IMPACT OF SUBSTRUCTURE IMPROVEMENT ON TRACK QUALITY

FRENCH TITLE

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ABSTRACT - Increasing passenger numbers, higher traffic loads, and budget cutbacks are just few examples, infrastructure managers have to consider within todays railway business. Therefore, infrastructure managers aim for efficiency and sustainability in order to reduce maintenance and renewal demands sustainably. One of the main cost drivers within the life cycle costs of track is a poor substructure as it can reduce service and increase maintenance demands dramatically. The installation of a formation rehabilitation layer can restore good track quality in areas with poor subsoil conditions. Analysis of track behaviour over time is a useful tool for infrastructure managers to shift from preventive to predictive maintenance in order to distinguish track sections where such a costly measure is necessary.

RÉSUMÉ - Translation to French?

1. Introduction

Efficient use of the available resources has become one of the main tasks for infrastructure managers. Due to budget cutbacks, increasing passenger numbers and higher traffic loads they face tough challenges requiring sustainable maintenance and renewal strategies. Therefore, it is crucial to execute the right measure at the right time ensuring track’s condition in order to realise high service lives. Former research (Veit, 2007) has already shown the negative impact of an inadequate substructure and water drainage. These are the biggest cost drivers in Life Cycle Costs causing a reduction of service life and bad track quality and thus lead to higher tamping demands and maintenance costs.

This paper focusses especially on track quality and quantifying the condition of substructure. The evaluation of substructure condition using in-situ measurements like cone penetration tests delivers detailed information but is also time-consuming leading to track closures and costs of operational hindrances. This paper points out the benefits of evaluating substructure condition with the already established approach using standard deviation of vertical alignment sigmaH and its deterioration rate as well as the rather new methodology of fractal analysis of vertical track geometry. The opportunity to combine these two approaches enables a condition based monitoring of specific components as well as the identification of reasons for bad track quality and higher maintenance demands. This allows for eliminating the cause and not only the effect of poor track quality.
2. Data warehouse

A precondition for any data analyses is a data warehouse providing all the data needed. The Institute of Railway Engineering and Transport Economy established such a data warehouse (Figure 1) in 2005 in close cooperation with the Austrian Federal Railways (ÖBB). One of the main reasons for doing so was the huge and steadily increasing amount of collected data. Up to now, this data warehouse contains track information of more than 4,000 track kilometres of Austria’s main network. The network is divided in cross sections in 5 m distance. Therefore, every cross section consists of linked information concerning three points:

1.) Asset information (includes type age of sleepers and rails, load and maintenance actions)
2.) Measurement signal (complete history of the measurement signal gathered by the Austrian track recording car)
3.) GPR (evaluations from the ground-penetrating radar)

Currently the information as shown in Figure 1 is linked to more than 800,000 cross sections within Austria’s main network and enables for analysing the network.

3. Longitudinal Level

The Austrian track-measuring car records the Austrian network several times a year since 2001. One of the most important measurements is longitudinal level of track geometry. This signal provides the basis for the subsequent time series analyses of track behaviour as it is the raw measuring signal for calculating standard deviation of vertical alignment as well as fractal analysis of vertical track geometry.

3.1 Standard deviation of vertical alignment
Standard deviation of vertical alignment bases on the raw signal of longitudinal level. Thereby, it calculates a sliding standard deviation over a length of 100 m (Auer, 2004). In Figure 2 track behaviour for a track section of 1.5 km is illustrated. Standard deviation sigmaH in mm is displayed on the y-axis, the higher the value, the worse the track quality at that point is. This information allows monitoring track’s behaviour of the entire network over time.

Figure 2. Track behaviour described by standard deviation (Adapted from Auer et al., 2007)

In order to describe the track behaviour over time deterioration rates of these measurements are calculated using a linear regression function (Vidovic, 2016). Thus, it is possible to predict the ideal point in time for a maintenance action considering the threshold value leading to a preventive maintenance strategy.

Standard deviation of vertical track geometry is an approach to predict maintenance measures, such as tamping, in order to restore track quality. However, the root cause for poor track quality leading to maintenance demands remains unknown. Hence, there is a need for condition based monitoring of specific components. This is provided by the fractal analysis of vertical track geometry, which interprets not only the amplitude, but also the wavelength of the raw signal.

3.2 Fractal analysis

When Mandelbrot (Mandelbrot, 1967) invented the methodology of fractal analysis in 1967, he surely was not aware of the possibilities for the railway sector. His intention was to calculate the exact length of Great Britain’s coastline. Therefore, he developed the Modified Divider Method (Mandelbrot and Blumen, 1989).

