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MONITORING THE STRUCTURAL RESPONSE OF REINFORCED CONCRETE POLES ALONG HIGH-SPEED RAILWAY TRACKS

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Abstract

With the ongoing expansion of railway systems in Europe, spun-cast reinforced concrete poles have become one of the most prevalent civil engineering structures. In this study, three spun-cast reinforced concrete poles along a new high-speed railway track in Germany have been instrumented with a structural monitoring system to capture the structural behavior of the poles, with particular focus on the structural response to trains passing. To remotely access the monitoring data, a data management framework has been designed. Data integration, data transformation, and data storage are executed by the data management framework, largely autonomously. As will be shown in this paper, the data management framework also supports statistical analyses, which have been used to study the effects of trains passing on the structural behavior of the poles. As a result, correlations of acceleration/strain measurements and the speed of passing trains as well as factors that influence the measurements during trains passing could be determined.

1. Introduction

The railway network in Europe has been continuously extended in the last decades. Therefore, spun-cast reinforced concrete poles have become one of the most prevalent civil engineering structures for railway systems. Understanding the structural behavior of the poles along railway tracks is of considerable importance.

Spun-cast reinforced concrete poles along railway tracks are complex, coupled structures. Hence, for the assessment of the structural behavior the following aspects have to be considered: Soil-structure interaction, influences of the electrification cable system attached to the pole, and the dynamic behavior of the pole itself. The structural behavior of concrete poles has been a matter of research for the last decade. Particularly, modal characteristics of spun-cast reinforced concrete poles in experimental and numerical approaches, respectively, have been studied. Insights into the dynamics of pole structures have been reported, e.g., by Chen et al. [1, 2, 3, 4]. The authors have studied experimentally and numerically determined modal characteristics of direct embedded concrete poles [1] as well as the influence of boundary conditions on the numerical modeling results [3, 4]. A large quantity of spun-cast reinforced concrete poles has been experimentally investigated by Olney et al. [5]. 26 poles have been identically equipped with acceleration sensors to conduct vibration tests on each of the poles. The stochastic variations of the dynamic properties have been determined.

Concrete poles for electrification purposes are located along railway tracks. Due to approaching trains, which displace the surrounding air laterally, the poles are exposed to short-term impacts. Studies on the effect of time-varying loads on the dynamic behavior of structures due to trains passing have been conducted, e.g. for noise protection walls [6, 7, 8]. Several damage incidents at noise protection walls along the rail track Köln-Rhein/Main (Germany) in 2003, shortly after its opening, motivated the consideration of dynamic effects under trains passing during the design process [6].

However, no studies have been reported on the structural behavior of spun-cast reinforced concrete poles at high-speed railway tracks. This paper investigates the structural response of the poles due to realistic environmental loadings, particularly due to trains passing. To quantify the structural response of concrete poles under real conditions, a structural monitoring system has been installed on three spun-cast reinforced concrete poles along a new high-speed railway track in Germany. Additionally, a data management framework is presented that has been designed to support data integration, data transformation, data management, and data analysis. Specifically, data analyses are conducted based on acceleration and strain measurements.

2. The structural monitoring system

2.1 Subsystems of the structural monitoring system

A structural monitoring system for spun-cast reinforced concrete poles has been designed for collecting structural and environmental data relevant for analysis of the structural behavior. The system consists of two basic subsystems, installed at different locations that are described in the following (more details on structural monitoring system frameworks can be found in [9, 10, 11]):

i. An *on-site hardware system* is installed at the railway track, composed of sensors, data acquisition units, and a local computer (on-site PC), is installed to collect structural and environmental data. The sensors are attached to three adjacent concrete poles.
ii. A *data management framework*, which is remotely connected to the on-site hardware system, persistently stores the monitoring data collected on site and provides remote access to the monitoring data; it also provides data integration, transformation, management, and analysis capabilities.

Using the aforementioned tools, statistical data analyses are evaluated regarding the structural response of the poles due to environmental as well as train passing influences.

