Rehabilitation of Ballast and Subgrade

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Abstract

The track structure has to distribute the wheel forces to the subgrade without overloading any of the material layers. With the increase of axle loads, the quality of the ballast under the ties and the quality of the subgrade becomes extremely important.

When the ballast does not fulfil its task any more, the only sustainable mode of rehabilitation is either ballast exchange or undercutting-cleaning. Examples on heavy haul railways show, that constantly lifting and reballasting of tracks does rather cause additional problems than solving them. Undercutter cleaners of the latest generation have the necessary high output, additional features like finger screens contribute to better ballast quality.

If ballast cleaning had been neglected, the subgrade can be overloaded and fail. The same can happen, if axle loads are increased. The stability of the whole track system will fail, extreme high track maintenance costs will arise.

European railways have successfully rehabilitated such trouble zones by installation of a subgrade protection layer, consisting of a defined gravel/sand mixture, compacted to 100 % Proctor density. Calculations of the Technical High School of Dresden show, that such protection layers would also be applicable for heavy axle loads.

Economic installation of such layers is carried out by subgrade rehabilitation machines. The investment is returned very fast by longer track service life and reduced maintenance costs.
The return on investment period is less than 6 years on concrete ties an less than 10 years on timber.

**REHABILITATION OF BALLAST AND SUBGRADE**

1. **INTRODUCTION**

The aim of infrastructure managers is to provide a track with optimal availability for traffic at the design speed. To achieve this, the necessary maintenance, should be optimised in frequency and cost. Today’s high traffic loads create enormous destructive forces to the track. A balance of reasonable good condition of all elements of the track system to optimise track maintenance cost and effort therefore is very important today. In this paper will deal specially with the role of the ballast bed and the subgrade within the track system. Examples of the state of ballast and subgrade after several years of use will be shown.

2. **THE LOAD TRANSFER FUNCTION OF THE TRACK**

The wheel loads are distributed via the rails, sleeper pads, base plates, ties, ballast and sub ballast to the subgrade.

2.1 *Longitudinal load distribution*

When a wheel loads the tie, the elasticity of the whole system determines how much of the wheelforce is distributed in longitudinal direction to the adjacent ties. If the system is very hard, the whole force acts at one point, the vertical force which is induced into the system is very high. If the system is soft and the rail can deflect under the load, the induced force becomes lower but the bending moment of the rail and thereby the tension in the rail base rises (figure 1). The
deformation behaviour of the track can be described by the track modulus. German Railways use the formula

\[ C_b = \frac{P}{y} \left[ \frac{N}{mm^2} \right] \]

P = induced vertical force, y = deflection

Figure 2 shows an example on concrete ties with UIC 60 rail and 20 t (metric) axle load\(^1\). For example: The minimum deflection for such tracks is defined by German Railways to be 1.2 mm (~ 0.05 inch)\(^2\).

If the ballast is hard and caked, no controlled deflection is possible, as there is either direct contact of the tie to the inelastic system or voids develop under the ties which cause pumping and hammering of the track. On the other hand, fouled soft ballast also causes too much deflection in the track.

2.2 Vertical Load Distribution

To obtain an optimum transmission of the traffic loads into the subgrade, the ballast must be thick enough, so the pressure on the subgrade is less than its bearing capacity. The fouling of the ballast bed leads to an unfavourable distribution of the pressure exerted on the subgrade. In fouled ballast the friction between the ballast stones is considerably reduced. This means that the aforementioned conditions of the ballast bed no longer prevail, which will lead to irregular track settlement.

3. INFLUENCE OF BALLAST QUALITY ON TRACK GEOMETRY

On fouled ballast restoration of track geometry is only effective for a short time. The track geometry deteriorates rapidly, while the subsoil is subjected to even greater stress. This continues
until loam and clay rise into the surface of the ballast bed. Dips occur in the track, increasing the risk of derailments. Figure 4 shows a track geometry report of Austrian railways to which a GPR (ground penetration radar) report was superimposed. Wherever the ballast is fouled, water can be observed in the ballast and the subgrade and track geometry deterioration is very fast.

4. CAUSES OF BALLAST DEGRADATION AND FOULING

Since grain composition determines the ballast properties, an excessive proportion of fines could impair, impede or even totally rule out certain desirable ballast properties. The permissible percentage of fines in relation to the total weight of the sample for new ballast is generally 3 to 5 %. The undesirable proportion of fines contained in old ballast therefore defines the utility value of the ballast and has to be considered as fouling.

