Evaluating the stability of existing earth structures taking the upgraded Hamburg–Berlin line as an example

Given the plans to increase the maximum speed on the Hamburg–Berlin line from 160 to 230 km/h, it was necessary to carry out a survey of all existing earth structures, (embankments, culverts and support structures). Track-dynamic and finite-element calculations were carried out to assess the impact of this increase in speeds on the stability and suitability for use of the earth structures. Based on these, the earth structures were then placed in the categories of “critical” or "uncritical" and recommendations drawn up for engineering measures, where appropriate.

1 The task in hand

In the course of engineering work which was completed in December 2004, the main railway line between Hamburg and Berlin was upgraded for a maximum service speed of 230 km/h, whereas beforehand the top speed for passenger trains had been 160 km/h. Such a change brings with it tougher requirements affecting the whole of the system comprised of the permanent way’s superstructure and substructure, the foundation soil beneath it and each of its individual components. For a railway line already in existence, such an increase in speeds might occasion a greater outlay on maintenance and might also necessitate certain engineering measures. It is particularly the older earth structures underlying the line that need to be appraised to establish whether the existing substance is going to be adequate to handle the more intense demands.

At Deutsche Bahn (DB AG), a set of rules known as “RIL 836” are applicable to earth structures. Module 836.0401 within those rules deals with appraising the effects of loads in existing earth structures, which are in service, have not suffered any damage and are maintained in accordance with Module 836.0900. Paragraph 4 of 836.0401 contains two important provisions:

▷ "If the future loads are no higher than those to date, it is permissible to assume that the earth structure is sufficiently stable and serviceable"; and
▷ "If the future loads are to be higher, surveys must be performed by an eminent expert in geotechnics to establish the changes in the load situation and the effects they will have on the structure. In so doing, it is possible to accept lower stability coefficients than would be applicable for a newly built line."

At all events, increasing the speed of passenger trains represents both a quasi-static and a dynamic change in the load pattern and may also represent an overall increase in loads.

2 The chosen solution

The purpose of establishing the impacts of increasing the maximum line speed from 160 to 230 km/h was to compare and assess the effects for the current and future state as regards the stability of the structures.

The EBA (the German Federal Railway Authority) thus decreed that, in accordance with RIL 836, during phase 2 of the upgrading work on the Hamburg–Berlin line each earth structure would have to be examined by an expert in geotechnics to establish what effects this increase in speed would have on its stability.

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ICE-T at 230 km/h, working on the upgraded line Hamburg–Berlin
earth structures and their ability to withstand loads. The chosen solution was as follows:

▷ systematic recording of effects,
▷ investigations into loads and ability to withstand them – i.e. performing track-dynamic calculations and building on them to carry out finite-element computations,
▷ comparison and weighting of the results and presentation of the consequences of increasing the speed of passenger trains from 160 to 230 km/h,
▷ drawing up of appraisal algorithms for assigning the earth structures to various categories,
▷ evaluation of the existing data regarding openings, embankments and support structures,
▷ placing each earth structure in a category as a function of effects,
▷ distinguishing between uncritical and critical earth structures,
▷ appraising the stability of the critical earth structures, and
▷ preparation of recommendations.

3 Systematic recording of effects

The following critical theoretical and characteristic load spectra were taken to represent the reference state:

▷ the UIC 71 load model as the basis for the evaluation in accordance with RIL 836 (Fig. 1),
▷ axle-load diagram for a “class D4” railway line reflecting the heavy freight trains permitted on the line beforehand with a top speed of 90 km/h (Fig. 2), and
▷ the operational load diagram for an ICE-T train set operating fast passenger services as permitted on the line beforehand with a top speed of 160 km/h (Fig. 3).

The characteristic load diagram for the future maximum line speed of 230 km/h was taken to be the high-speed train as detailed in the Technical Specification for Interoperability (TSI) (Fig. 4).

4 Investigations into loads and the ability to withstand them

Computations using track dynamics and finite elements were used to investigate whether or not future high-speed traffic at 230 km/h would cause a greater stress than the decisive load heretofore.

Time and frequency-dependent loads were simulated for both ideally round and out-of-round wheels. The out-of-roundness (OOR) values were worked out on the basis of the results of a statistic appraisal of long-term measurements of the ballast pressure caused by more than 100000 axle passes with ICE wheels. This also included giving proper consideration to the different elasticity values of the various rail pads:

▷ the Zw 687a rail pad in combination with the load diagrams of the “class D4” route, the ICE-T and the TSI high-speed train, and
▷ the elastic Zw 700 rail pad in combination with the load diagram of the TSI high-speed train.

