# Stange Overpass: Finite Element Model Updating of an Unconventional Railway Bridge

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**Abstract.** Stange Overpass is a three-span railway reinforced concrete bridge on the Dovre line that connects the cities of Oslo and Trondheim in Norway. It was built in 2002 and has been extended by 1,5 meters in each direction in 2004. During the extension operation, the part of the deck that has been extended from the abutments had not been placed on a foundation but, instead, had directly been constructed over the soil mass. Within the context of the Intercity project that has recently been undertaken by the Norwegian Railway Authority (BaneNOR), passenger trains that cross Stange Overpass will be upgraded to high-speed trains. For this, the existing bridge needs to be evaluated for the new train type. This requires a finite element model that correctly and reliably models the dynamic behavior of the bridge under various environmental and loading conditions. Preliminary analysis results show that the most significant parameter that governs the dynamic behavior of the bridge is the load-deformation behavior of the soil that directly supports the ends of the deck that extends outwards from the abutments. The load-deformation behavior of the soil can be expected to be highly sensitive to the environmental conditions and the changes in these conditions from summer to Nordic winter. To provide a reliable estimate of the load-deformation behavior of soil as well as a reliable finite element model, an instrumentation set-up will be installed in the bridge by Oslo Metropolitan University in collaboration with BaneNOR. A new finite element model updating algorithm will be developed that can not only estimate the traditional linear parameters but also the non-linear force-deformation relationship of the soil mass that supports the bridge deck. This article provides a summary of the project together with initial results that include sensitivity analysis that has been conducted to quantify the effects of the soil model on the dynamic behavior of the bridge.

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## 1 Introduction

The existing railway bridge infrastructure in Norway and Europe is aging rapidly. As of 2017, more than 35% of half a million railway bridges in Europe are over 100 years old with many more on the wrong side of their 50-year design life [2]. In addition, the bridge infrastructure is subject to ever-increasing speeds and heavier axle loads due to the rapid advances in train technology.

Bane NOR is responsible for monitoring, maintenance and control of over 3000 railway bridges in Norway. With an increase in the design velocity and design axle load of the trains that will be used on a specific line, Bane NOR is required to ensure that all the bridges on that line is capable of carrying the new design loads safely and without hindering the comfort of the passengers. This often requires detailed finite element (FE) analysis of the bridges under generic or specific train loads [4]. The accuracy of verification of a bridge under the changing train loads and the entailing decision with regards to the future of the bridge depends solely on the accuracy of the finite element model. As such, an accurate FE model that is capable of simulating the actual behavior of the bridge is indispensable for the verification of existing bridges under changing loads. However, FE models are generally created based on design drawings and material specifications. The results obtained from these models do not usually match the field measurements [3]. The differences are generally related to material properties and uncertainties in boundary conditions. Therefore, calibration of finite element models to accurately replicate the behavior of the bridge to be evaluated is crucial. This is especially true for bridges that have unique structural systems which potentially have significantly different behavior compared to regular bridges.

Stange Overpass is a bridge with such a unique structural system. It is located near the Stange Station and spans over the Fv222 road. The bridge, which was designed in 1999 and constructed in 2002, is part of the Dovre line (*Dovrebanen*) project. The Intercity project aims to build a double-track train line between Oslo and Lillehammer and is part of the Intercity development. As part of this project, Stange Overpass, which was originally designed for speeds up to 200 km/h, needs to be verified for train speeds up to 250 km/h. Stange Overpass, which is a set of twin bridges that house one track each, has a unique structural system as the extensions of the bridge from the abutments were designed as cantilevers without any contact between the bridge deck and the abutment. The field observations show that one of the two twin bridges indeed has such a structural system. However, the deck of the second bridge sits on a concrete slab that covers the top of the abutment, which, in turn, is seated on the soil mass that is filled in the u-shaped abutment.