The fouling of the ballast is regarded as the proportion of fines – expressed as a weight percentage of the total sample – exceeding the permissible proportion according to the technical specifications. Fines are the grain size falling below the smallest permissible grain size. (Generally grain sizes with a diameter below 22.4 mm (~ ¾ inch) are designated as fines.)

4.1 Attrition of Ballast

The main source for ballast fouling by attrition is the traffic load. Before passing over a sleeper, the wheels rolling over the track make the sleeper ahead lift off slightly. The moment the wheel passes on the sleeper, the latter rebounds abruptly on the ballast, which causes ballast splintering at the contact points, re-arrangement of the stones and friction processes leading to a rise in the portion of the fines. The rate of development of fines is about 3.6 – 5.2 kg (8 – 11.5 lbs) per million ton of traffic. Tamping is also frequently mentioned wrongly as a main cause of ballast degradation. Test tamping has shown, that its influence on ballast degradation can be neglected,
only 1.8 – 3.9 kg (4 - 8½ lbs) are developed per tamp and tie. For example: if a 30 ton axle load track is tamped after every 50 million gross tons, the fines due to traffic would amount to 260 kg (570 lbs), whereas tamping causes a maximum of 3.9 kg (8½ lbs).

Figure 4 shows examples of ballast fouling, mainly caused by traffic. From a lot of photos which were taken on Austrian Railways, a few typical examples are shown. Photo 5.1 is a longitudinal cut, the fouling under the sleepers is always higher than in the cribs. Photo 5.2 is a close-up, showing the percentage of fines at different levels. The photos were taken 27 years after track and ballast renewal.

4.2 Other Sources of Fouling

Additional sources of ballast fouling are contamination from outside by air (wind), spillage, and penetration of subsoil from underneath. If the ballast layer is not thick enough, this provokes an unfavourable load distribution on the subgrade. The subgrade is destroyed and fines will rise into the ballast bed. Insufficient cross-fall of the subgrade leads to the formation of water traps. The pumping effect generated by the trains causes the subsoil material to penetrate into the track ballast. This causes the formation of mud spots and wet patches on the ballast bed crown, which may result in frost heaves and ruptures. If soft spots are not maintained in time, a vicious circle starts: Further deformations of the track subgrade cause more water traps and troughs, the water is not drained away and the pumping up of subsoil material is further increased. A progressive deterioration of the track geometry will occur (figure 6).

5. BALLAST CLEANING

5.1 Criteria for Rehabilitation of Ballast Bed
Rapid deterioration of track quality and necessity of frequent surfacing are indicators of fouled ballast. Further information can be gathered from the measuring chart produced by a recording car. In the case of a heavily fouled ballast bed, the measuring chart parameters longitudinal level left and right as well as the twist measured over a 5 m basis of the measuring chart show considerable deviations (fig. 7). Plasser & Theurer recording cars fitted with the ADA II analysing computer program, are capable of evaluating these results in the form of quality coefficients and thus give an indication of the urgency of ballast cleaning.

Visual inspections and sampling of the ballast bed then provide a deeper insight of the state of the ballast. If the ballast contains more than 30% of fines, ballast cleaning becomes appropriate, if there are more than 40 %, ballast cleaning is inevitable. Another criteria, which is used is the Fuller criteria. In this state, the ballast has developed so many fines, that the closest possible position of the grains to each other is reached, the ballast has become completely impermeable and cannot drain anymore. Figure 8 shows a sieve analysis of ballast taken from a mud spot. The grain distribution (red curve) is very close to the Fuller curve and the ERRI criteria of 30 % of fines is far exceeded.

5.2 Cost-efficiency

Cost-efficiency of ballast cleaning is provided by the reduction of track cost at clean ballast. A perfect track geometry can be achieved and speed restrictions are avoided. The intervals between maintenance are extended. On fouled ballast there can be irregular settlements of the track. Restoration of the track geometry by „tamping“ is only effective for a short period. After track maintenance the track geometry deteriorates very quickly and in some cases the track has to be tamped 2 – 3times a year. Speed restrictions have to be imposed to keep damage as low as
possible in the event of derailments. Even on tracks carrying heavy traffic, the intervals between maintenance in the cleaned ballast bed can be 3 – 5 years. The service life of the track is extended. A fouled ballast bed no longer possesses the required elasticity. With concrete sleepers there is a danger that these may be cracked by impacts from non-round wheels (flat spots). Wooden sleepers become rotten due to poor drainage.