For appraising the earth structures it is interesting to consider not only the direct load through the main sleeper but also simultaneous loads through adjacent sleepers. For the purpose of computations, the working assumption was that three sleepers are involved in taking up the load.

Track-dynamic computations

Track-dynamic computations were performed for each of the following situations:

▷ for embankment situations (representative for soil bodies and support structures), and
▷ for rigid and semi-flexible opening situations with various cover heights above them.

The track-dynamic calculations supplied insights into:
by considering Figs. 5 and 6 together:

- the maximum forces acting on the rail’s support point,
- the sleeper’s maximum elastic settlement,
- the maximum oscillation velocities in the plane of the sleeper’s lower edge, and
- the time-dependent vertical stress in the plane of the sleeper’s lower edge.

Figure 5 contains an example of the surface pressures for the embankment situation calculated at the height of the sleeper’s lower surface in the form of the total load on the main sleeper and the adjacent sleeper. Figure 6 shows those surface pressures that result from the additional dynamic excitation caused by wheels with a mean out-of-roundness.

The following interrelationships are derived by considering Figs. 5 and 6 together:

- The total load for the sum of the surface pressure acting through the main sleeper and the adjacent sleepers for the high-speed train defined in the TSI running at 230 km/h is higher than for the ICE-T at 160 km/h but lower than for the “D4” load diagram at 90 km/h.
- The Zw 700 rail pad reduces the load considerably compared with the Zw 687a model. Firstly, the softer pad produces a more pronounced bending curve and thus around 12% of the load is transferred from the main sleeper to the adjacent sleepers. Secondly, the additional dynamic component affecting the main sleeper is reduced by approximately 33%. This more than compensates for the extra loading caused by the TSI train.

Finite-element computations

Whereas the track-dynamic computations showed the load situation in the vicinity of the track, finite-element computations brought out the propagation of stresses and the oscillation velocities in the substructure and subsoil in a manner that came very close to reality. The three principal findings concerned:

- maximum vertical stresses on the subgrade,
- maximum section forces and deformations in culverts, and
- maximum oscillation velocities at various depths.

A precondition for reliable results was to capture the geometric and physical boundary conditions in a manner that was as close to reality as possible. PLAXIS was the finite-element program used to establish the complex interrelationships between the different subgrade rigidities in soil bodies and openings as well as the complex interrelationships between the time-dependent loads and thus the frequency-dependent loads too. PLAXIS is a finite-element program that was developed especially for analyses in the field of soil and rock mechanics. It offers the possibility of carrying out dynamic computations on a flat or axially symmetric model – i.e. of simulating time-dependent loads.

Figure 7 shows the finite-element results for the embankment situation as equivalent surface loads on the top edge of the subgrade. The following three distributions were worked out transversely for the width of 2.60 m selected for the finite-element model:

- the static component,
- the dynamic component, and
- the total load.

Fig. 7: The embankment situation showing equivalent surface pressures at the top edge of the subgrade over a distribution width of 2.60 m due to wheels with a mean out-of-roundness

Fig. 8: The embankment situation showing the effective oscillation velocities for passing trains whose wheels have a mean out-of-roundness as a function of the load diagram and depth below the top edge of the sleeper.
The additional dynamic excitation was set as that caused by wheels with a mean out-of-roundness. In order to assess the dynamic behaviour, the effective oscillation velocity was input after it had maintained its value for a time window of 0.125 s. According to Rump et al. [2], this effective oscillation velocity is between a half and a third of the maximum oscillation velocity. Figure 8 shows the effective oscillation velocity for passing trains with mean out-of-round wheels as a function of the load diagram and the depth beneath the top edge of the sleeper for uncritical subsoil conditions. The following conclusions can be drawn from Fig. 8:

- Increasing train speeds to 230 km/h leads to higher effective oscillation velocities at greater depths too. The effective oscillation velocity is 10-20% higher when the elastic Zw 700 rail pad is used;
- the elastic Zw 700 rail pad causes a reduction in the effective oscillation velocity of around 15% at the height of the bottom edge of the sleeper compared with the Zw 687a rail pad or around 5% at a depth of 2.0 m below the top edge of the sleeper.