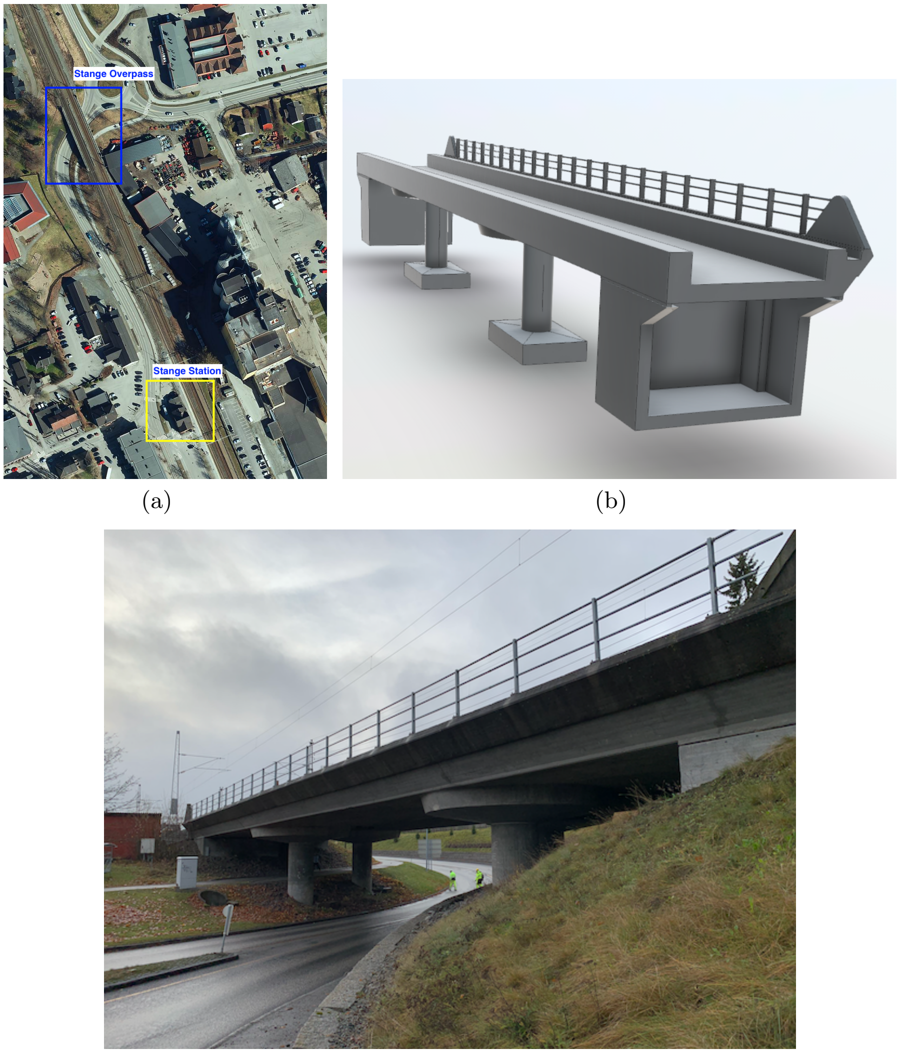
Recently, an assessment of the bridge using sophisticated finite element models for HSLM-A train load for speeds ranging from 30 km/h to 300 km/h. As a result of this assessment, which is based on a FE model created using design drawings, it was concluded that the bridge is far from satisfying neither the safety nor the comfort criteria set forth by current standards. For the comfort criteria, EN 1991-2 [4] requires that maximum accelerations should not exceed 3.5 $m/s^2$. However, the analysis results show that the maximum accelerations reach up to 35 $m/s^2$. The computed accelerations exceeded the limit by three folds even for train speeds of 30 km/h. These excessive vibration levels should have led to significant displacement in the ballast, which in turn could have led to track misalignment and derailment. Furthermore, the acceleration levels exceeding the gravity of acceleration should have led to between the wheel and the rail [9]. Despite the extremely high acceleration levels computed using finite element models based on the design drawings, the trains continue to cross the bridge several times each day without any problems or any reported passenger discomfort. These observations suggest that the finite element model based on the design drawings is far from providing reliable estimates of the acceleration levels occurring on the bridge due to train traffic.

Within this context, Bane NOR and Oslo Metropolitan University (OsloMet) has commenced on a collaborative research project (*NEAR: Next Generation Finite Element Calibration Method for Railway Bridges*) that aims to develop a finite element model updating method for railway bridges that can reliably estimate the acceleration demands under various boundary and environmental conditions and train loads. This article summarizes the outline of the project as well as the initial results.

