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How the ballast carries its load – ballast pressure measurements performed on the permanent way SYSTEME GRÖTZ BSO/MK

Summary

In situ measurements of pressure acting on ballast were performed under real service conditions for the permanent way SYSTEME GRÖTZ BSO/MK (conventional ballasted track installed in a concrete trough and placed on ballast mats).

The measurements yielded new findings relating to the load bearing behavior of the ballast in the track. They provided information about the three-dimensional propagation of stress in the ballast under various loading conditions.

The results obtained from the investigation of the system contribute to the further development of innovative ballasted tracks. As a result, cost-intensive overdimensioning can be eliminated without any restrictions to safety and quality requirements. Also, the results of the investigation allow the ballast simulation to be further improved within calculations.

1 The permanent way SYSTEME GRÖTZ BSO/MK

1.1 General information

In contrast to underground railway lines, measurements for the reduction of vibrations are available to a limited extent only in aboveground railway traffic. The permanent way SYSTEME GRÖTZ BSO/MK now also offers the possibility of achieving vibration protection for tracks above ground.

This track is made up of a solid concrete trough onto which a conventional ballasted track is placed on appropriately chosen ballast mats (figure 1). In contrast to slab track, the trough consists of a base plate without reinforcement (base plate thickness at least 40 cm) and of reinforced shoulders which are attached to the sides of the base plate.
Compared to conventional ballasted track this permanent way offers these benefits:

- Significant reduction of the exposure of the substructure/subsoil. Owing to the load-distributing effect of the base plate the peak pressure in the area of the top level of the subgrade is reduced by up to 50%. The system allows for compensation of local weak spots or irregularities in the subsoil. There is no need to provide frost protection layers (FSS) and subgrade protection layers (PSS).

- The track is highly stable. As a result of the lateral limitation of the ballast, a multi-axis state of stress is achieved.

- The resistance of the track skeleton to lateral displacement and the resulting buckling stability are extraordinarily high. The system also handles increases of the normal forces in the rails as a result of the use of eddy current brakes in modern railway fleets in compliance with safety specifications.

- Owing to the integrated active vibration-reducing system, emission of vibrations and secondary airborne noise is largely reduced. Also it is possible to adjust the system within a large frequency range to any specified insulation requirements by using appropriate and optimized concrete base plates and resilient elements such as ballast mats or sleepers with sole pads [1.11, 1.12].

- The track possesses a high loading capacity and a high track bed quality, and allows maintenance and emissions to be reduced to a minimum.

This track type has been developed by the German contractor GRÖTZ. Compared to alternative technologies available on the market it represents a cost-efficient solution. In cooperation with railway experts this new kind of permanent way was put into practice on a trial section for the first time in 1997 on the Basel-Karlsruhe line of the Rheintalbahn at the latitude of Baden-Baden. [1.1 to 1.7].

1.2 Operating experience obtained from the trial section

The (single-track) trial line has been in service for four years. So far, no maintenance has been required despite a total of more than 120 million tons of load which have acted on the trial section so far. There have not been any signs of wear or settlement observed so far. The results obtained from quality measurements (Q-values equal to 18 up to 24, and remaining constant [1.6]) correspond to the ones usually obtained for slab track, and prove that the quality of the system’s track bed is still excellent). The comprehensive range of measurements performed along the trial section [1.5, 4.1] have confirmed not only the calculations and forecasts made, but also the efficacy of the vibration-reducing measures used.

- The action of railway-induced vibrations on people and buildings has been reduced by at least 3 dB which corresponds to a vibration reduction of at least 30%. To give an example figure 2 shows the results obtained from free field measurement – at ground top level – on the trial section in Baden-Baden.
Any secondary airborne noise can reasonably be expected to be reduced by far more than 3 dB depending on the structural situation.

1.3 Use of the system on the extended / newly laid Rheintalbahn line

For the extended / newly laid Karlsruhe-Basel line, a type of permanent way offering reduced structure-borne noise had to be used due to legal requirements on the line section of Sinzheim (v = 250 km/h). The permanent way SYSTEME GROTZ BSO/MK was chosen because of the high vibration protection and other benefits offered. Compared to other systems it was also found to be much more economic for this application. Presumably, the double-tracked line of approx. 2 km in length shall be put into service by the end of the year 2003.

In this application, the plain concrete trough has been classified as attached bridge structure in agreement with the constructional regulations of DB AG, especially of DS 804 on railway bridges/ civil engineering works. The requirements specified by DB AG in respect of security against fracture, serviceability, resistance to continuous stress and serviceable life (> 60 years) have been complied with since the system has been dimensioned to cope with fatigue-relevant collective loads according to Eurocode 1, part 3.

The specifications yielded high demands on the system not only in respect of the plain concrete base plate, which is approx. 60 cm thick, but also in respect of the trough shoulders [1.3, 1.4].