2.2 On-site hardware system

The on-site hardware system is attached to three concrete poles along a new high-speed railway track that has been built connecting the cities of Leipzig and Erfurt, as shown in Figure 1. The track, built within the framework of the German Unity Transport Project 8 [12], has been designed for train speeds up to 300 km/h. Since December 2015, the railway track has opened for public transportation. The poles, denoted as Pole I, Pole II, and Pole III, are installed along the track distances of 65 m.

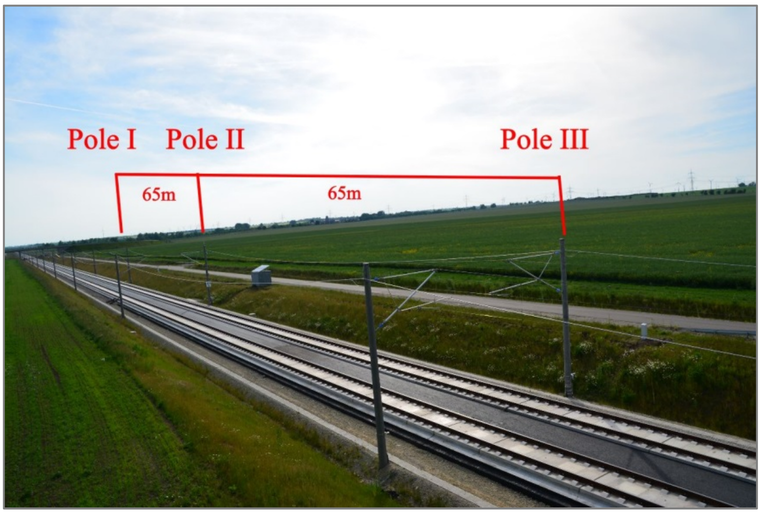

Figure 1. Concrete poles along the high-speed railway track instrumented with the on-site hardware system

The on-site hardware system contains different types of sensors, which are installed inside and outside the concrete poles as well as at their foundations. The outside sensor arrangement differs for each pole. A detailed installation schema is shown in Figure 2. The application of strain gauges at the pole foundations and of an earth pressure sensor at the middle pole permit predictions about the soil-structure interaction. Temperature sensors are attached within the poles as well as on the concrete surface of Pole II. During the production process, strain gauges have also been applied to the reinforcement as well as the tendons inside the poles.

At Pole II, additional sensors are installed. A 3D anemometer at the top and a cup anemometer at mid-height give information about wind loads. Two 2D accelerometers of type PCB Peizotronics 393A03 are installed to Pole II parallel to the rail track. At each of the outer poles (Pole I and Pole III), a photoelectric sensor is installed. The photoelectric sensors serve as triggers for trains passing – recording a signal from the light barriers of the photoelectric sensors. Integrating all sensors into one measurement system allows a direct correlation of the individual monitoring data. For that purpose, a precise time synchronization of all measurement positions has to be assured.