## 2 Stange Overpass

Stange Overpass is a 48m long, three-span railway bridge situated on the Dovre line (Dovrebanen) which connects the cities of Oslo and Trondheim in Norway. The bridge is situated right by the Stange station and is heavily trafficked by both passenger and freight trains. The bridge is constructed as twin bridges; each one housing one set of tracks. The bridges were constructed in 2002 and originally both were 9.0 m shorter than their current length. The original bridges were seated at elastomeric bearings at each end that are mounted at the top of U-shaped abutments. In 2004, the bridges were extended 4.5 in each direction from both abutments. During the extension operation, the newly constructed bridge deck have not been seated on the wings of the U-shaped abutments but have been left as cantilevering at both sides. The decks were then connected to the rest of the tracks with the help of transfer plates that are seated at the edge of the deck at each end of the bridge. The bridge is supported by two reinforced concrete circular piers. Figure 1 shows the location and overhead view of the bridge (a), a 3D rendering of the bridge with focus on one of the abutments (b) as well as the view from the east side of the bridge (c).

The site inspection conducted by the authors revealed that the twin bridges have significantly different boundary conditions at the ends of the bridge decks. The first bridge is constructed as shown in the design drawings with the extended



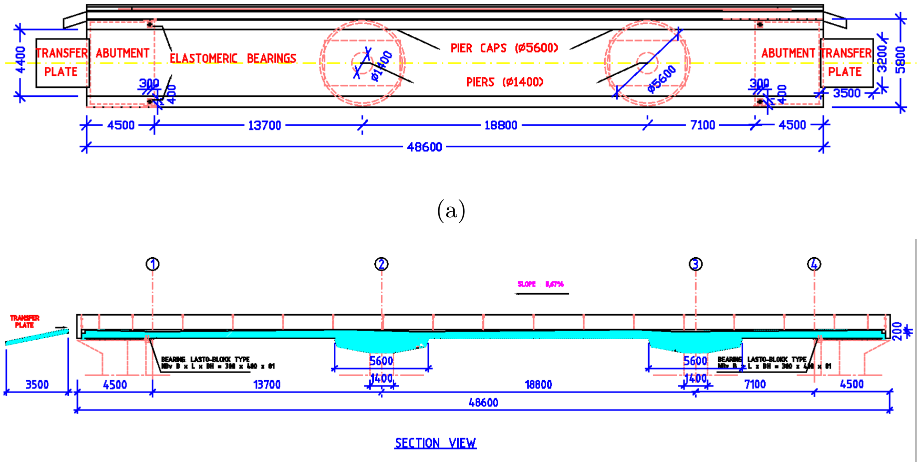
(a) (b)

(c)

Fig. 1: Overview of the Stange Overpass

parts of the deck cantilevering from the elastomeric bearings at each end with a clear separation between the deck and the wings of the abutment. On the other hand, the other bridge, which has the exact same structural configuration has been seated on concrete slabs that are placed on the backfill material that fills the abutments (see Figure 1 (c)). Therefore, the two bridges can be expected to have a significantly different behavior. In addition, the temperature difference between summer and winter, which has previously been documented to impact the stiffness and damping of ballast and track [6], can be expected to have an even more significant impact on the dynamic behavior of Stange Overpass due to the unconventional boundary conditions.

Figure 2 depicts the plan and the elevation views of the Stange Overpass where the overall dimensions of the bridge along with the placement of the elastomeric bearings are shown.



(a)

(b)

Fig. 2: (a) Plan and (b) elevation view of the Stange Overpass

## 3 State of the Art, Knowledge Needs and Preliminary Results

Calibration of finite element models, also known as FE model updating, is a procedure to determine the uncertain physical properties in the FE model based on experimental results to achieve a FE model that can represent the observed behavior of the structure accurately. As the need for accurately assessing the existing structures under varying conditions continue to increase, so does the need for accurate finite element models. As such, calibration of FE models of engineering infrastructure has been gaining attention in the last decade. Among the different type of field experiments, use of vibration data from traffic loading remains the most useful and popular approach as this data is readily available to harvest and process.