1.4 In situ measurements for the purpose of optimization of the permanent way system

If the real exposure of the superstructure components are known, it is possible to eliminate unnecessary and cost-intensive overdimensioning. In order to translate this idea into practice and in order to get more scientific and technical information, with participation of DB, pressure measuring gauges have been installed in the trial section (in situ for the first time, as far as we know) at the bottom level and on the lateral limits of the ballast.

In the meantime, several measurement campaigns have been performed, and a multitude of new findings have been obtained, which relate not only to the type of permanent way discussed here, but to ballasted track in general.

2 Measurements
2.1 Installation of pressure pads

The compressive stress acting on the ballasted track was measured using pressure measuring gauges (pressure pads) made by Glötzl [2.1]. The arrangement of the pressure pads is shown in figure 3.
The pressure pads located at the bottom level of the ballasted track were installed in mortar beds on the concrete base plate, underneath the ballast mats. The pressure pads located laterally were inlaid into precast concrete parts which were installed along the shoulders. Thus the concrete trough was adapted to the standard track cross sections approved by the construction supervisory board.

For reasons of cost the interesting areas could not be covered completely with pressure pads. So it was necessary to position the pressure pads in a way which nevertheless yielded comprehensive information about the stress distribution, and even detailed information where necessary. It was indispensable to assume certain symmetric features in both the longitudinal and transverse directions.

In order to determine the deformation of the track elements acceleration sensors were installed in specific locations (refer to figure 3). The displacements were determined using the double integration method developed by imb-dynamik [2.2, 2.3].

Supplementary sleeper voids and track position measurements revealed that installation of the pressure gauges had caused neither sleeper voids nor faults in level. Especially, it was shown that as a result of the trough effect there has not been any initial settlement of the track, which usually must be expected for ballasted tracks.

2.2 Measurement campaigns

In the meantime, several measurement campaigns [2.4] have been performed.

Initial measurements in October/November 2000:

- Measurement during installation: pressure acting on the ballast during compacting, packing and tamping.
- Measurement subsequent to the installation: ballast pressure and acceleration.
- Continuous measurement: ballast pressure recorded for the total of train service for a period of approximately one week.

Second measurements in March 2001:

- Measurement during service on the consolidated ballast: ballast pressure and acceleration.
- Measurement during compacting operation: ballast pressure during alignment, packing and tamping, and application of a dynamic track stabilizer (type DGS B2 N).
- Measurement subsequent to compacting operation: ballast pressure and acceleration.
- Continuous measurement during service subsequent to compacting operation: ballast pressure recorded for total train service for a period of approximately one week.

Preparation and performance of such new and demanding measurement tasks were completed successfully. All of the important sensors worked properly. Also they withstood the enormous stress caused by compacting operations and by DGS tamping without being damaged. Thus all important loading conditions – i.e. packing, tamping, train passage, alignment, DGS action, for which only been theoretical stress data and load models had been available so far – could be measured precisely.

3 Results

3.1 Time signals caused by train passage

In figure 4, the measured vertical acceleration of the left end of the central sleeper (inner side of curve), the displacement determined from it by way of double integration and the measured pressure acting on the pressure pad located underneath are given using the example of an ICE train passing at a speed of 160 km/h.
A comparison of the displacement and of the pressure acting on the ballast shows that especially the data obtained for out-of-round wheels of the first and second carriage match each other perfectly even in small details. Thus dynamic forces e.g. due to out-of-round wheels are passed on to the ballast and the subgrade even at high frequencies.

The highly evident maximum amplitudes obtained for the acceleration curve approx. 0.2 secs prior to the first axle of a bogie originate from the train’s passage over a welding joint located approx. 10 m from the measuring point.

### 3.2 Pressure distribution below ballast

Figures 5a to 5c show the pressure acting on the ballast at the level of the ballast mat below the first axle of the ICE1 engine at a speed of 160 km/h in three different measurement situations:

- **Figure 5a** Situation 1: measurements performed directly after installation of the pressure pads and after packing (October 2000).
- **Figure 5b** Situation 2: measurements performed after a consolidation period of 4 months (March 2001).
- **Figure 5c** Situation 3: measurements performed subsequent to compacting operation (March 2001).
Bild 5a Normierte Schotterdruckverteilung nach Einbau an der Unterseite des Schotterbettes
(100 % = maximale Druckspannung nach Einbau, ICE-Triebkopfachse, ca. 20 t Achslast, 160 km/h)

normalized ballast press. [%] p. placing

Bild 5b Normierte Schotterdruckverteilung nach Konsolidierung

norm. pressure [%] p. consolidation
**Fig. 5a-c:** Ballast pressure distribution (normalized to 100% = max. pressure after installation), a) after installation, b) after consolidation, c) after compacting

The compressive stress was standardized to 100%, corresponding to the maximum stress measured under the right-hand support of the middle sleeper during initial measurement (measurement situation 1).

Results of the analysis:

- There were highly significant differences obtained for the distribution of pressure on the base plate:
  - maximum distribution (100%) below the regular sleeper bearing surface,
  - 80% below the center of the sleeper (unexpectedly high, resulting from sleeper bending),
  - 50% in front of the sleeper end,
  - 65% in the space between sleepers (on the outside of the curve, average value between sleepers).