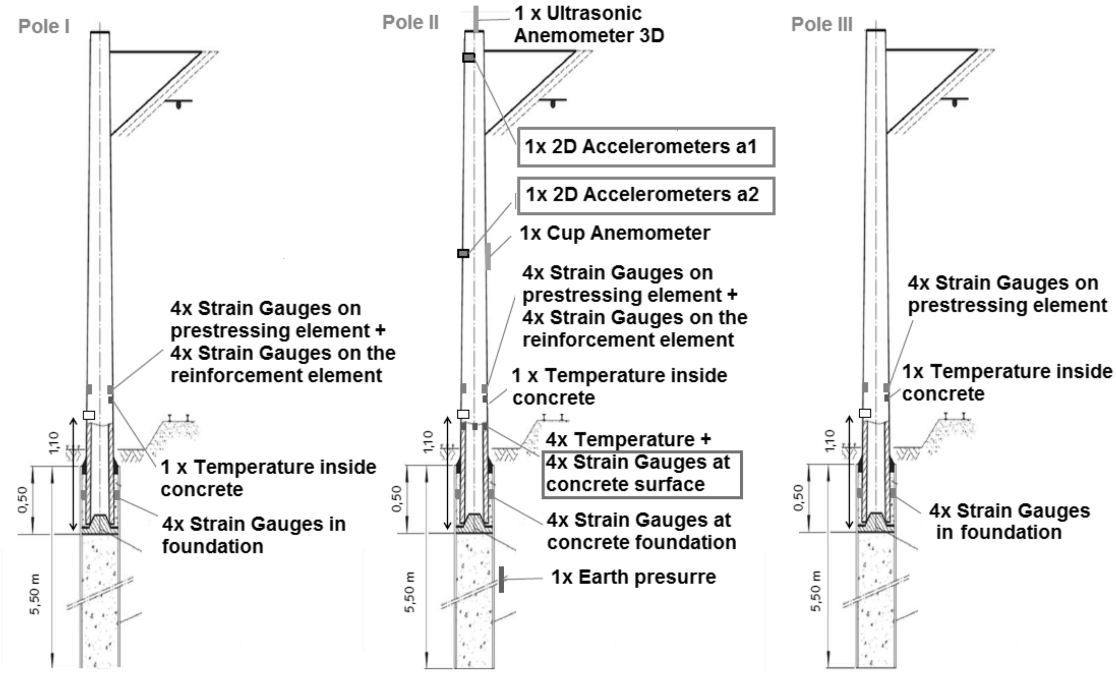

Figure 2. Sensor setup at the three concrete poles

2.3 Data management system

For data management, the decentralized software system is installed on different computers at the Bauhaus-Universität Weimar, Germany. The software system is designed for two major purposes: First, it provides storage for the monitoring data taken from the poles, supporting automated data management and processing; second, it provides remote access to the monitoring system via a set of program modules. The monitoring data collected from the poles are stored temporarily on the on-site PC in binary format. The collected data are transferred to the main server in Weimar, transformed, integrated, and stored in a MySQL database system.

3. Data analysis

3.1 Data assessment

The data are recorded in binary format and TST files. The binary files contain the monitoring data from all different sensors, and in the TST files general information on the measurements is included. Not all binary files recorded contain an actual train passing, e.g. if the photoelectric sensors have triggered a recording due to an animal instead of a train passing. Hence, in order to correctly assess the train passing effects on the structural behavior of the reinforced concrete poles, the selection of the relevant files is an elementary step regarding the data analysis, which is conducted before analyzing the monitoring data.

The selection of files containing trains passing is based on the trigger signals of the photoelectric sensors. Using the trigger measurements, different properties of the trains, such as the train speed, the train length, and the direction of the train (Erfurt to Leipzig or Leipzig to Erfurt) can be identified. To select valid files, the following assumptions have been made:

i. Both triggers should be activated during one measurement.
ii. The magnitude of the trigger signal should reach a previously defined value.
iii. Only train speeds between 30 km/h and 350 km/h are valid.
iv. Only train lengths between 15 m and 400 m are valid.

Applying the assumptions to the files – 903 are currently available – has led to a number of 242 files containing trains passing. In each binary catman file, the pre-trigger time, i.e. the time being recorded before the actual train passing, is set to a duration of two minutes. The total measurement time varies between eight or nine minutes, depending on the train speed and the train length. The trigger signals are visualized in Figure 3. For investigations of the structural response of the reinforced concrete poles, accelerometers and strain gauges data of Pole II are analyzed, which is described in the following subsection. The data analysis comprises the identification of peaks in the measurement signals in order to determine their correlation with the train speed.