FE model calibration methods can be divided into two based on their approach to the problem: (i) Direct methods and (ii) Indirect methods [3]. The first approach directly updates the mass and stiffness matrices of the structure but it is very difficult to apply to large structures with very large matrices. It can also lead to ill-conditioned problems for very complicated models [5, 8]. The iterative methods, on the other hand, rely on updating the physical properties behind the FE model such as material and geometric properties. As a result, they are more flexible and efficient for large scale structures [3].

Almost all available methods that leverage vibrations due to regular traffic on bridges aim to accurately match either the vibration frequencies, mode shapes or a combination of these two parameters [7]. These vibration parameters are popular because they depend solely on the material and geometric properties of the structure, i.e. independent of the loading. On the other hand, the evaluation of bridges is based on the maximum accelerations and forces occurring on the bridge under different train loads. So far, to the best of our knowledge, no available method tackled the challenge of calibrating FE models to provide accurate estimates of observed accelerations under different loads. Furthermore, all the available methods in literature [7] have been developed and validated for bridges that are supported by conventional foundations at both ends. Stange Overpass provides an important challenge as each of the twin bridges has very unconventional boundary conditions: In one of the bridges, the deck is cantilevering 4.5m from the bearing in each direction, while in the other bridge this portion rests on a concrete slab of unknown thickness, which, in turn, sits on backfill material with unknown properties. Here, it should be noted that, even though the first bridge has been described as cantilevering from the bearings, the bridge is connected to the rest of the track by a 20 mm thick concrete transfer plate at each end. However, this transfer plate had not been designed to transfer any loads and it has been placed on a seating on the deck that is 200mm deep and 4400 mm wide; Figure 3. On the other hand, despite the lack of a stiff connection, the transfer plate can be assumed to be held in place by the weight of the ballast and track impeding the deck from behaving as a cantilever. In short, both bridges have challenging boundary conditions that are highly likely to impact their dynamic behavior and the maximum accelerations occurring on the bridge due to various train loads.

In order to evaluate the impact of the boundary conditions on the dynamic behavior of the bridge, a series of preliminary analysis was conducted. For this, a detailed 3-D model of the bridge was developed in the finite element program SAP2000. The deck and the columns of the bridge were modeled using 8-node solid elements while the elastomeric bearings have been modeled using elastic springs in three orthogonal direction. An overview of the preliminary analysis model is shown in Figure 4. This model, where the last 4.5m of the bridge deck

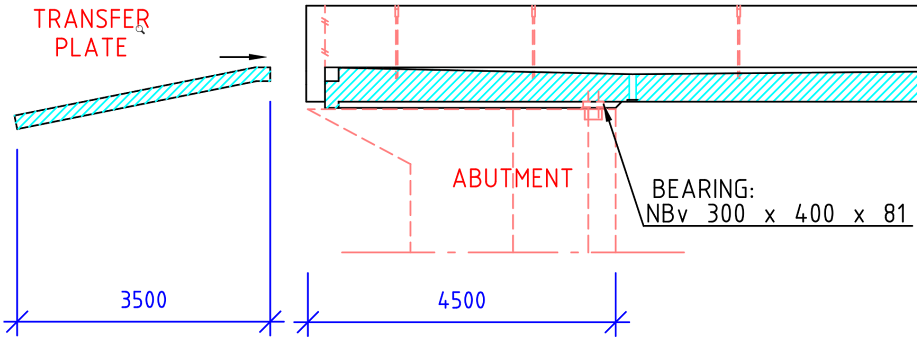


Fig. 3: Detail of the connection between the bridge deck, abutment and the transfer plate

(i.e. from the elastomeric bearings to the edge of the deck) is working as a cantilever, was used as the baseline model. The effect of the concrete slab seated on soil mass is then modeled using surface springs acting at the bottom of the bridge. Since the soil properties are unknown, a range of spring stiffnesses, that were taken from [1], has been applied to simulate various soil conditions from soft to stiff soil. It should be noted that, the values given in Table 1 for soft soil stiffness can represent both loose sand and clayey soil with a tip resistance lower than 200 kPa while the stiff soil can represent both dense sand and clayey soil with a tip resistance higher than 800 kPa. Thus, the preliminary analysis covers both sandy and clayey soils as the soil type is unknown. Table 1 summarizes the properties of concrete, the elastomeric bearing and the stiffness of the surface spring that simulates the behavior of soft and stiff soil. The stiffness of the point springs that simulate the elastomeric bearings computed using the mechanical and geometric properties of bearings are also given in Table 1

