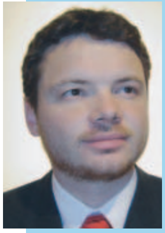
13 years of experience with rail-mounted formation rehabilitation on the Austrian network

Since 1994 the rehabilitation of tracks with subsoil problems has been performed on the network of Austrian Federal Railways (ÖBB) using Plasser&Theurer's AHM 800R and RPM 2002 mechanised track systems. The success of the project can be shown in economic terms on the basis of life cycle costs and in technical terms with the help of track recording charts.

One of the most important parameters for stable track geometry is a substructure which is sufficiently drained and has good bearing strength. Negative influences from the subsoil are expressed in a high level of maintenance expenditure for the track, a reduction of the life span of the track components and quite frequently in a temporary drop of the permissible speed. Problems with the subsoil are as old as the railways. The increased loads and speeds as well as operational factors have led to the development of rail-mounted mechanised substructure improvement systems. Since 1994 protective track-bed layers have been installed on 542 km of track in the network of Austrian Federal Railways (ÖBB) using the AHM 800 R and (since 2002) the RPM 2002 mechanised systems.



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1 Condition evaluation of the track

Condition evaluation of the track is performed at the ÖBB by cross-linking various analysis options. The geotechnical line report is used for the approximate allocation of the "extended track" (sum of track installations with influence on the track geometry) in 100 m steps. The permanent way measuring coach supplies a variety of track geometry parameters, and the longitudinal level signal is the best indicator of negative influences from the subsoil. The rate of change of the longitudinal level signal provides an objective basis for the assessment of the track geometry stability. Using 2D geo-radar evaluations it is possible to obtain a simple representation of the longitudinal section of the track in respect of the moisture content of the ballast and the subsoil, the ballast soiling and the installed bearing layers.

At the ÖBB the so-called geotechnical line report is applied for preliminary diagnosis of the track as shown in Table 1 [1].

This combines various kinds of information, from the quality of the permanent way to the quality of the substructure, in a table and the geotechnical track quality figure is derived from this.

The main task of track geometry maintenance is to ensure an adequate track geometry quality. To do this, the track geometry is measured at regular intervals using the permanent way recording coach and the most important signals are track gauge, track twist, longitudinal level of the rail, alignment and cross level. With regard to the course of settlement of the track, the longitudinal level signal is the most important parameter, because this signal reflects the relative settlements of the track. The absolute degree of settlement is not detected by the measuring coach because long-wave track geometry irregularities are filtered out of the raw signal (Fig. 1).

With the help of gliding standard deviations of the longitudinal level signal assigned to the respective measuring date, it is possible to to see the deterioration of changes in the track geometry in a simple and clear manner (Fig. 2).

Geo-radar runs are also performed when drawing up the geotechnical line report. The radargrams that were once difficult to decipher for track engineers, are supplied nowadays in a ready converted 2D format. Information concerning track-bed layers, polluted areas and wet zones in the ballast

Permanent Way	• poor track geometry	local experience
	• high maintenance expenditure	
	• wet track ballast	
	• polluted track ballast	
	• poor ventilation	
	• wet track ballast	georadar
	• polluted track ballast	
Rate of deterioration	• Track data	track measuring coach
Substructure	• track-bed layer	database
	• short tamping interval	local experience
	• troughs	
	• mud spots	
	• frost heaves	
	• embankment	geotechnical inspection on foot
Subsoil	• embankment contact area	geotechnical inspection on foot
	• level	
	• cutting	
Water situation	• embankment	geotechnical inspection on foot
	• level	
	• cutting	
	• drainage system	
	• groundwater	
	• seepage water	
	• stratum water or dammed-up water	
	• slope water	
	• capillary water	

Table 1: Influencing factors in the geotechnical line report

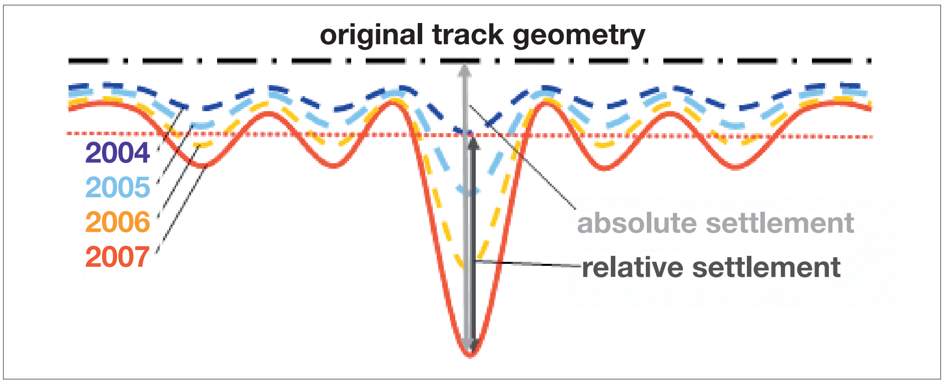

Figure 1: The longitudinal level signal reflects the relative settlement of the track

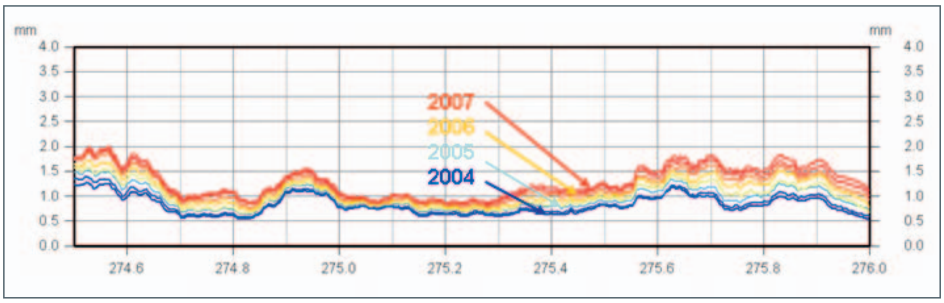

Figure 2: Clear illustration of the changes in track geometry using gliding standard deviations of the longitudinal level

or in the subsoil is therefore now available in a new appearance (Fig. 3).