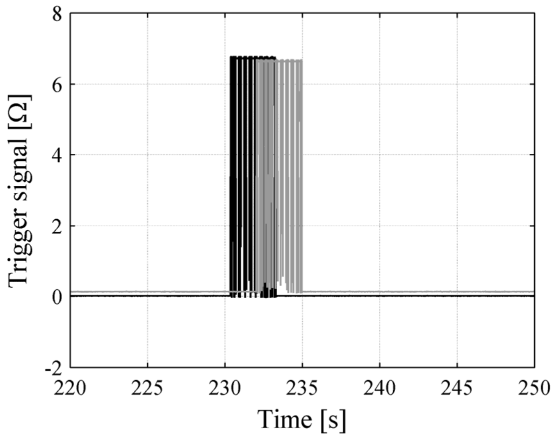

Figure 3. Visualization of the trigger signals (black – Trigger 1, grey – Trigger 2)

3.2 Acceleration measurements

The upper accelerometer is located 1.10 m and the middle sensor 4.15 m beneath the pole top. For the peak identification, a baseline correction of the acceleration data is implemented to remove signal offsets. The peak of acceleration is identified in the time window of the train passing both triggers. Figures 4 and 5 show the acceleration peaks as functions of train speed for the two train directions.

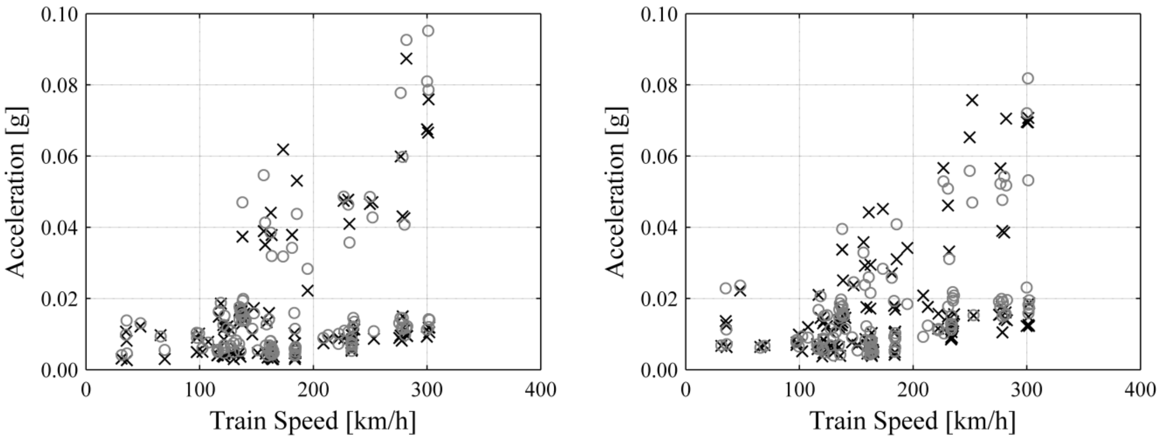

Figure 4. Peak accelerations as functions of the train speed for the direction Erfurt to Leipzig: Perpendicular (left) and parallel (right), the top sensor (x) and the middle one (o)

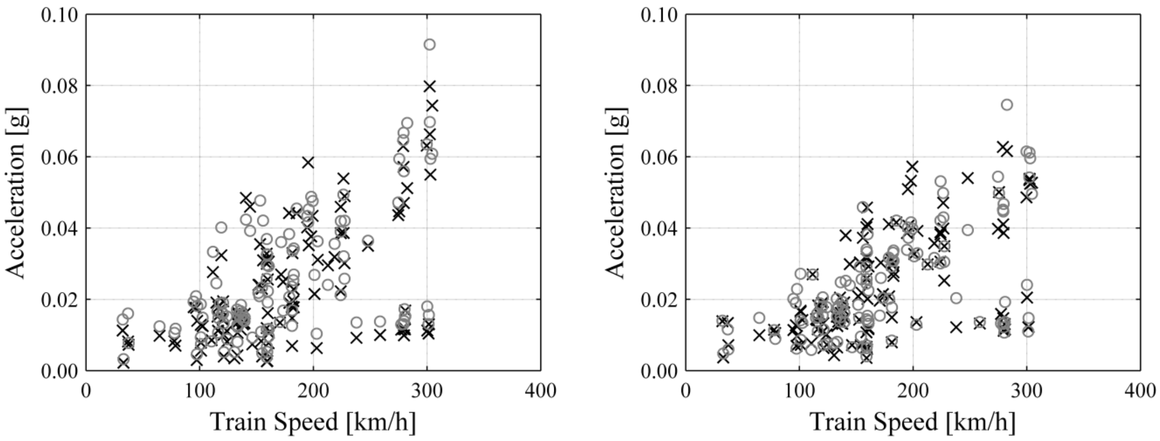

Figure 5. Peak accelerations as functions of the train speed for the direction Leipzig to Erfurt: Perpendicular (left) and parallel (right), the top sensor (x) and the middle one (o)