The first time this new methodology has been applied to a railway track was by Hyslip (Hyslip, 2002). Thereby, he approximated the already existing measuring signal by using a polygonal chain. The polygonal chain is composed of partial segments of uniform length. This calculation method reduces the length of the partial segments and the polygonal chain fits better and better to the measuring signal (Figure 3). With the aforementioned methodology the fractal dimension of a curve is calculated which increases with its roughness.
Further research has shown that the Richardson plot can be used to describe three sectors by using tangents (Landgraf and Hansmann, 2013). Hereby, the calculation of tangent slopes in each sector describes the roughness of the signal and gives an indication about the impact of the different wavelength on the signal.

In Figure 4 the chosen wavelengths are shown with various slopes. Thereby, the dotted line has a steeper slope within the long-waved range suggesting a failure in the substructure. The continuous line has a very steep curve within the mid-waved range. Therefore, a ballast issue is assumed (Landgraf, 2016).

This methodology was thoroughly tested and validated in Austria, Switzerland (net-wide analyses) and parts of the Danish and American network (Landgraf, 2016, Hansmann 2015). It was possible to show that fractal analysis is able to detect whether the root cause of irregularities in track geometry lies within the ballast and/ or substructure condition.

A typical result of the fractal analysis looks as in Figure 3 displayed. The darker the colour of the signal is, the more current the value is. As part of the aforementioned validation process, alert limits were defined.
The Alert Limit for the mid-waved range is -8 and for the long-waved range -1.1 (Hansmann, 2015, Landgraf 2016). If these values are exceeded, a failure regarding the ballast (mid-waved) or an insufficient substructure (long-waved) is assumed.

4. Track quality, track behaviour and settlements

4.1 Theoretical settlement curve

For time series analyses of track behaviour and calculation of degradation rates any regression function can be used. Nevertheless, the upcoming deterioration rates base on a linear regression model. Among various other functions, the results proved that the linear regression adapts to the best (Vidovic, 2016). Other reasons for choice of linear model are the simple implementation and that the deterioration rates can be compared among each other. The steeper the rate the faster the track deteriorates. Therefore, the deterioration rate is characterized by its value and do not depend on the length of the curve (e.g. logarithmic curve). Thereby, the degradation rate describes changes in vertical alignment over time and track irregularities. These irregularities appear as relative settlements when using standard deviation. Two independent institutions (Selig and Waters, 1994) derived the correlation between settlement and standard deviation in four different experiments.

The settlement of the soil is characterized by three different areas (Terzaghi et al., 1996). At first, there is an initial compression. The next part within a settlement procedure are Primary Consolidations. They take the longest and are characterized by the highest values. At the very end of a settlement event, there is Secondary Consolidation. These settlements are very small and amount slightly a few percent. Although, the consolidation theory is permitted only conditionally when describing track behaviour, such a behaviour can be observed when track gets older and tamping actions are neglected.

Figure 6 displays the theoretical settlement curve. In this illustration, the y-axis is named as sigmaH_mod because the effects of maintenance actions such as tamping are excluded. These considerations assume a steady increase of sigmaH and should show the settlement behaviour over time. In the first years track deteriorates faster, therefore the degradation is steeper and track quality decreases. This behaviour is similar to Primary Consolidations. Because of dynamic track stabilization, the effects of Initial Compressions do not occur in a track’s behaviour. After several years degradation rates flattens and settlements become
vanishingly small; this effect is visible in Figure 6 after year six. This behaviour shows certain similarities to soil settlements and their settlement curves.

![Theoretical settlement curve of a track when it gets older](image)

Figure 6. Theoretical settlement curve of a track when it gets older

The upcoming analyses focuses on track behaviour and the component specific condition, especially on those areas with substructure remediation.

### 4.2 Track quality and behaviour

The installation of a formation layer is always associated to the expectation of an enhanced behaviour and quality. However, an improved substructure is a costly measure and in-depth evaluation process needs to be carried out in advance.