The almost linear change over time of the relative settlements of the track (the "rate of deterioration" of the standard deviation of the longitudinal level in mm/year) represents an objective signal to determine the vertical stability of the track geometry. This was also integrated into the new ÖBB track geometry analysis system (Fig. 4).

The connection between track geometry and moisture in the track structure is obvious. Protective track-bed layers can only fulfil their function when there are sufficient drainage possibilities for both the track formation and the earth formation in the form of railway ditches, sub-surface drainage and suchlike. The installation of a protective layer will not yield the desired results unless the correct ballast bed profile is produced and maintained, ensuring adequate drainage. Stable track geometry is only achieved when there are well-supported and sufficiently drained tracks.

2 Cost-efficiency

Various studies about the cost-efficiency of the tracks were carried out in the "Track Strategy" project conducted since 1997 by University Professor Dipl.-Ing. Dr.techn. Peter Veit [2]. The investigations were carried out on the basis of life cycle costs (LCC).

The first task was to determine the cost-drivers of a track. Fig. 5 shows the breakdown of the normalised annual costs into depreciation costs, purely maintenance costs and operational hindrance costs of an average track with differing traffic loads.

The goal of the maintenance planning, to reduce the life cycle costs for the track, can be achieved by extending the service life (which brings a reduction of the depreciation) and by reducing the operational restrictions. The maintenance costs themselves make up the smallest portion of the life cycle costs. A decrease in track maintenance which brings a reduction of the service life is therefore not economical.

Generally, the results for tracks and turnoutes can be summarised very simply:

▷ A high initial quality is the key to success.
▷ Speed restrictions are extremely uneconomical.
▷ From an economic point of view prolonging service life is a worthwhile target, even if it means spending money.

Different substructure qualities also have a very different effect – depending on the traffic load – on the LCC of the permanent way. On lines with light traffic the LCC of the track rise when the substructure is very poor – in comparison to good substructure – by the factor of 2 to 3, and on main lines with heavy traffic by the factor of 8.

In view of the many benefits of rail-mounted formation rehabilitation, such as the high working output, no disruption of traffic on the adjacent track, all formation rehabilitation to be carried out in the ÖBB network is performed in principle by the AHM 800 R or the RPM 2002. Conventional substructure improvement using diggers and lorries is performed only in exceptional cases (no machine available, very high number of bridges in the section of track under repair).

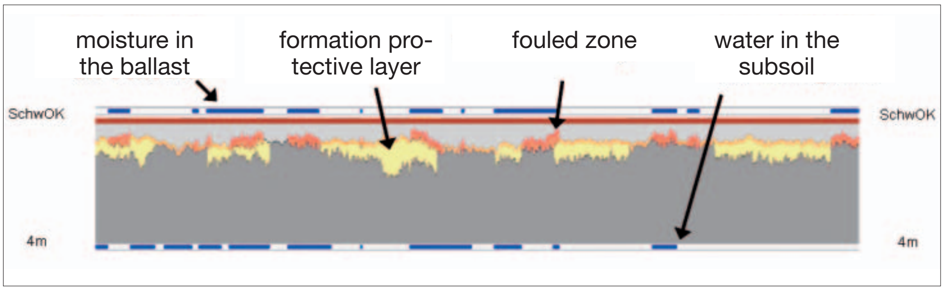

Figure 3: Example of a 2D geo-radar image

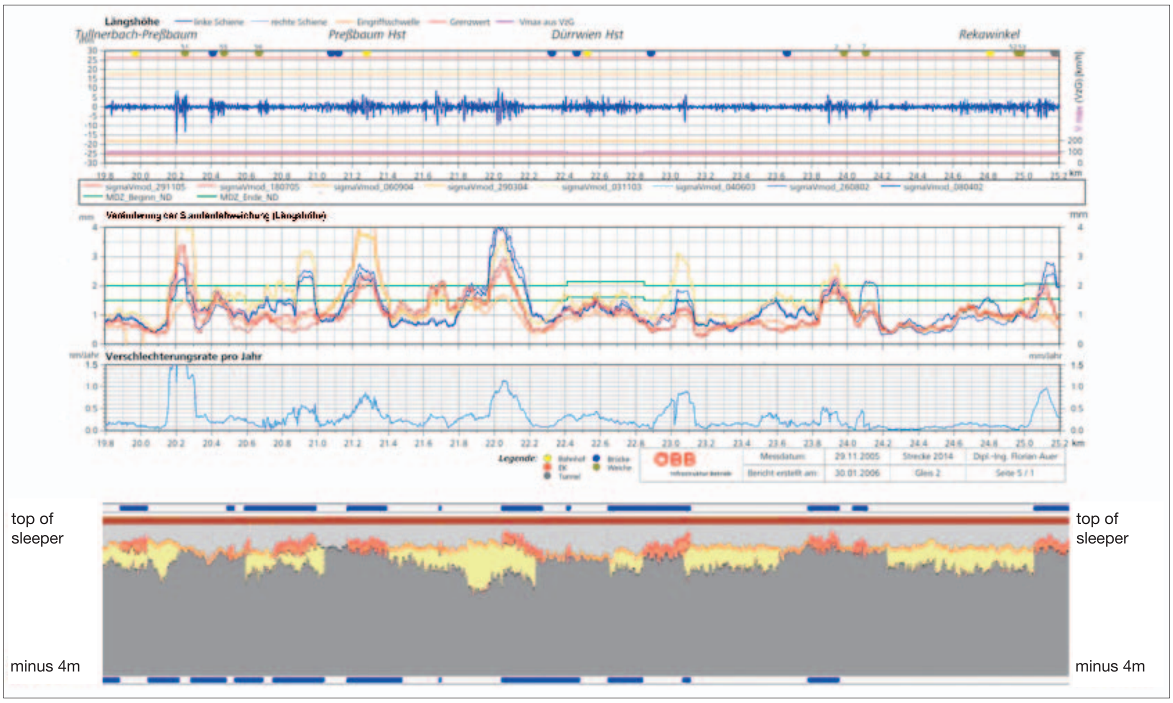

Figure 4: Comparison of the longitudinal level signal with the 2D geo-radar evaluations gives a good overview of the changes in track geometry