5.3 Mechanised Ballast Cleaning

5.3.1 Shoulder Cleaning

Shoulder cleaning is a wide spread practice in North America but not much applied in other continents. It can improve the drainage when the ballast on the shoulder is fouled but not substitute undercutting. It is utmost important to cut the full shoulder down to the subgrade. Leaving part of the shoulder untouched or pushing part of the ballast to the side can do further damage to the track instead of improving it, because such a practice creates water traps (fig 9).

5.2.3. Undercutting Cleaning

When the ballast does not fulfil its task any more, the only sustainable mode of rehabilitation is either exchange or deep screening. Examples on heavy haul railways show, that constantly lifting and re-ballasting of tracks does rather cause additional problems than solve the problem. The example in figure 10 shows that due to the impact of traffic, the ballast broke down under the sleepers so that track correction work could not be carried out effectively any more. It is clearly visible, that the ballast on top and in the cribs looks good, due to the frequent supply of fresh ballast. Nevertheless, shoulder cleaning or tamping could not improve the situation any more, it is necessary to undercut and clean the ballast to prevent further damage.
The ballast excavating device should be designed to facilitate the production of a straight cut subgrade in respect to longitudinal and cross direction with the prescribed cross-fall of approx. 4 – 5% (1: 25 to 1: 20). According to expert opinions, this is best achieved by combining an excavating chain with a cutter bar. The ballast must be excavated over the entire width of the ballast bed. It is therefore necessary to provide an extension of the cutter bar, if required (fig. 11).

The fines in the ballast usually build up from the bottom to the top (fig. 12). Shallow undercutting just under the ties, which does not go down right to the subgrade or sub ballast is therefore not solving the problem. The possible excavating depth should be about 1.0 m (40 inch) measured from top of rail of the non-superelevated rail. This means that the required cross-fall can also be achieved on superelevated tracks with opposite inclination of the subgrade.

The increasing traffic density demands optimal use of work windows, there is a growing demand for high output ballast cleaners. As mentioned above, output should not be achieved on the cost of quality (shallow cutting). Full section undercutting is enabled by high capacity undercutting chains, but the crucial unit is the vibrating screen system. For High capacity ballast screening double and triple screen units have been developed, which enable high output and perfect cleaning quality (fig. 13). Additional features like finger screen or ballast washing contribute to better ballast quality.

6. SUBGRADE REHABILITATION

6.1 Subgrade protection layers

The need to protect and improve the subgrade has existed ever since railways have been in use. In 1889, H. Frazier of the Chesapeake and Ohio Railway wrote: “The stability of track depends upon the strength and permanence of the roadbed and structures upon which it rests: whatever
will protect them from damage or prevent premature decay should be carefully observed. The worst enemy is "water", and the further it can be kept away from the track or the sooner it can be diverted from it, the better the track will be protected.”

The approach to the problem was:

- exchange the subgrade material itself or improve it by mixing it with enforcement substances or
- protect the subgrade and enforce the structure by a protection layer.

Today both methods are still applied but it has been found that the application of a correctly dimensioned and compacted blanket of a specified mixture of gravel and sand shows the most durable results. In the 1930's German Railway (DB) found natural pits with the right composition of gravel/sand. They started to rehabilitate track sections on clay in the Nurnberg area and these sections still have sufficient bearing capacity today.

In the years 1954/55 DB investigated extensively gravel/sand blankets that had been installed in the 1930's and developed their “substructure construction standard DV°836” which contains exact instructions how to build a Subgrade Protection Layer (FPL) (fig. 14). This standard has been continuously improved according to the latest research results and is the model for similar standards in other countries.

6.2 Methods of subgrade rehabilitation

The classic method of subgrade rehabilitation is to dismantle the track and use road construction equipment to excavate ballast and subgrade material, bring in the new material, distribute and
compact it and then lay the track again. This “open construction” method provides good access to the subgrade but has also major disadvantages:

- The track is closed to traffic for the whole rehabilitation period, this can last several weeks
- Large amounts of material have to be transported by lorries
- Very often the subgrade is too weak to carry the trucks and the construction equipment, water traps are created which will very soon cause new subgrade problems.

The alternative is to use on track equipment which can carry out subgrade rehabilitation without the necessity to dismantle the track. In 1984 the first track bound subgrade rehabilitation machine PM 200 was developed by Plasser & Theurer and put into operation by a German contractor. This machine excavates the ballast and subgrade under the existing track, loads the fouled material onto special cars in front of the machine, inserts the gravel-sand mixture behind the excavating chain, grades and compacts the material, inserts the first layer of new ballast and tamps the track using an integrated continuous action tamping unit so that traffic can commence immediately at 70 km/h (45 mph).