From Figures 4 and 5, a general tendency regarding the correlation between acceleration peaks and the train speed can be observed: The higher the train speed, the higher the acceleration peak. The correlation is more distinct in the direction of Leipzig to Erfurt in comparison to the opposite direction. This observation seems to be reasonable, since the poles equipped with the on-site hardware system are located next to and therefore closer to the track of the direction from Leipzig to Erfurt. Hence, with the lower distance of the poles, the recorded accelerations due to trains passing are higher. This is confirmed by the correlation coefficients of the train speed and acceleration measurements, as shown in Table 1. The values are higher in case of the direction Leipzig to Erfurt. Furthermore, the train speed is stronger correlated to accelerations perpendicular to the railway than to parallel accelerations.

The relatively low correlation coefficients as well as outliers in the plots lead to the assumption that the trains passing are not the only factor influencing the acceleration signals. Other effects, such as wind during the measurements or train lengths, should be taken into account for the data analyses.

Table 1: Correlation coefficients for the train speed and the acceleration sensors attached at two different pole heights (top and middle) measuring two directions (*par – parallel and per – perpendicular to the rails)

Direction	top/par*	top/per*	middle/par*	middle/per*
Leipzig-Erfurt	0.41	0.55	0.37	0.56
Erfurt-Leipzig	0.31	0.38	0.34	0.40

3.3 Influence of the wind speed on acceleration measurements

To illustrate the influence of the wind speed on the acceleration measurements during the train passing, acceleration signals for two cases – low wind speed (15 km/h) and high wind speed (37 km/h) – are shown in Figure 6. As can be seen, the acceleration peak due to a train passing at a time of approximately 125 s is more distinct in case of low wind speed. Higher wind speeds are associated to higher accelerations during the whole time slot of measurement. Therefore, the effect of the train passing is less considerable during high wind speeds.

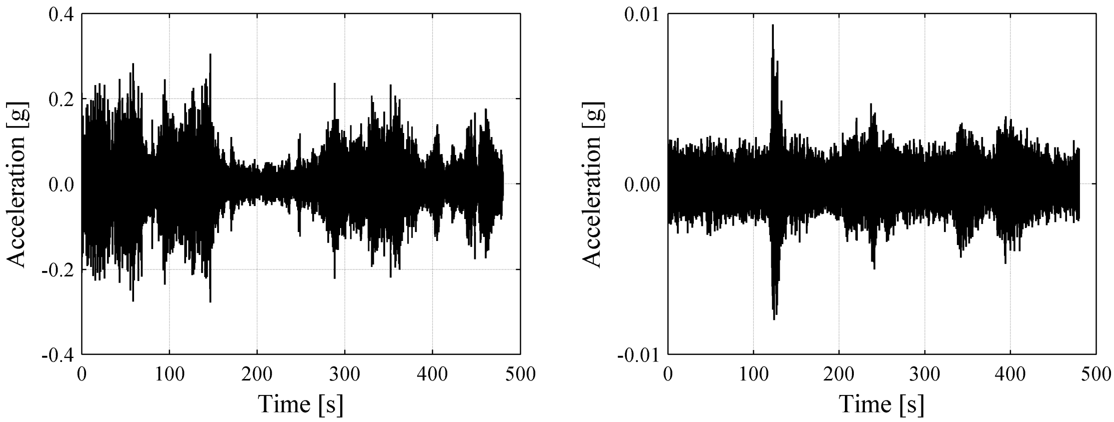

Figure 6. Acceleration measurements during high (left) and low wind speed (right)

3.4 Influence of train passing on the earth pressure sensor

Another influencing factor on the acceleration measurements are vibrations of the poles caused by ground motions during train passing. Thus, the earth pressure sensor, which is installed in the soil close to Pole II, is investigated in more detail.