3 Rail-mounted installation method

3.1 General

Since 1994 for rail-mounted installation of formation layers the excavating machine AHM 800 R (Fig. 6) is in use, with a throughput capacity of 800 m^3/h [3] and [4].

The AHM 800 R has an internal recycling plant for used ballast. Optimised consolidation of the track-bed layer material is achieved by adding water to the mixture in the machine. Since 2002 individual sections have also been rehabilitated using the RPM 2002. In total, 542 km were treated from 1994 to 2007 using the AHM 800 R and RPM 2002 formation rehabilitation machines.

The advantages of rail-mounted formation rehabilitation are:

- ▷ installation of the new track-bed layer without dismantling the existing track,
- ▷ recycling of the old track ballast for use as track-bed layer material,
- ▷ consolidation and/or smoothing of the substructure formation using the machine,
- ▷ option of simultaneous placement of geo-synthetics and track-bed layer
- ▷ high working output (40 linear m/h on average),
- ▷ on double track lines, rail services can continue on the adjacent track,
- ▷ short, open construction pit,
- ▷ various thicknesses (track-bed layer up to 50 cm) can be laid in one pass,
- ▷ up to 50 % new material can be saved by adding the recycling material,
- ▷ reduction of track closures by up to 50 %,
- ▷ no need to build temporary access roads.

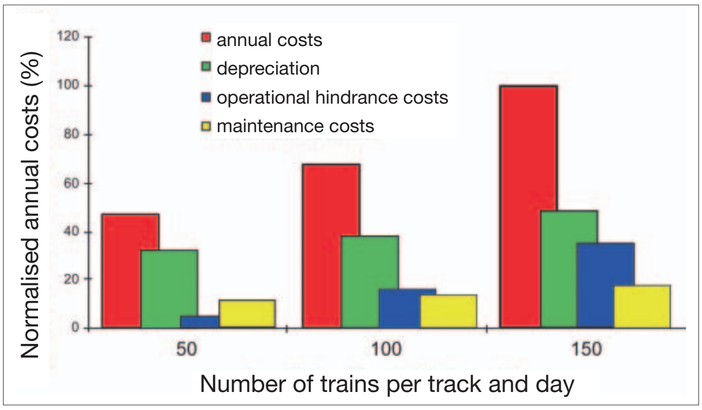

Figure 5: Depreciation is the cost-driver of the track

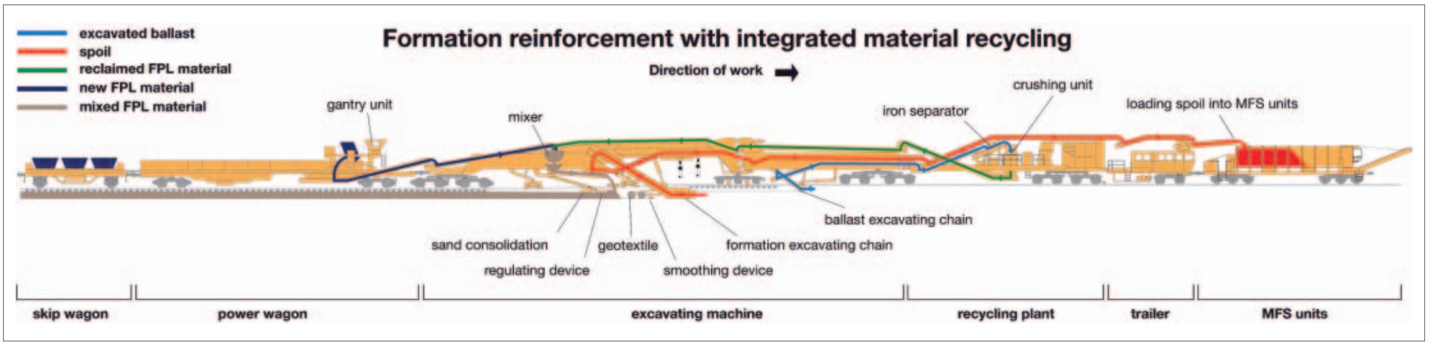

Figure 6: Diagram of the work sequence of the AHM 800 R

3.2 Preliminary Work / Ancillary Work [5]

The high quantities of material to be transported require detailed planning of the machine operation. To achieve the desired condition of the track installation following the work, it is necessary to observe various aspects:

- ▷ Installation of a protective track-bed layer is performed only after making a geotechnical expertise. Soil mechanical findings from the test pits, taking into consideration the results of the condition evaluation of the track (rate of deterioration, geo-radar information, tamping intervals, etc.), lead to the definition of the thickness of the track-bed layer and of the necessary geo-synthetic.
- ▷ Adaptations in the cross-section profile are necessary when the location of the cesses, the noise-protection walls, the catenary poles, the cabling and the drainage systems are not harmonised to each other. For example, if the foundation of a catenary pole has been laid in a drainage ditch, the lack of drainage will cause a drop in the bearing strength in this area and therefore lead to increased maintenance expense at the track level (tamping). Despite a high quality of the track-bed layer, the desired result cannot be seen on the recording chart. Therefore it is vital to convey this understanding of the comprehensive view of things to all the specialist fields.
- ▷ Special attention should be given to integration into the existing and/or newly constructed drainage system. Defective execution of this work will lead to a reduction of the bearing strength of the track and thus, once again, to increased maintenance expenditure. Track rehabilitation is costly and requires track closures once again (Fig. 7).
- ▷ The installation of cable crossings is generally only permitted before placement of the track-bed layer. The irregularities caused by "ripping-up" the track-bed layer (Fig. 8) at a later date are the cause of localised track-geometry faults which cannot be eliminated afterwards, even after repeated tamping.
- ▷ Localised track-geometry faults are frequently found in the vicinity of bridges. If the annual increase in the longitudinal level fault exceeds the threshold for the permissible speed, it will be necessary to correct the track sections next to the bridge separately before installation of the track-bed layer. Correction measures performed after the installation of a track-bed layer can jeopardise the success of the operation.

3.3 Track-bed layer material and geo-synthetics

The track-bed layer material consists of a mixture of reclaimed track ballast and added new material. This makes it possible to achieve a saving of up to 50% in new material. The particle mixture must meet the highest standards. The particle size distribution must comply with the particle size distribution curve (Fig. 9). The maximum proportion of grain sizes smaller than 0.03 mm is 3%, the material must contain at least 90% crushed stone. The track-bed layer material is supplied for the entire ÖBB territory by a few authorised firms. In these factories the track-bed layer material is already moistened when loaded into the skips (optimum water content).

Since the start of operation of the AHM 800 R, geo-synthetics have been laid between the bordering top soil and the track-bed layer. With regard to the mechanical properties, the geo-synthetic layer has three tasks to fulfil:

- ▷ stabilisation of the track-bed layer during the consolidation phase,
- ▷ separating and filtering in the operating phase,
- ▷ drawing off precipitation water, seepage water or capillary water in conjunction with the crossfall, especially a task of geotextiles.

Therefore the geotextile must extend beyond the lower edge of the track-bed layer (Figs. 10 and 11). Generally, geotextiles with 400 g/m^2 are used and in special cases geomeshing with additional mechanical reinforcement is chosen [6].

Figure 7: When the track-bed layer is integrated in the previously installed drainage system, this will increase the quality

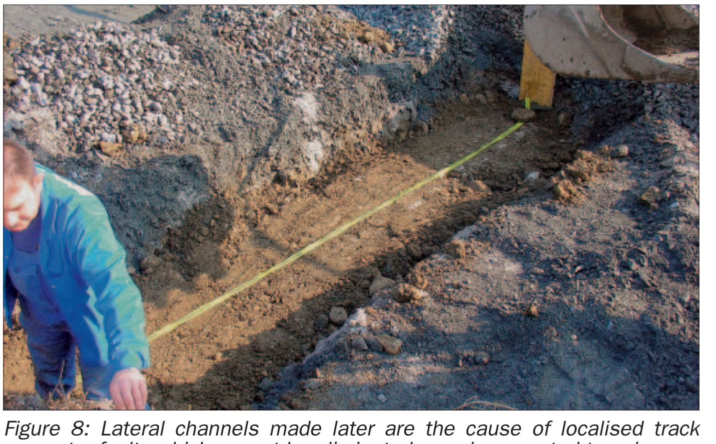

Figure 8: Lateral channels made later are the cause of localised track geometry faults which cannot be eliminated even by repeated tamping

3.4 Installation of the Track-bed Layer

The ÖBB requires for the minimum compaction (density) value DPr,min and the minimum resiliency modulus $E_{v,1}$ or $E_{v,2}$:

V > 160 km/h	$D_{Pr,min} = 97\%$	$E_{v,1} > 35$ MN/m²	$E_{v,2} > 80$ MN/m²	$E_{v,2}/E_{v,1} \leq 2,5$
V ≤ 160 km/h	$D_{Pr,min} = 95\%$	$E_{v,1} > 20$ MN/m²	$E_{v,2} > 50$ MN/m²	$E_{v,2}/E_{v,1} \leq 2,6$

To achieve the required degree of compaction, the optimum water content is regulated in the intermediate screening unit by calculated addition of water. According to the laboratory test report, the ideal water content is 7.4%. Compaction of the track-bed layer is carried out using plate consolidators (Fig. 12). The surface consolidation leads to a very uniform and high consolidation of the track-bed layer. The Proctor density D_{Pr} of the track-bed layer is on average 100.6%.

The uniformity of the produced track-bed layer is not disturbed by traffic travelling on the substructure formation, which is required for conventional installation of a track-bed layer.

In sections with turnouts, it is particularly necessary to rehabilitate poor quality subsoil due to the higher vertical dynamics and associated higher loads. The turnouts are dismantled temporarily and replaced by track panels. Mechanised rehabilitation of the subsoil is performed with the help of the installed track panels. After the track-bed layer has been installed, the existing or new turnouts can be laid again.

3.5 Quality control

The internal routine quality controls include a continuous check of excavation depth, track-bed layer thickness and formation crossfall as well as the daily assessment of the particle size distribution and the water content of the track-bed layer material. Up to around 1997 compaction checks of the installed track-bed layer were performed primarily in the form of complex static plate load tests (Fig. 13), which held up the track machine. Sometimes the density and the water content were obtained by radio-metric measurements using an isotope probe (Troxler probe).

Due to the good correlation between the resiliency moduli E_{v1}-E_{vd} and E_{v2}-E_{vd} and the time saving during measurement, deployment of the dynamic pressure plate tests (Fig. 14) using the light drop weight device was introduced from 1998. This made it possible to perform density checks faster and over a wider area. The dynamic pressure plate checks are normally carried out by the machine project engineer of the Austrian Federal Railways in a designated grid of 100 linear metres.