In autumn 1994 the contracting company Swietelsky started to work on Austrian Railways with the AHM 800. The fundamental improvement compared to previously known methods lies in the application of a recycling concept and in the improved consolidation of the protective layer by adding water in the plant. This machine operates in the same mode as the PM 200, but the top layer of the existing ballast is conveyed to a ballast crusher where it is graded down to the desired grain size to serve as protection layer material.
Another machine with an integrated innovative ballast cleaning concept, which went into service in the year 2000, is the subgrade rehabilitation machine RPM 2002 (fig. 15). As a new method for ballast processing, a ballast processing plant has been incorporated which frees the ballast of cohesive material and reshapes the rounded edges of the ballast stones. A large amount of ballast can be recovered and is put back on the compacted subgrade protection layer that had been inserted under the track by the machine.

6.3 Efficiency of Subgrade Rehabilitation

On track sections with weak subgrade, mechanised subgrade rehabilitation pays back in very short times. On such sections the annual track costs can be eight times as high as on sections with good subgrade. In May 2006 the Institute for Railway Engineering and Transport Economy of the Graz University of Technology (Head of Institute: o.Univ.-Prof. Dipl.-Ing. Dr.techn. Klaus Riessberger) made a study about costs and return on investment of formation rehabilitation under North American conditions. The results were very promising on concrete ties as well as on timber. The cost figures were purposely kept on the high side, nevertheless the result was, that subgrade rehabilitation with a RPM 2002 would pay back in less than 6 years on concrete and less than 10 years on wood (fig. 16).

6.3.1 Quality Results

Measurements prove that the machines do jobs of outstanding quality. The specified bearing capacities and densities are achieved by the machines. In a test series of more than 190 bearing measurements, Austrian Railways also tested the work result after 6-12 months. It is remarkable that in any single case the strength of the protection layer had further increased, in many cases by more than 80%\(^5\).
The uniformity of the layers is not only controlled during the working process, measurements with geo radar years later show that protection layers last, if they are installed using on-track machines. When using road construction equipment for rehabilitation of soft subgrade, the results are not that good.

The most significant sign of quality improvement are the extended track tamping and ballast cleaning cycles. On tracks with badly damaged formation, tamping cycles of 6-12 months become necessary, ballast cleaning is done every 10-12 years and the track itself has to be relayed every 12 years (experience on lines with 50 to 60 million gross metric tonnes of traffic per year). After rehabilitation, tamping cycles rise to 4-6 years, ballast cleaning and track renewal cycles can be extended to 35-40 years.

7. CONCLUSION

Increased axle loads ask for track systems that contribute to reduction of stress on vehicles and permanent way material. Clean ballast with ballast stones according to specification is a prerequisite for the distribution of wheel forces to the rails and the subgrade without causing overloading. When Ballast cleaning is carried out, it is essential to use high output machines that undercut the full ballast section and provide excellent cleaning quality.

Subgrade problems cause severe damage on track and rolling stock material. Poor subgrade is a major cost driver as very frequent maintenance and slow orders for the trains will become necessary. European railways have tackled this problem successfully with the use of formation rehabilitation machines that insert a subgrade protection layer between the ballast and the soil formation.
Despite the relatively high cost of such an operation, the return on investment is remarkable. Payback periods of one year are achieved on very poor subgrade, payback periods of 5 to 6 years are quite common. North American railroads also face severe subgrade problems in certain areas. First rough calculations show a high potential of cost reduction by the introduction of on track subgrade rehabilitation machines. For an introduction period it can be recommended, that two or three railroads join up, which would keep the initial costs for the single parties on a lower level.

TABLES AND FIGURES

Figure 1: Longitudinal load distribution by deflection

- No deflection (hard and caked ballast)
- High spot force
- High dynamic forces on ballast
- Low tension in rail base

- High deflection (soft, wet ballast)
- Low spot force
- Low dynamic forces on ballast
- High tension in rail base
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Figure 4: Fouled ballast causes wet spots and non lasting track geometry
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Figure 13: Double screening unit for 1000 m³/hr (1300 y³/hr)
Figure 14: State of the art formation protection layer

Figure 15: Subgrade rehabilitation machine RPM 2002

Figure 16. Cash flow – Amortisation of subgrade rehabilitation
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ANNEX

Biographical Sketch

Rainer Wenty

Rainer Wenty, a mechanical engineer, is Manager of Technical Sales and Marketing for Plasser & Theurer in the company’s Vienna, Austria main office. He has been with the company since 1967 and has wide spread international experience in the application of track maintenance and -construction machines - both, technically and economically. Rainer Wenty has also authored numerous technical papers for trade publications and conferences.

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