Improving ballast tamping process

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Under train loading, the ballast particles rearrange and gradually induce an inhomogeneous settlement of the track. Tamping process is applied in order to restore the correct geometrical position of the ballasted track and in order to guarantee the safety and comfort of traffic. During the tamping actions, the penetration of the vibrating tines into the ballast causes a progressive rupture of the edges of the grains that generates smaller particles. On the other side, the traffic wears the ballast particles surfaces, which become rounder and smoother [1]. At long term, this leads to a progressive loss of the elasticity and drainage properties, as the spaces between the particles are filled with these fine particles. The degradation of ballast angularity induces also faster settlements in the future, because the interlocking is less effective as the particles become round. The main consequence is that the interval between two tamping operations decreases during the service life, from one intervention every 5 to 8 years to even twice a year! Hence, ballast degradation occurs both under train running, and geometry restoration [2]. This vicious circle can be broken only by ballast renewal, as the tamping process is neither effective nor economic anymore. It has been estimated that the maintenance of the ballast and geometry represents 40 to 50% of the total railway maintenance budget during a track’s service life.

These motivations lead to a PhD research at the Swiss Federal Institute of Technology in Lausanne. The aim is a better understanding of ballast degradation during traffic and tamping, in order to decrease the degradation of ballast during its lifetime by improving the ballast process.

The research is organized in two parts: real scale laboratory tests and finite elements 2D and 3D simulation. This paper will treat only about the experimentation. More details can be found in [3].

Measuring the ballast performances in situ

The first objective of the research is to find a measure of the ballast performances, in order to track their evolution along the service life. The purpose is to measure the ballast mechanical properties under the sleeper, where the stresses due to traffic loading and tamping action are concentrated. However, the properties of the ballast in situ, and especially in depth are very difficult to be measured. Most of the mechanical parameters can only be measured in laboratory after the extraction of a sample.

The selected approach consists on calculating the ballast stiffness after applying a force and measuring the displacement of ballast with a plate load test. This trial is usually performed on foundations, in order to determine the supporting strength, by applying two loading cycles and one discharge cycle, according to the Swiss standard SN for ground and infrastructure [4]. During the test, the bearing capacity modules, Ev1 and Ev2, related to the two loading cycles, are calculated. Ev1 is related to the density of ballast in place and its very short time behaviour, while Ev2 is more correlated to the mid-long term behaviour. The ratio between the two modules Ev2/Ev1 represents the instability of the bearing capacity. If the ballast capacity is constant with time, the ratio tends to 1, i.e. the minimum value for the granular materials.

In order to perform this measurement in the zone of tamping (i.e. applying the load directly on the ballast under the sleepers), a special device has been developed in laboratory to make possible the test in these specific conditions. The tested sleepers have been have been pierced in order to insert a rod, which transmits the load to the plate below.
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In order to measure the displacements of the plate, an LVDT displacement sensor is fixed to an independently supported beam. The evolution of the ballast behaviour is assessed by plate load test before and after each and tamping operations. This measurement is very interesting, because it makes possible to follow the mechanical state of ballast in the zone of the track where it's the most loaded, during its service life, and in the real stress state.

Real scale simulation of tamping and traffic

A full-scale railway infrastructure, of 19m long and 2m proof has been realised in the laboratory hall, especially for this research. The track is composed of UIC60 rails, elastic fastenings and concrete sleepers. Two types of subgrade have been constructed: one stiff and one soft. The two types of subgrades are wholly separated by a wall (see figure 3, in blue). In order to prevent the boundaries effect, the measurements are taken at least 2 m away from the separation wall as well as from the border walls. The 19m track has been divided equally into 6 test sections.

The simulation of tamping action and dynamic traffic loading are performed on this installation. The tamping process is simulated with a small sized machine, equipped with a high performance tamping unit which reproduces the real sequence of actions on the tracks. For this study, all the parameters can be controlled manually within the available intervals. The whole process and the equipment are completely instrumented in order to control and measure the evolution of all the tamping parameters in real time.

The traffic simulation at real scale is performed with a dynamic hydraulic actuator. A 22.5 tons load is applied on the track for 7 million cycles (equal to 157 million TBC) at a frequency of 4 Hz, representative of freight trains. The settlements during the traffic simulation are measured continuously in the ballast and in the infrastructure layers at different depths. The settlement speeds of each layer are then calculated and compared between each traffic series. After each tamping and each traffic series, a plate load test is performed too, in order to follow the evolution of the mechanical state of ballast.
Results and validation

The first test series concerns the tamping parameters (principally frequency and depth), in order to evaluate the impact on ballast quality and geometry stability. Four different frequencies have been tested within the range of ballast “viscous” behaviour (between 35 and 45 Hz). This range of values is considered as optimal for the geometry correction, according to [5] and [6]; therefore the tested frequencies are chosen within this frequency range. The tamping tests are performed on similar sections with the same infrastructure and new ballast. Plate load tests are done before and after tamping, and compared. The results show that, within the “viscous” behaviour range, higher frequencies give higher bearing modulus and a lower instability (ratio Ev2/Ev1 30% lower). This result is justified by the fact that the penetration and squeezing movement of the tamping tines into the ballast are faster and easier than at lower frequencies.