The following correlations exist:

▷ Earth formation:
$E_{v2} = 2.11 \cdot E_{vd}$ $E_{v1} = 0.78 \cdot E_{vd}$

▷ Surface of track-bed layer:
$E_{v2} = 2.04 \cdot E_{vd}$ $E_{v1} = 0.73 \cdot E_{vd}$.

In addition to this, random static and dynamic load plate tests, radiometric density and water content measurements and laboratory investigations (particle size distribution, Proctor test) are carried out by external testing institutes.

4 Geotechnical aspect

4.1 Structure of the track

The function of the skeleton track/ballast/track-bed layer system is to transmit the dynamic loads from the passing trains into

Screen [mm]	Siftings M % from	to
0.02	0	3
0.063	3	8
0.125	4	11
0.25	5	14
0.5	6	17
1	11	28
2	19	36
4	28	50
8	40	60
16	61	79
22.4	83	92
31.5	100	100

The proportion <2,0 mm should be close to the upper limit while also observing the Casagrande criterion of max. 3 % < 0,02 mm

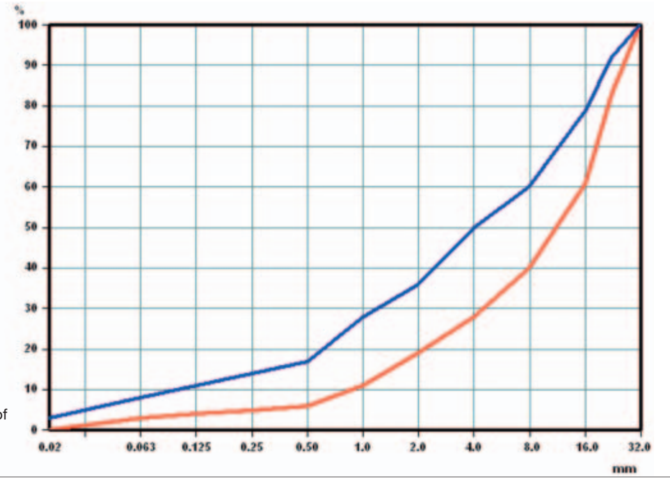

Figure 9: Required particle size distribution curve (upper and lower limit) for the track-bed layer material

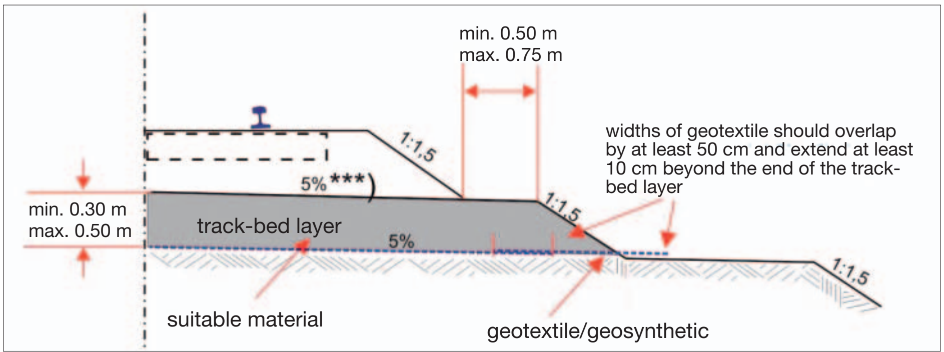

Figure 10: The standard drawing specifies that the geotextile must cover the lower edge of the track-bed layer

Figure 11: The water-draining properties of the geosynthetic can only be achieved when installed beyond the lower edge of the track-bed layer

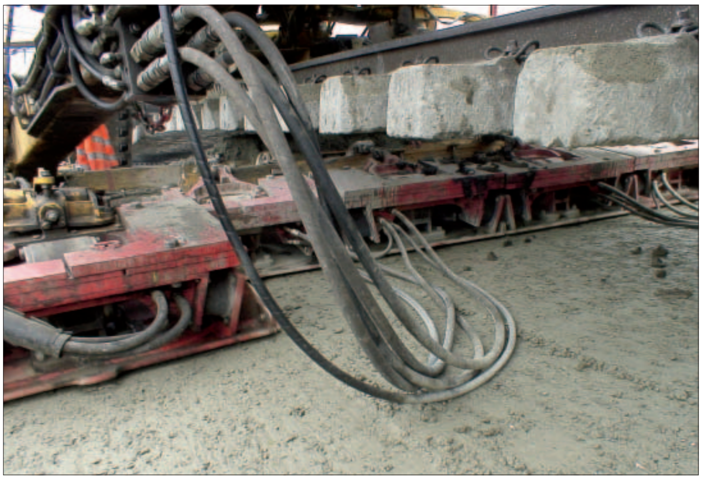

Figure 12: High uniformity achieved by plate consolidation

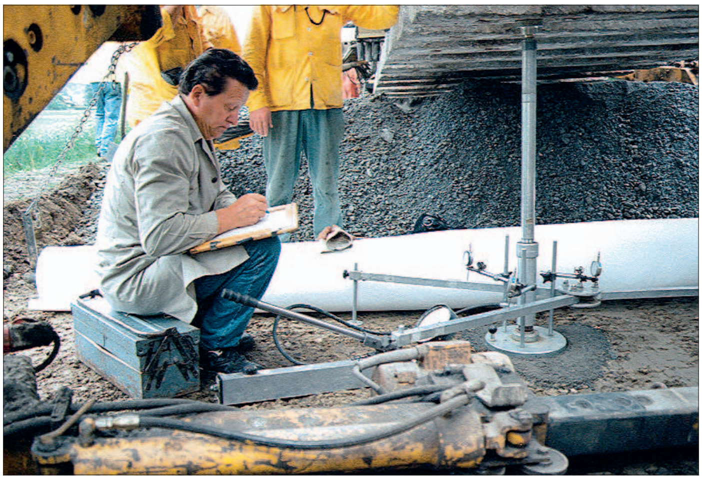

Figure 13: Resiliency measurements using static load plate delays progress of work

the substructure so that neither the shear strength nor the deformation behaviour of the substructure leads to a sudden or long-term loss of bearing strength and usability of the permanent way.