Table 1: Modeling parameters used in the preliminary analysis

| Parameter | Value | Spring Stiffness |
|---|---:|---:|
| Modulus of Elasticity (E), Concrete | 38 000 $MPa$ | - |
| Modulus of Elasticity (E), Elastormeric Bearing | 550 $MPa$ | 815 000 $kN/m$ |
| Shear Modulus GE), Elastormeric Bearing | 0.90 $MPa$ | 1 500 $kN/m$ |
| Soil stiffness - Soft Soil | 16 000 $kN/m^3$ | - |
| Soil stiffness - Stiff Soil | 64 000 $kN/m^3$ | - |

Modal analysis have been conducted to evaluate the impact of the boundary conditions on the vibration frequencies and mode shapes of the bridge. Table 2 summarize the frequencies and the modal mass participations of the first three modes in the vertical direction for different boundary conditions. The corre-

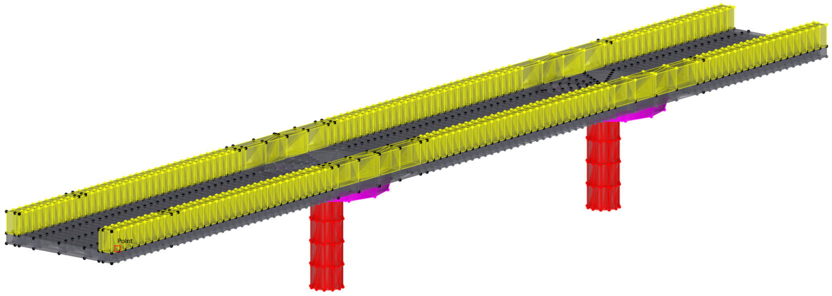


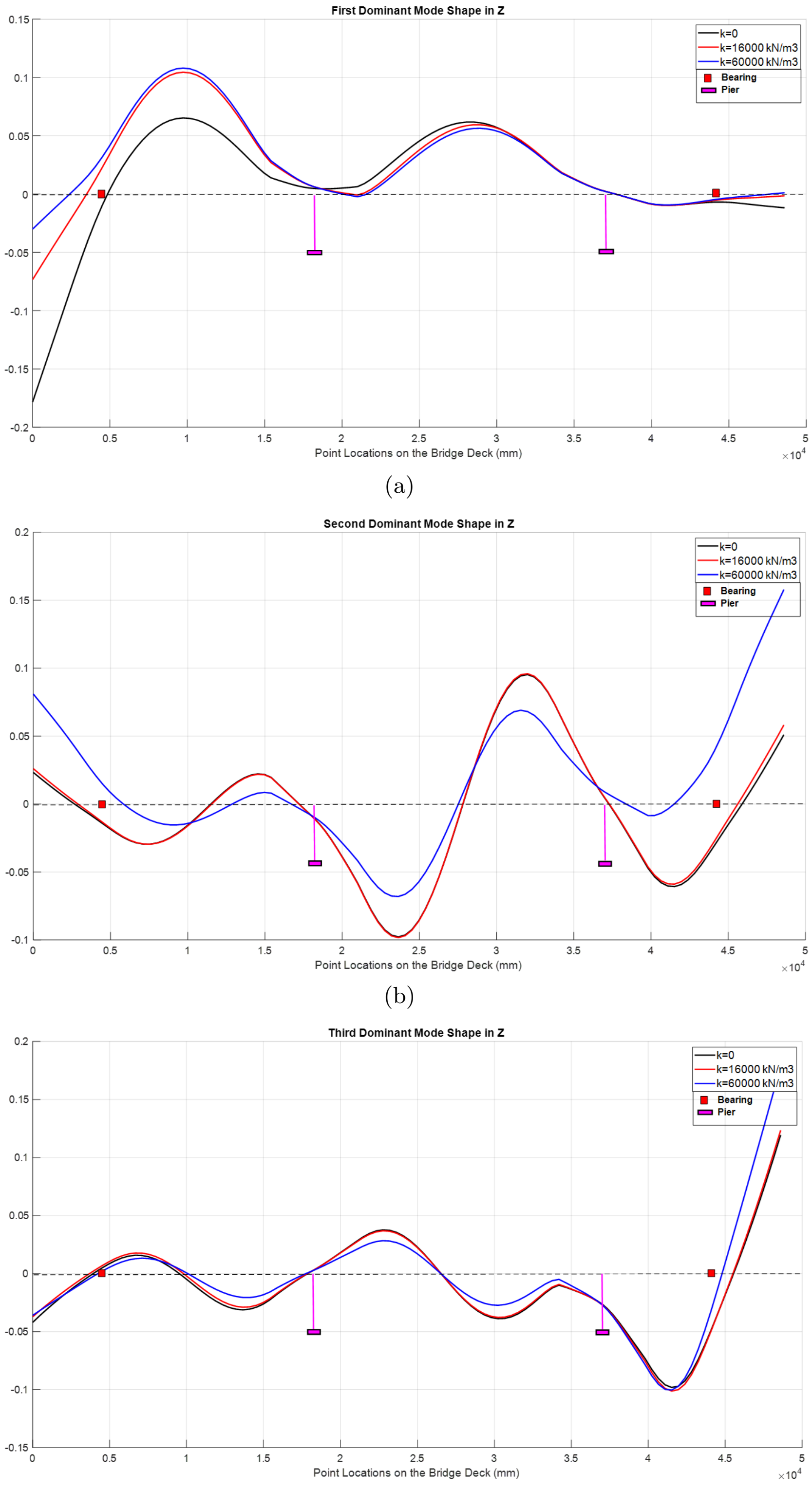
Fig. 4: Overview of the Preliminary Analysis Model