Figure 7 shows two datasets that illustrate measurements from the earth pressure sensor. The two datasets only contain train lengths of more 100 m to ensure a sufficiently large quantity triggering the earth pressure sensor. Figure 7 (left) shows the earth pressure peaks as a function of train speed. No interrelationship is observable, i.e. the peak of earth pressure is independent of the train speed. The dependence of the acceleration peaks on the upper limiting earth pressure is shown in Figure 7 (right). A general tendency can be recognized: The higher the earth pressure peak values, the higher the acceleration. This correlation is even more obvious when only considering trains with speeds higher than 200 km/h (black). Since the railway tracks are designed for high speeds up to 300 km/h, it is reasonable to put the focus on fast trains.

It can be concluded that the accelerations observed during a train passing are caused by different sources: the aerodynamic pressure stemming from the approaching train and the vibration that is transferred from the train via the soil.

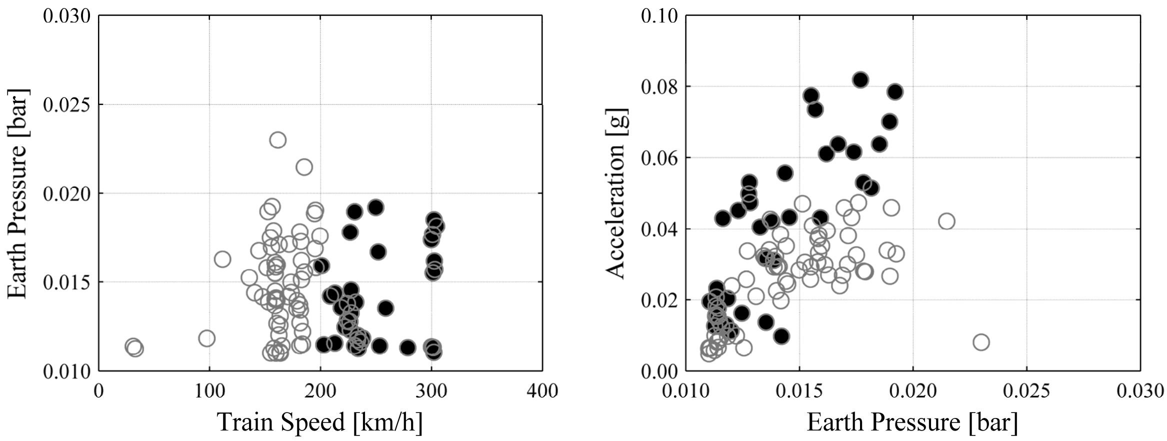

Figure 7. Measurements from the earth pressure sensor: The peak earth pressure as a function of the train speed (left) and the acceleration peaks as a function of the earth pressure peaks (right), containing all train speeds (grey) and train speeds higher than 200 km/h (black)

3.5 Strain measurements

To investigate if trains passing can also be detected by the strain gauges, these measurements are analyzed and the strain peaks are identified as described in the previous section. At Pole II, four strain gauges are distributed over the circumference at the concrete surface, each in an angle of 90°. In the following, the strain gauges are named according to their position as South, West, North, and East. The southern and the northern strain gauges measure parallel and the western as well as the eastern strain gauge measure perpendicular to the rails. Exemplarily, the strain peaks of the southern and the western sensor are shown in Figure 8 as functions of train speed. Low correlations can be observed.