The effect of the tamping depth has also been tested, together with track lifting (which corresponds to the geometry correction, plus a margin). These two parameters have been combined because they define together the amount of ballast which is handled during the tamping process, as well as the available volume/space under the sleeper. Four combinations depth-lift have been defined and performed twice on similar sections with the same ballast conditions. A lower depth of 6 cm has been tested and compared to a normal 2 cm deep tamping. The plate load tests show that, independently from the track lifting, a lower tamping depth makes the bearing modulus more stable with time (the instability ratio Ev2/Ev1 is lower), see next figure:
This result means that handling a bigger number of ballast particles gives a more efficient and stable-with-time tamping, no matter which is the geometry correction to be applied during maintenance.

In order to validate these results, the normal tamping and the deeper tamping have been performed on two different sections under traffic simulation, and compared. The first section has a stiff subgrade under the ballast layer, while the other section presents a soft subgrade layer. On both sections 157 million tons of freight traffic are simulated with a dynamic hydraulic jack. Every 45 million tons of traffic, a tamping is performed. Before and after the traffic series and tamping, a plate load test is performed in order to follow the ballast mechanical properties during the whole simulated period (correspondent to 10 to 20 years, in relation to the traffic density). The next table shows the characteristics of the two sections and the performed tests.

Table 1: The two compared sections and their characteristics

<table>
<thead>
<tr>
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<th>Stiff subgrade (E=170 MPa)</th>
<th>Soft subgrade (E=20 MPa)</th>
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<tbody>
<tr>
<td>Traffic</td>
<td>157 million tons (7 million cycles)</td>
<td>157 million tons (7 million cycles)</td>
</tr>
<tr>
<td>Tamping</td>
<td>normal (2 cm under the sleeper)</td>
<td>deep (6 cm under the sleeper)</td>
</tr>
<tr>
<td></td>
<td>6 plate load tests performed</td>
<td>6 plate load tests performed</td>
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The results of the plate load tests are shown in the next graphics. The yellow bars represent the values measured after tamping, while the grey bars refer to the measures after traffic (before tamping). The instability ratio Ev2/Ev1 obviously changes with traffic and tamping, and is normally higher after tamping. However, deep tamping shows a more homogeneous ratio over time, with lower values (graphic on the right). This means that the bearing modulus is more stable over time, and especially at a short term, during the first traffic cycles. The effectiveness of deep tamping are confirmed and validated.
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Figure 5: The ratio $E_{v2}/E_{v1}$ measured after 3 series of traffic and tamping (normal on the left and deep on the right)

These results have been also confirmed by the global settlements measured in the ballast layer and within the infrastructure layer, along with the traffic simulation. After 157 million tons simulated, the measured cumulated settlements of the whole infrastructure were similar in the two sections.

If we see the next figures, we can notice that the settlement of the soft infrastructure is 1.4 mm against 0.6 mm for the stiff infrastructure. The dark lines in figure 6 show the vertical settlements measured from the ballast base. This result shows once more the importance of the infrastructure stiffness. If a too soft infrastructure settles, the geometry correction, which is performed on the ballast layer, has no effect on the cause of the problem.

Figure 6: Settlements of the ballast and the infrastructure layers in the two sections after 157 MTBC: on the left stiff infrastructure, and normal tamping; on the right soft infrastructure and deep tamping.

However, the ballast layer’s settlement after traffic and deeper tamping is just a half of the one measured in the section submitted to normal tamping (1.7mm against 3mm). While the settlement of the stiff infrastructure represents 2.5% of the total settlement of the track, the settlement of the soft infrastructure represents 9.5% of the total. This means that the ballast layer on the soft infrastructure settled less! This result confirms once more that the deeper tamping keeps geometry more stable and the consequent ballast settlements are reduced, even on a softer infrastructure.

Conclusions and perspectives

This PhD research has verified the link between the plate load test bearing ratio and the ballast settlements at the long-term. The plate load test has been performed on the ballast under the sleepers, where the stresses induced by tamping and traffic are the highest. In practice, it's not
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possible to perforate the sleepers in situ, so it's necessary to adapt the test in order to apply the charges directly. Two possibilities can be studied: either the charges are applied on the rails and the stiffness of the rails, pads and sleepers are separated while calculating the result, or, eventually the charges are applied on the ballast between the sleepers.

The laboratory real-scale simulation has made possible to analyse separately the long-term effects of traffic loading and track tamping on ballast degradation and its consequent behaviour. The knowledge of the exact causes of ballast degradation permits to apply a maintenance strategy which increases the ballast lifetime and the effectiveness of tamping operations. The results show that a 6 cm-deep tamping, combined with a frequency on the higher side of the viscous range, permits to increase the ballast performances. Not only a higher short-term stiffness than 2 cm-deep tamping is achieved, but also the stiffness remains stable with time and under traffic.

The improvement of the ballast compaction increases the durability of the track geometry and lets more traffic circulate between two tamping operations. The main consequences are an important reduction of the maintenance operation frequency and of the maintenance costs for the railway companies. Less tamping operations mean a longer ballast lifetime and reduced track possessions As ballast and geometry represent up to 50% of the global maintenance costs of the track, it's easy to imagine the important impact on the Life Cycle Costs of the railway track.