sponding mode shapes are depicted in Figure 5. Both the values summarized in Table 2 and the mode shapes shown in Figure 5 show that the dynamic behavior of the Stange Overpass is significantly influenced by the boundary conditions. It should be noted that, the modal contributions of the three first vertical modes of the bridge is relatively low. This can be attributed to the high stiffness in the vertical direction with potentially six support points, i.e. two piers, two elastomeric bearings and two parts supported by a slab resting on elastic foundations (Figure 2) within a total span length of 50m. This would lead to a higher number of modes contributing significantly in the vertical direction and, hence, lower mass participation ratios for the individual modes. Apart from the effect on the modal shape values at the ends of the bridge, which can be stated to be expected, the modal mass contributions of different modes are also significantly influenced by the boundary conditions. More specifically, the predominant mode shape in the vertical direction in terms of modal mass contribution shifts from the second mode to the first mode with increasing soil stiffness at the bridge ends.

Table 2: Frequencies and modal mass contributions of the first three modes in the vertical direction

| **Parameter** | **Cantilever** | **Soft Soil** (k=16000 $kN/m^3$) | **Stiff Soil** (k=64000 $kN/m^3$) |
|---|---:|---:|---:|
| First Mode Frequency $Hz$ | 14.75 | 16.05 | 16.35 |
| First Mode Mass Part $\%$ | 7.0 | 29.1 | 36.2 |
| Second Mode Frequency $Hz$ | 17.50 | 20.93 | 30.42 |
| First Mode Mass Part $\%$ | 37.0 | 20.3 | 7.0 |
| Third Mode Frequency $Hz$ | 33.72 | 33.90 | 38.69 |
| Third Mode Mass Part $\%$ | 14.1 | 13.2 | 3.1 |

The preliminary numerical analysis presented above indicate that, the boundary conditions at the ends of the bridge is by far the most important parameter



(a)

(b)

(c)

Fig. 5: Effect of soil stiffness on the first three dominant mode shapes in the vertical direction

as far as the vibrations on the bridge is concerned. Hence, accurate estimation of the boundary conditions is of paramount importance for the calibration of the finite element model. As the behavior of soil varies significantly with the load it is exposed to as well as the environmental conditions, the boundary conditions of the bridge can be expected to be dependent on the weight and the speed of the train crossing the bridge. As such, conventional finite element models updating methods that are based on estimating the modal frequencies and the mode shapes of the structure, which considers only the linear behavior of the structure, cannot be expected to be sufficient for the calibration of the finite element model of the Stange Overpass.