- The pressure acting on the ballast was found to become, not more regular with time, but even more irregular, causing the maximum pressure to increase.

- The pressure acting on the ballast was found to shift towards the track axis in the course of consolidation (with bending of sleepers increasing). This is typical of type B 90 sleepers and is not caused by any permanent way features, but is exclusively due to the sleeper geometry.

### 3.2.1 Cross section

Figure 6a shows a cross section of the ballast compression in the three measurement situations, and figure 6b shows the corresponding displacement and sleeper bending. Displacement of the sleepers, i.e. resilience (elasticity) of the ballast, is reduced as a result of both consolidation and compacting measures.
Despite the fact that comparably rigid type B 90 sleepers were used and that the ballast was resting on ballast mats, the distribution of the pressure acting on the ballast was found to be far from even, as can be seen from the cross section. It should be noted that consolidation will generally not cause the distribution of pressure to become more regular, but more irregular. This tendency was successfully counteracted by compacting measures.

### 3.2.2 Longitudinal section

Figure 7 shows a longitudinal section of the compressive stress acting on the ballast and caused by an ICE carriage. The normalization corresponds to the one shown by figures 5a to 5c.
This shows that there are only minor differences in the longitudinal section between the results obtained in various measuring situations. It follows that there are hardly any changes to longitudinal load distribution. Consequently, there is hardly any interaction of the adjacent ballast “columns” (in the longitudinal direction), nor will any such interaction be established in the course of time.

3.4 Horizontal forces acting on the shoulders of the concrete trough

The normal forces acting on the pressure pads located on the shoulders of the concrete trough were determined by means of integration over the length of one shoulder section (7.5 m). In the definitive case of ICE 1 engines (with one bogie located in one shoulder section), a horizontal resultant of 33 kN was obtained at a height of 15 cm above the level of the ballast mat. These results were far below the system’s load rating.

3.5 Trough deformation

Figure 8 indicates the deformation of the sleeper and concrete trough when exposed to the passage of an ICE carriage.
Owing to the concave deformation of the base plate, the shoulders move inwards despite the horizontal forces acting towards the outside. This effect contributes to the so-called “fixation” of the ballast.

The displacement of the base plate observed for ICE carriages is approx. 0.3 mm. It is higher than the base plate displacement usually observed for slab track. This is due to the fact that there were no subsoil improving measures performed at the time the trial section was installed in 1997. At that time, such measures were considered to be unnecessary – an assessment which proved to be correct owing to the excellent behavior of this permanent way as far as the system’s outstanding track position stability and the low degree of settlement of the entire system are concerned.

### 3.6 Continuous measurements

Figure 9 shows a histogram of the maximum pressures caused by wheel passages over the ballast pressure pad below the right-hand sleeper support for a total of approx. 2,000 train passages.
When analyzing this figure, it should be considered that the measuring section was not only passed over by passenger trains travelling at speeds of up to 160 km/h and by freight trains travelling at speeds of up to 120 km/h, but also by trains just leaving the railway station and travelling at low speeds. For the latter, maximum dynamic stress levels have been measured which only slightly exceed the corresponding static stresses.

At the same time, the axle loads can be divided into the categories lightweight (passenger carriages and lightweight freight cars) and heavyweight (locomotives and heavy freight cars). Together with the running speed categories slow and rapid, four groups are obtained. The four groups are represented by the four peaks in figure 10. Each of the groups exhibits a normal (Gaussian) distribution. The entire histogram is obtained by summing up the four individual normal distribution curves. Against this background, the dynamic factor of the pressure acting on the ballast – maximum pressure during passage of the wheel in relation to static pressure – can reasonably be estimated to be approx. 150% for passenger carriages and approx. 155% for engines.

4 Summary and forecast for the type of permanent way developed by SYSTEME GRÖTZ BSO/MK

In situ measurements of pressure acting on ballast were performed under real service conditions for the permanent way SYSTEME GRÖTZ BSO/MK (conventional ballasted track installed in a concrete trough and placed on ballast mats).

The measurements yielded new findings relating to the load bearing behavior of the ballast in the track. They provided information about the three-dimensional propagation of stress in the ballast under various loading conditions.

The results obtained from the investigation of the system contribute to the further development of innovative ballasted tracks. As a result, cost-intensive overdimensioning can be eliminated without any restrictions to safety and quality requirements. Also, the results of the investigation allow the ballast simulation to be further improved within calculations.

Owing to its high stability under load, its low maintenance requirements and its low level of emission, the permanent way SYSTEME GRÖTZ BSO/MK is particularly suited for heavy-load trains and for railway lines crossing built-up areas.

Apart from the vibration-reducing properties the system’s suitability for high running speeds, high axle loads and unrestricted use of eddy-current brake equipment has been proved.

The investigations mentioned above, and the further evaluation of the results of such investigations are expected to yield a multitude of supplementary information about the type of permanent way described above and about ballasted tracks in general, which shall be reported in future publications [also refer to 4.1].

5 Literature