For the rail-mounted substructure reinforcement there is only a limited area of approx. 0.5 m available for rehabilitation in which track-bed layers can be installed as a "swimming" formation. The thickness of the track-bed layer should be calculated firstly as regards the bearing strength and secondly as regards sensitivity to frost. The greater of the two calculated values should be chosen. In road construction, frost protective layers at least 40 to 50 cm thick have proven to be reliable under the climatic conditions in Austria even based on normal assumptions for frost penetration depth between 80 and 100 cm. On the Austrian Federal Railways track-bed layers ≥ 40 cm are usually taken for rail-mounted installation of a track-bed layer, which also

Figure 14: Establishing the resiliency modulus Evd using the dynamic falling weight without disrupting progress of work

corresponds to the greatest possible excavating output of 40 to 50 cm maximum of the track machines used. Only on subsoil which is proven to be insensitive to frost, which normally also has favourable bearing strength properties and therefore has few substructure problems overall, is it possible in special cases (e.g. new track construction with installation of a track-bed layer to produce a level formation for draining off the water) to reduce the track-bed layer thickness to 20–30 cm [7].

With regard to the bearing strength of the track, it is necessary to have an optimum coordination of the elasto-plastic behaviour of the individual track-bed layer sections (skeleton track/ballast/track-bed layer). Equivalent to the vertical tension which decreases with the depth, there should also be a layer structure for the loaded overall system skeleton track/ballast/track-bed layer/subsoil with a continuous rise in stiffness towards the skeleton track. Sudden changes should be avoided if possible. Criteria for the progression of the Evd value (mean value from existing earthwork technical regulations) from sleeper base were derived for the load transfer into the subsoil. With the stiffness curve shown in Fig. 15 the threshold values of the shearing resilience in coarse-grained and fine-grained soils are not exceeded.

4.2 Consolidation when track-bed layer is installed

Decisive for the quality and efficiency of a track-bed layer is the type of consolidation, which achieves the optimum compaction to enable a uniform load transmission (grain to grain tension). The major part of consolidating work is concentrated on pressing the grains into their most dense arrangement. The interstitial water should remain evenly distributed and bound on the surface of the supporting grains. The geotextile separating layer has a special task. It serves not only to separate subsoil and track-bed layer material, but also achieves a stabilisation of the grains during consolidation.

This supporting effect enables the input of compacting energy even when the subsoil (earth formation) is soft and of mushy consistency. This "careful" consolidating work using plate consolidators allows the installation of a well compacted and sufficiently stiff track-bed layer on soft subsoil during rail-mounted stabilisation.

The measuring results are shown in Fig. 16 as light blue dots in the lower part of the diagram. Immediately after installation the compacted track-bed layer has a resiliency modulus E_{vd} which is two to five times the value at the earth formation, when the earth formation has E_{vd} values of 5–15 MN/m². At higher E_{vd} values, the percentage increase of the bearing strength will fall.

4.3 Further consolidation under traffic load

Further consolidation of the track-bed layer is performed in two steps: In the first days following installation of the track-bed layer, the track-bed layer will dry-out. This drying-out leads to a consolidation of the dust particles in the contact points and therefore to an increase in the effective surface of load transmission which causes a rise in stiffness.

In the long term, the rearrangement of particles under traffic load also has the effect of an increase in the stiffness modulus.

The result of repeat measurements on the track formation after traffic operations over approx. 2000 days is shown as dark blue dots in the upper part of Fig. 16:

- ▷ 2000 days after installation of a track-bed layer, average E_{vd} values of 45–50 MN/m² on the track-bed layer are obtained
- ▷ it is characteristic that the improvement over time due to traffic load will

increase disproportionately according to the dimensioning for a soft subsoil (E_{vd} < 20 MN/m²).

▷ in sections with E_{vd} values of 5 MN/m₂ resiliency modulus at the earth formation, the originally attained E_{vd} value of approx. 20 MN/m² will be further increased by the traffic load by the factor of 2 to approx. 40 MN/m².

In the ÖBB network the rail-mounted track-bed layer installation with a thickness of 40 cm is normally applied on track with an E_{vd} value >5 MN/m² at the soil formation. For even poorer subsoil conditions it is sometimes necessary (depending upon the geotechnical expertise) to install a conventional track-bed layer with greater track-bed layer thicknesses.

5 Periodical inspection of the track geometry

The periodical inspections of the track geometry quality using the track recording coach document the success of the track-bed layer installation. Some examples as follows:

5.1 Formation rehabilitation near Timelkam in 1997

In 1997 track renewal with formation rehabilitation was performed on Line 2 of the section Timelkam–Redl-Zipf (western main line, km 254,0 – km 258,5; 21 million gross tonnes/year). Installation of a track-bed layer (40 cm) was carried out using the AHM 800 R. Ten years after the new track was laid, the track geometry quality (longitudinal level) is in a very good condition. The track had to be tamped only once (2003). This means that the tamping cycle was extended from the previous approx. 2 years to 7 years. The longitudinal level signal currently shows no prominent single faults or localised greater tendency to change. Since 2002 the track data have been stored in the ÖBB data base ("transparent track") [8]. An initial quality of $\sigma_{vertical}$ = 0.4 mm can be derived from the available measured data (Fig. 17).