## 4 Open Challenges and Proposed Methodology

The conventional finite element calibration procedures rely mainly on predicting the mode shapes identified from acceleration measurements. By their nature, modal analysis and modal parameters are based on linear structural behaviour. However, for the structures where soil structure interaction is expected to be significant, these methods may not be sufficient as the behavior of soil can become nonlinear even at relatively small strains. For structures, where nonlinear behaviour of soil is expected to play a significant role, an improved finite element calibration method that provides reliable estimation of the nonlinear force-deformation relationship of the soil and its interaction with the structure is required.

The NEAR project will develop a two-step iterative procedure to overcome this shortcoming. For this, Stange Overpass will be used as the testbed as its behavior is expected to be significantly impacted by soil-structure-interaction. Figure 6 provides an overview of the proposed methodology.

The first step of the proposed methodology will utilize the free-vibration measurements and the response parameters such as the vibration frequency and the mode shapes to calibrate the physical parameters of the finite element model. The physical parameters to be calibrated will be selected from a large set of parameters based on the sensitivity study carried out on the initial FE model out of a larger set. This set will include but not be limited to Young's modulus of the deck, Young's Modulus of the piers, mass of the sleepers and ballast, mass density of the bridge deck, stiffness of the bearings between the abutments and the deck, stiffness of the support springs at the two ends of the deck. The preliminary numerical analysis show that the stiffness of the support springs at the ends of the bridge, which simulate the behavior of the bridge deck sitting directly on soil, is arguably the most important parameter that affects the vibrations on the bridge. Considering this unique behavior, the methodology will have special focus on estimating this parameter accurately and reliably by sensor clustering at the ends of the bridge, i.e. by deploying an array of accelerometers and displacement sensors near and at the ends of the bridge. The data from the sensor clusters will be evaluated and analyzed using various methods including machine learning and artificial intelligence to provide an accurate estimate of the boundary conditions

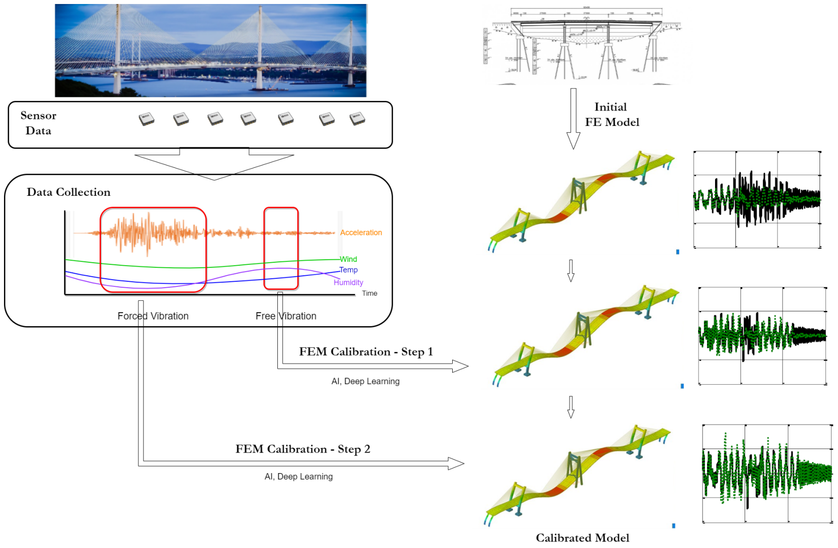


Fig. 6: Methodology of the NEAR project

under varying environmental conditions using the free vibration data. Due to the nature of modal analysis and modal parameters, the estimated structural parameters at this stage will be limited to equivalent linear values. Therefore, one short coming of the finite element model calibrated using free vibration data in this stage will be its inability to capture the potential nonlinearity in the soil behavior that would lead to a change in behaviour for various train loads and speeds as well as the environmental conditions.

In order to capture the nonlinear soil behaviour, the finite element model will be further calibrated using the recorded forced vibration data, i.e. vibrations induced by train crossings. The linear parameters computed from the first step will be used as the starting point of the second step in order to obtain a more reliable, accurate and effective machine learning algorithm. The second step will focus solely on the calibration of the nonlinear force-deformation relationship of soil that directly supports the deck at both ends of the bridge. More specifically, the structural parameters that are expected to remain elastic such as Young´s modulus of concrete, mass of the sleepers and ballast, mass density of the deck will be taken directly from the first step and will be kept constant in the second step. The linear springs that are used in the first step will be replaced by nonlinear springs that can capture the effects of the loading on the spring stiffness.