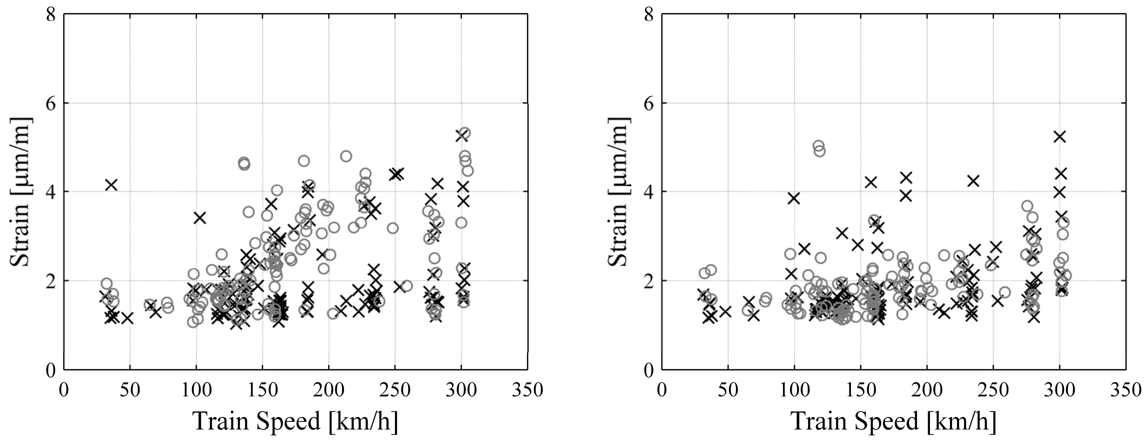

Figure 8. Peak strains as functions of the train speed, the southern strain gauge (left) and the northern strain gauges (right) for the two train directions Erfurt to Leipzig (o) and Leipzig to Erfurt (x)

The correlation coefficients between train speed and strain gauges are provided in Table 2 for both train directions. The train speed is stronger correlated to the strain peaks in case of the direction from Leipzig to Erfurt, which is closer to the rails, than for the opposite direction. Only the value of the western sensor is higher for the direction from Erfurt to Leipzig, what can be explained by the fact that this train is approaching from the western direction. The parallel sensors show higher correlations than the perpendicular ones (eastern and western). There is a linear correlation between the southern and the northern strain gauge, which does not seem to be very surprising due to their opposite location to each other. Although the western and the eastern strain gauges also have opposite positions to each other, their correlation is not strong. A reason for this observation might be the cable system attached to the poles for electrification purposes which is aligned in the direction East – West. This setup probably reduces vibrations.

Table 2: Correlations between the train speed and the strain measurements at the concrete surface of Pole II for the two directions (1 – Erfurt to Leipzig, 2 – Leipzig to Erfurt)

	Train Speed	**South**	**West**	**North**	**East**
Direction	1 | 2	1 | 2	1 | 2	1 | 2	1 | 2
Train Speed	1	0.32 | 0.45	0.36 | 0.31	0.34 | 0.49	0,22 | 0.24
South		1	0.50 | 0.39	0.74 | 0.86	0.45 | 0.36
West			1	0,52 | 0.41	0.51 | 0.55
North				1	0.32 | 0.34
East					1

4. Summary and conclusions

In this paper, a structural monitoring system has been presented, which has been deployed at a new high-speed railway track to capture the structural behavior of spun-cast reinforced concrete poles. Particular emphasis has been focused on the effects of trains passing on the structural behavior of the poles. Three poles along the high-speed railway track have been equipped with different types of sensors. Using the monitoring data provided by the structural monitoring system, statistical analyses on the train passing effects and the structural response of the concrete poles have been conducted. In particular, acceleration and strain measurements have been analyzed, and the correlations between these measurements and train speed have been determined. As a result, it has been shown that acceleration peaks as well as strain peaks increase with the train speed. Moreover, relatively low correlation coefficients reveal that other factors influence the acceleration and strain measurements. For example, wind speeds and train lengths as well as the cable system attached to the poles significantly affect the acceleration peaks. Future research efforts may be devoted to the identification of factors that influence the acceleration and strain measurements in order to clearly distinguish between effects of the train passing and effects of the environment, e.g. wind. Using new data to be measured within the next year, the results presented in this paper will be complemented. Furthermore, the effects of different train lengths may be further investigated. Last but not least, coupling effects (e.g. interactions between soil and the poles) may be considered in future studies.

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