5.2 Formation rehabilitation near Hallwang in 2003

In the Hallwang-Elixhausen section after Salzburg-Maria Plain (western main line, km 305,8 – km 309,2; 21 million gross tonnes/year) track renewal with formation rehabilitation was carried out in 2003 (AHM 800 R). For better load distribution, concrete sleepers with under-sleeper pads were installed. Before rehabilitation, the entire section had to be tamped every 1½ years, now the current tamping interval is approx. 10 years. The best illustration of the improvement can be seen in the trend of the standard deviation of the longitudinal level (Fig. 18).

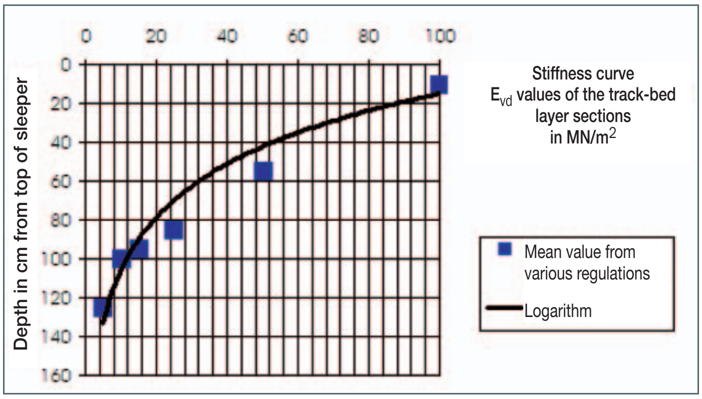

Figure 15: Favourable build-up of stiffness in track-bed layer (mean value from existing earthwork technical regulations)

5.3 Formation rehabilitation near Attnang in 1997

Figure 25 shows a track near Attnang (western main line 245,5 carrying 21 million gross tonnes/year). In 1997 a formation protective layer was installed in the course of track renewal (AHM 800 R). Initially, due to the poor subsoil conditions, there were further settlements in the substructure which had to be compensated by tamping particularly in the first years. But the settlements are decreasing continually. These consolidation processes in the subsoil can be observed well in the deterioration rate of the standard deviation, 10 years after formation rehabilitation (Figure 19) it is still decreasing. A further improvement is to be expected.

5.4 Comparison with conventional installation of track-bed layers

In 2002 track renewal with formation rehabilitation was carried out on both tracks of the section Zell/See – Saalfelden (km 107,7 – 111,7 of the line Zell/See – Wörgl; 8 million gross tons / year). Using an AHM

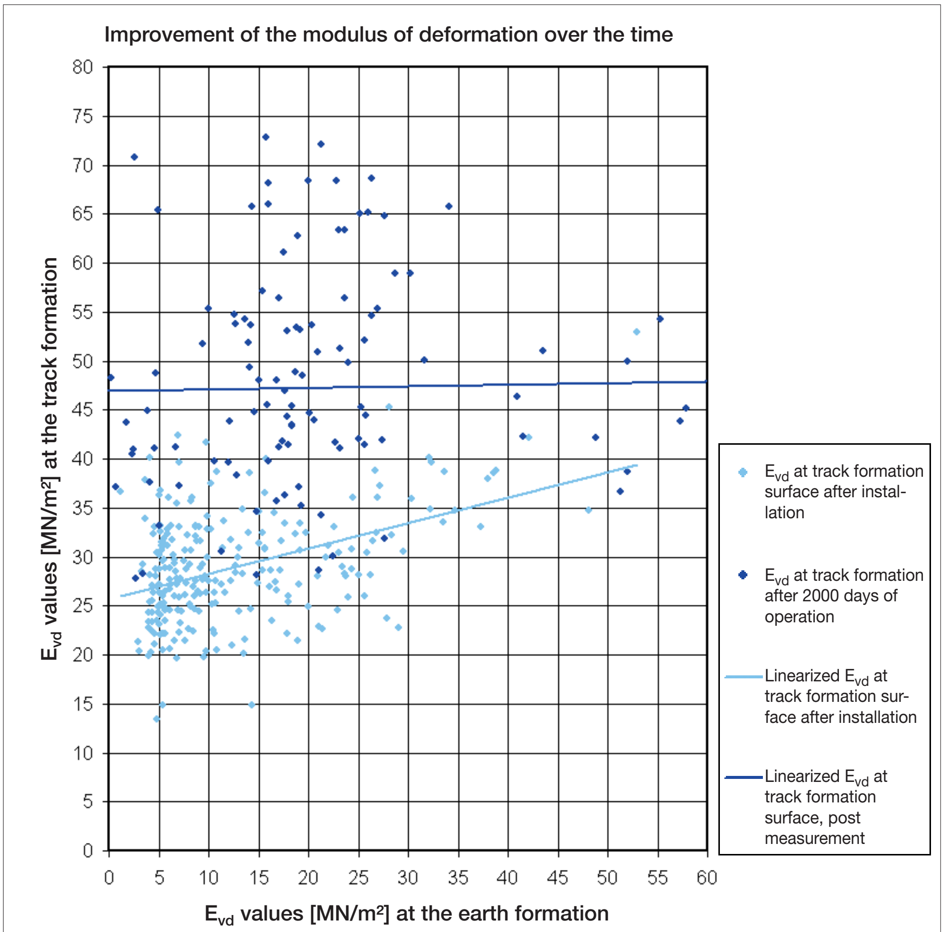

Figure 16: Improvement of the modulus of deformation Evd immediately after installation of the track-bed layer and after 2000 days