As shown in Figure 7, the track quality before a substructure improvement deteriorates considerably. The presented results represent more than 50 km of track and are mean values. The deterioration rates increase steadily from $b = 0.25$ to $b = 0.38$. Thereby, $\sigma_{H}$ stays at 0.8 mm and this quality cannot be improved. This entails shortened tamping cycles to achieve the required track quality and higher maintenance costs. Furthermore, the economic service life of track is defined by the minimum of annuities. This minimum is reached when increasing maintenance demands due to age counteracts the decreasing costs of depreciation. This strategy is part of the Life Cycle Management strategy developed by the Institute of Railway Engineering and Transport Economy and the Austrian Federal Railways (ÖBB) (Veit, 1999). Since the higher tamping demand leads to shortened tamping cycles, the annuities increase track renewal is necessary. This date is marked as year 0 in Figure 7.
In the first years after installing a formation layer, the deterioration rate \( b \) is 0.25 and decreases accordingly by reaching \( b = 0.17 \). The initial track quality is at 0.4 mm and remains stable at 0.5 mm after the first two tamping actions. Even though track quality is much better than before and deterioration rates are lower, the root cause for this decrease in quality remains unclear. Hence, the condition of the substructure before and after installing the formation layer needs to be analysed. Standard deviation of vertical alignment is used to describe track quality as a whole; therefore, it cannot characterize the condition of specific components like substructure. As already mentioned, it enables the implementation of a maintenance strategy by setting intervention limits in order to ensure the required track quality. Fractal Analyses however can be executed in order to evaluate the condition of substructure.

Comparing the long-waved fractal dimension before and after an installation of a protective layer shows whether the substructure improvement was the right measure or not (Figure 8, left part of the Figure). Therefore, only cross-sections were selected showing values in the long-waved dimension below -1.1 (Alert Limit). It is important to understand that the installation of a protective layer nowadays is a continuous measure meaning that also short sections with good substructure can be rehabilitated as longer construction sections are targeted. The light grey boxplot in Figure 8 on the left emphasizes the much better substructure condition after the substructure improvement, especially underlined by the median value. The protective layer leads to some 80 % better values in the long-waved fractal dimension. Because of this, the track quality and hereby in particular the initial track quality improves considerably.

![Figure 7. Track quality before and after installing a formation layer](image-url)
Consequently, lack of track quality, higher maintenance demands and track failures are not attributable to insufficient substructure condition.

The fractal analyses of vertical track geometry enables a component specific evaluation. By means of that, the strategic substructure renewal demand can be determined leading to a sustainable renewal strategy; this requires an in-depth evaluation of the entire network without substructure improvement. Analysing the substructure of the remaining network is therefore the first step within this approach.

Based on the aforementioned Alert Limits in Figure 8 on the left the values of the long-waved fractal dimension are displayed in Figure 8 on the right for those areas with no substructure improvement. These are the values for the remaining network and areas, which did not get an improved substructure. The dark boxplot in Figure 8 on the right represents sections with poor substructure conditions, which already exceeded the Alert Limit of -1.1. Compared to the values in Figure 8 on the left it is apparent that approximately 10% of the remaining network need a substructure improvement (Landgraf, 2016). The substructure of the remaining part of the network is in a proper condition following this methodology. The median value of -0.21 elaborates this good substructure condition of the remaining network without an improved substructure.

Figure 9 shows the mean deterioration rate b for those areas with no substructure improvement. These are the same areas mentioned in Figure 8 on the right. The light grey bar represents sections showing values of the long-waved fractal dimension better than -1.1.

Figure 8. Fractal Long-waved, Left: before and after substructure improvement, Right: no substructure improved areas of the remaining network
These areas have mean deterioration rates of $b = 0.11$ which is even better than the deterioration rates of Figure 7 of the substructure improved areas.

![Diagram](image)

**Figure 10.** Deterioration rate of the remaining net, no substructure improvement.

On the other side, the darker bar illustrates areas with already exceeded values regarding the Alert Limit for substructure condition based on fractal analyses. The mean deterioration rate $b$ is 0.27 in this case. Compared to the deterioration rates of areas with improved substructure the present values are more than 30 % worse. This result suggests that a failure occurred in long-waved fractal dimension emphasising that the examination of the subsoil condition should be considered.

**5. Conclusion**

Two main points assess the success of a substructure improvement. On the one hand, it is the better initial quality and therefore a remarkable lower sigmaH. On the other one, it is track behaviour and thereby especially degradation, which flattens. Achieving these aims means the installation of a protective layer meets its requirements. This leads to a decrease of maintenance demand and money savings.

Nevertheless, it is not possible to identify with standard deviation whether the rapid track deterioration occurs due to ballast or insufficient subsoil. The detection of the root cause for poor track quality can be delivered by using fractal analysis. This methodology enables condition based monitoring to verify the condition of the sleepers, ballast or substructure separately. This paper elaborates the possibility to combine standard deviation and track behaviour in order to predict maintenance demands with fractal analysis. Furthermore, it is possible to monitor the component specific condition of the asset.

This two-sided approach allows for sustainable asset management of railways track.
6. References


