pile foundation), and different prediction quality scenarios are analysed in order to assess the influence of the coupling on the global model prediction quality. In addition to the PM pile foundation stiffness, the physical non-linear description of the concrete, the geometric non-linear kinematic, the thermal action, the creep of the concrete, the cyclic creep of the concrete, the shrinkage of the concrete and the relaxation of the prestressing tendons are considered in the quantitative evaluation of the global model prediction.

In the context of reliability analysis, the paper by Guo et al. [15] mentioned the importance of the consideration of different phenomena (creep, shrinkage, stress relaxation, cracking of concrete and corrosion) in order to develop a more precise time-dependent reliability evaluation methodology. Some previous studies like [7,34] were mainly focused on the importance of corrosion according to the reliability of prestressed concrete bridge girders and reinforced beams, respectively. A major conclusion of the analysis by Guo et al. [15] was, that creep and shrinkage of concrete have a significant influence on the reliability analysis. For the simulation of the long-term behaviour of long-span prestressed concrete continuous rigid-frame bridges, Pan et al. [26] applied the uncertainty analysis of the creep and shrinkage effects in order to compare different models with experimental measurement data. The uncertainty

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propagation method for the estimation of losses in structures due to earthquake damage by Baker and Cornell [1] declare the model uncertainty to be a important and necessary component in the assessment. Another example of the importance of the model choice is the interdependency between the modelling error and the parameter estimation using structural health monitoring data [32].

The above-mentioned research investigations of different structural engineering fields show the importance of the model selection on the simulation results. In consequence, the coupling of different phenomena (partial models) can be crucially necessary for the global structural model. The consideration or the negligence of a certain partial model and the coupling in the global model are often based on expert opinion and subsequent investigations, such as the reliability analysis, the risk analysis or the simulation of the load-bearing behaviour of structures, are done for only one global model of the object. In consequence, some question arise:

- What is the influence of a certain phenomenon in comparison with other phenomena according to the structural response?
- What is an adequate complexity (respectively quality) of each partial model for the various phenomena?
- How should they be coupled together in the simulation of the entire structure?
- How can a quality of the coupling be assessed?
- Is there a method to combine these quantitative informations into a global model prediction quality?

The evaluation method for the assessment of coupled partial models in structural engineering was published by Keitel et al. [18]. The application of the developed method was performed on a conservative prestressed concrete box girder bridge without any consideration of the coupling quality. In the present paper, this developed algorithm is applied on a semi-integral concrete bridge. This structural system lead to a soil–structure interaction with respect to the stiffness of the pile foundation and the stiffness of the concrete bridge components. Therefore, the influence of the coupling between both parts and the importance of the coupling quality on the global model prediction quality is additionally evaluated in this paper (see Section 2 and Section 3). The influence of each partial model and their coupling with respect to the prognoses of the structural load-bearing behaviour, expressed by various structural response values, is considered in the assessment method in a quantitative manner.

For any engineering calculation, the consideration of the quantitative informations – the sensitivity of each partial model, the quality of the partial model itself, the influence of the coupling and the coupling quality itself – enables a holistic evaluation of the prediction quality of the global model, which is presented in this paper. The paper is organised as follows: following this introduction the theoretical background of the evaluation method is explained in Section 2. The application of this method to a semi-integral bridges is presented in Section 3 and finally conclusions are drawn.

2. Evaluation method

The quality of coupled partial models is defined by the individual quality of the partial models, the influence of the partial models on the output quantities, and the coupling qualities of the partial models. In the following, methods to determine each of these components is described.

2.1. Influence of partial models

Sensitivity analyses quantify the influence of input parameters on the output of a model. As proposed in [18], variance-based global sensitivity analysis can also be used to study the influence of partial models on the output of the global model. This procedure detects the most influential classes of partial models on specific output quantities. Hence, when evaluating the prediction quality of the global model, the quality of the partial models with a high influence on the output quantities is more important than the quality of non-influential partial models. The method to calculate the sensitivity indices and, thus, to quantify the influence of classes of partial models is the basis of this investigation of the coupling quality as well as the total prediction quality. In the following, the algorithm described in [18] is revealed.

Each of the classes of partial models i, e.g. creep of concrete, is represented by a discrete random parameter with the two discrete values:

$$X_i \in \{0, 1\}, \text{ with } i = 1, \ldots, M, \tag{1}$$

wherein M represents the number of partial models involved. A value of $X_i = 0$ denotes the deactivated partial model class i, for example creep is not included, and $X_i = 1$ denotes the activated partial model class i, e.g. creep is considered. The global model Y is calculated for all possible combinations of X_i with $i = 1 \ldots M$. The total number of combinations is denoted N_P and can be calculated with:

$$N_P = 2^M. \tag{2}$$

The exclusive influence of the parameter X_i or partial model i, respectively, is quantified by the first-order sensitivity index S_i [33]

$$S_i = \frac{V(E(Y|X_i))}{V(Y)} = \frac{V_i}{V(Y)}. \tag{3}$$

Herein $V(E(Y|X_i))$ is the variance of the expected value when the conditioning the model Y to parameter X_i and $V(Y)$ is the total variance of Y when all parameters vary simultaneously.

In order to take into account coupling effects, the total-effects sensitivity index S_{Ti} was introduced by Homma and Saltelli [16]. Besides the exclusive influence of the parameter X_i on the variance of the response, the S_{Ti} index considers the interaction of X_i with all other parameters and is defined by

$$S_{Ti} = 1 - \frac{V(E(Y|X_{\sim i}))}{V(Y)}, \tag{4}$$

with $V(E(Y|X_{\sim i}))$ as the variance of the expected value when conditioning to all parameters but X_i, denoted as $X_{\sim i}$. The interactions are quantified by the difference of S_i and S_{Ti}.

In addition to S_i and S_{Ti} the higher-order indices S_{ij} directly apportion the interaction effects to specific parameters/classes i and j of partial models. For S_{ij}, the following definition holds [31]:

$$S_{ij} = \frac{V(E(Y|X_i, X_j)) - V_i - V_j}{V(Y)} = \frac{V(E(Y|X_i, X_j))}{V(Y)} - S_i - S_j. \tag{5}$$

In the present case of discrete input parameters all first-order, total-effects, and high-order indices can be calculated directly from the results of model Y for the N_P combinations of input parameters without the usual need of specific sensitivity estimators, which require high computational effort.

2.2. Coupling quality

Usual coupling types in engineering are uni- and bidirectional coupling [14]. The first one denotes the data transfer from PM k to PM l, but not in the opposite direction. In contrast to this, the bidirectional coupling allows for the additional data transfer from PM l back to PM k. In the following, a methodology is proposed to quantify the quality for the cases of uni- or bidirectional coupling.

Within the scope of this paper, coupling is defined as data coupling and the quality of coupling is related to the quality of data