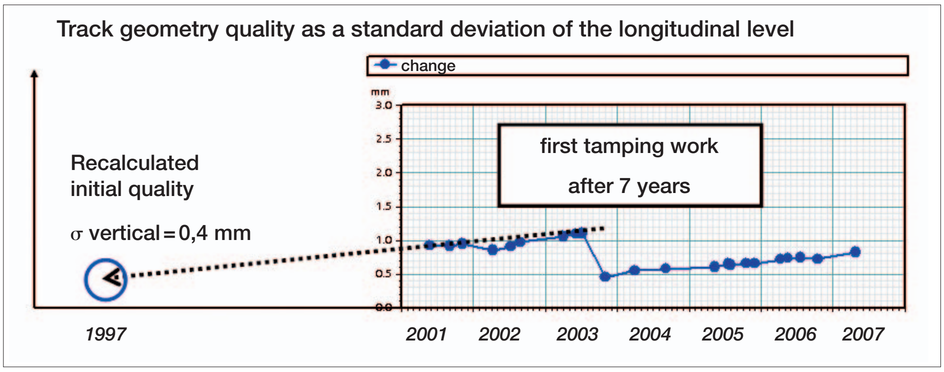

Figure 17: At the time of track renewal the standard deviation of the longitudinal level was approx. $\sigma_{vertical}$ = 0.4 mm

800 R a uniform track-bed layer 40 cm thick was installed on Line 2. In the same year conventional formation rehabilitation was performed on Line 1 with a track-bed layer 70 cm thick. Both tracks are currently displaying approximately the same track geometry quality. Despite the much lower track-bed layer in the AHM 800 R–built section, the rates of deterioration are almost identical (Fig. 20).

6 Summary

In the early 90's the higher physical, operational and commercial requirements placed on the track in the ÖBB network, such as higher traffic loads, the desire to reduce track possessions and the pressure of rising costs for track maintenance, led to the development of the AHM 800 R formation rehabilitation machine. The AHM 800 R can install a track-bed layer with high performance (50 m/h) and high quality compaction, and it can reuse a part of the excavated ballast as formation layer material.

The economic efficiency of substructure improvement in the rail network was investigated by Graz University of Technology. The results of this study were incorporated in the ÖBB's Permanent Way Strategy and have led to an increase in the rail-mounted installation of track-bed layers. Since 1994 substructure improvement work has been carried out on 542 km of track using the AHM 800 R and RPM 2002 formation rehabilitation machines.

The experience gained in the course of 13 years of substructure improvement is as follows:

- ▷ When planning substructure improvement, special attention should be given to the good functioning of the drainage. Stable track geometry can only be achieved on well-supported and adequately drained tracks.
- ▷ The rail-mounted track-bed layer installation method is particularly suitable for improving tracks lying on soft subsoil (fine-grained soils) where the Evd values are in the range of around 5–20 MN/m².
- ▷ The outstanding feature of the rail-mounted method is that it achieves uniform results. A test section shows the same results for a track-bed layer 40 cm thick inserted by the rail-mounted method as for a 70 cm track-bed layer laid using the conventional method.

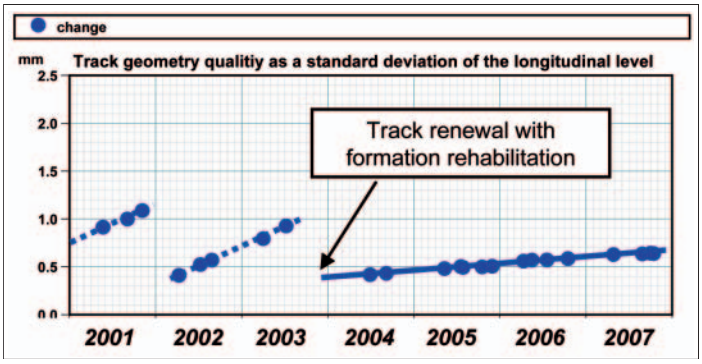

Figure 18: Reduction of the rate of deterioration of the longitudinal level clearly shows the effects of the work

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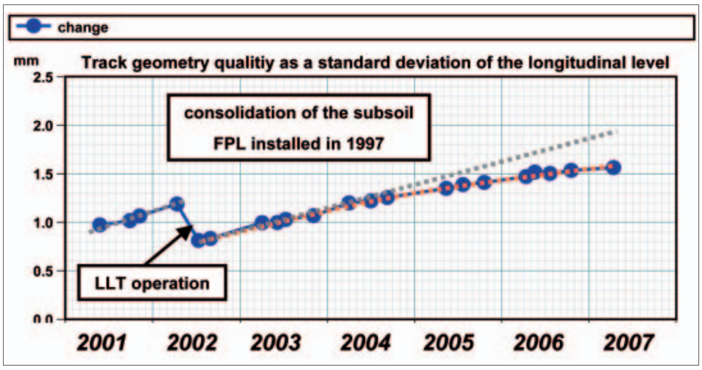

Figure 19: The consolidation process effects a decreasing deterioration of the longitudinal level

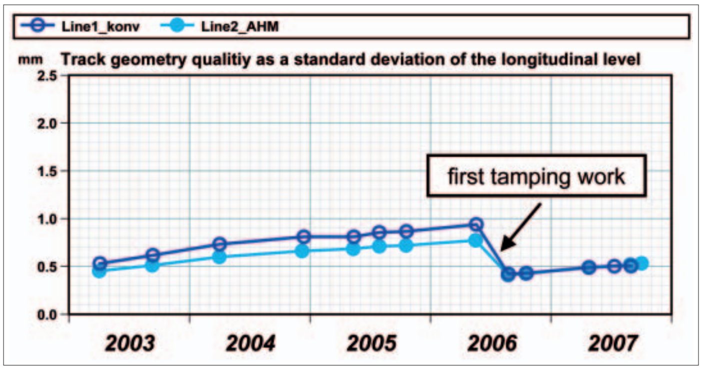

Figure 20: Conventional formation rehabilitation (70 cm) and rail-mounted installation method (40 cm) shows similar behaviour