For the analysis of the FE model under the train load, first the train load including the number of axles, the weight of each axle and the speed of the train will be determined using the strain gauges placed on the rail tracks. This data will then be combined with the information recorded at the accelerometer and displacement sensors and strain gauges to calibrate the weight at each axle. The train loading data will then be used as input to the finite element model and several numerical analysis with various nonlinear force-deformations for the soil springs will be conducted in order to create the training data for the machine learning algorithms. These numerical analysis will be repeated under various train types and speeds. The trained machine learning algorithm will provide the best estimates of the nonlinear-force deformation relationship that will emulate the behavior of the soil on which the ends of the bridge deck rests. This second step, where the objective is to calibrate the nonlinear force-deformation relationship for the soil springs based on the estimations of the maximum accelerations recorded under external loads, is a novel approach to finite element model calibration as current state-of-the art methods consider only the first step, i.e. free vibration, which is limited to linear models.

The novel two-step calibration procedure will be repeated several times during the project duration for different types of trains and various environmental conditions in order to fine-tune the finite element model and to ensure that the model can capture the effects of variations in the environmental conditions on the dynamic behavior of the bridge.

## 5 Summary and Conclusion

This article summarizes the background of a collaboration project undertaken by the Norwegian Railway Authority and the Oslo Metropolitan University. The project aims to develop a two-step finite element model calibration methodology that can be used to reliably and estimate the accelerations on railway bridges whose behavior is significantly influenced by non-linear soil-structure-interaction. The methodology will be developed based on long term monitoring of vibrations on the Stange Overpass. Numerical analysis conducted on initial model of the Stange Overpass reveals that the dynamic behavior of the bridge is dominated by the boundary conditions at each end of the bridge where the bridge deck had been extended 4.5 m from the elastomeric bearings. Through long term monitoring of the accelerations, extensive numerical analysis and machine learning algorithms, the finite element model of the bridge will be calibrated with particular attention to the nonlinear soil structure interaction at the bridge ends.

The proposed method aims first to use classical finite element model calibration methods in order to calibrate the linear structural parameters using the free vibration data. As the next step, the nonlinear force-deformation relationship of the springs that represent the soil behavior will be calibrated by training machine learning algorithms so that the acceleration estimates from the numerical models will match the forced vibration data for various train loads and speeds.

## References

1. Bowles, J.: Foundation Analysis and Design. McGraw-Hill Company, New York, NY (1996)

2. Casas, J.R., Moughty, J.J.: Bridge damage detection based on vibration data: past and new developments. Frontiers in Built Environment **3**, 4 (2017)
3. Chen, X., Omenzetter, P., Beskhyroun, S.: Calibration of the finite element model of a twelve-span prestressed concrete bridge using ambient vibration data. In: $7^{th}$ European Workshop on Structural Health Monitoring (2014)
4. EN: EN 1991-2 Eurocode 1: Actions on Structures - Part 2: Traffic Loads on Bridges. CEN, Brussels (2003)
5. Friswell, M., Mottershead, J., Ahmedian, H.: Finite element model updating using experimental test data: Parametization and regularization. Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences **359**, 169–186 (2001)
6. Gåsemyr, H., Aziz, K.: Dynamic modelling regarding stresses on existing bridges in heavy haul operation considering track irregularities on ofotbanen. In: International Heavy Haul Conference (2019)
7. Moravej, H., Jamali, S., Chan, T., Nguyen, A.: Finite element model updating of civil engineering infrastructures: A review literature. In: $8^{th}$ International Conference on Structural Health Monitoring of Intelligent Infrastructure (2017)
8. Wang, H., Li, A., Li, J.: Progressive finite element model calibration of a long-span suspension bridge based on ambient vibration and static measurements. Engineering Structures **32**, 2456–2556 (2010)
9. Zacher, M., Baeßler, S.: Dynamic behaviour of ballast on railway bridgese. In: Dynamics of High-Speed Railway Bridges. pp. 99–112. Taylor & Francis (2009)