The finite-element computations for rigid culvert were used to simulate all duets that are appreciably more rigid than the soil surrounding them (such as culvert in the form of concrete pipes, slabs, frames and arches). For rigid pipe duets, no horizontal soil-reaction stresses were mobilized (or only negligible ones). So the external forces from the soil’s own mass and the loads from moving trains are carried away solely through uniaxial bending and the longitudinal force (Fig. 9). The vertical deformation in the pipe caused by the load of a passing train is less than the settlement in the soil surrounding it when subjected to the same load. This results in a load concentration above the top centre of the pipe. The structure taken as representative of rigid openings was a DN 800 concrete pipe with the following material properties:

- external diameter: = 1040 mm
- internal diameter: = 800 mm
- specific gravity (\(\gamma\)) : = 25 kN/m³
- modulus of elasticity (\(E_{\text{Concrete}}\)) = 30000 N/mm²
- Poisson’s ratio (\(\nu\)) : = 0.20

The decisive parameter for assessing the stability of rigid culvert was the maximum tensile force on the inside of the pipe’s cross-section at its highest point. Figure 10 shows the maximum tensile forces in the pipe’s cross-section as a function of the load diagram and the height of the cover (\(h_c\)) for train wheels with a mean out-of-roundness.

The static behaviour for culverts in the form of steel and plastic pipes was assessed through the calculations for semi-flexible culverts. The vertical load causes vertical deformations at both the top and bottom of such culverts. At the same time the pipe undergoes outwards deformation at its abutment, which activates horizontal soil-reaction stresses. The amount of vertical deformation in the pipe caused by a passing train is roughly the same as the settlement in the soil next to the pipe when subjected to the same load. In this case, there is no really appreciable load concentration above the top centre of the pipe (Fig. 9). The structure taken as representative of semi-flexible openings was a DN 1000 steel pipe with the following material properties:

- external diameter: = 1030 mm
- internal diameter: = 1000 mm
- specific gravity (\(\gamma\)) : = 77.0 kN/m³
- modulus of elasticity (\(E_{\text{Steel}}\)) = 210000 N/mm³
- Poisson’s ratio (\(\nu\)) : = 0.20

The static behaviour for semi-flexible culverts was assessed through the calculations for semi-flexible culverts. The vertical load causes vertical deformations at both the top and bottom of such culverts. At the same time the pipe undergoes outwards deformation at its abutment, which activates horizontal soil-reaction stresses. The amount of vertical deformation in the pipe caused by a passing train is roughly the same as the settlement in the soil next to the pipe when subjected to the same load. In this case, there is no really appreciable load concentration above the top centre of the pipe (Fig. 9). The structure taken as representative of semi-flexible openings was a DN 1000 steel pipe with the following material properties:

- external diameter: = 1030 mm
- internal diameter: = 1000 mm
- specific gravity (\(\gamma\)) : = 77.0 kN/m³
- modulus of elasticity (\(E_{\text{Steel}}\)) = 210000 N/mm³
- Poisson’s ratio (\(\nu\)) : = 0.20
Table 1: Categorization of openings as regards suitability for increasing train speeds from 160 to 230 km/h

<table>
<thead>
<tr>
<th>Category</th>
<th>Cover (h_c)</th>
<th>State of repair</th>
<th>Effects/required measures</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>h_c &gt; 1.0 m and h_c &gt; 0.50 m + d_a</td>
<td>A</td>
<td>None /None</td>
<td>V_{eff} &lt; ≈ V_{guideline} Very good to good repair and with adequate cover</td>
</tr>
<tr>
<td>II</td>
<td>0.60 m &lt; h_c &lt; 1.00 m or 0.60 m &lt; h_c &lt; 1.00 + d_a</td>
<td>A</td>
<td>Minor/ Additional expert surveys</td>
<td>V_{eff} &lt; ≈ 1.3 · V_{guideline} Very good to good repair but with little cover</td>
</tr>
<tr>
<td>III</td>
<td>h_c &gt; 4.50 m</td>
<td>C</td>
<td></td>
<td>V_{eff} &lt; ≈ V_{guideline} Critical state of repair but with good cover</td>
</tr>
<tr>
<td>IV</td>
<td>h_c &lt; 0.60 m</td>
<td>A, B</td>
<td>Present/ Special expert survey to be obtained at once</td>
<td>V_{eff} &gt; V_{guideline} Very good to good repair, but with little cover</td>
</tr>
<tr>
<td></td>
<td>1.50 m &lt; h_c &lt; 4.50 m</td>
<td>C</td>
<td></td>
<td>V_{eff} &gt; V_{guideline} Critical state of repair with moderate cover</td>
</tr>
<tr>
<td></td>
<td>h_c &gt; 4.50 m</td>
<td>D</td>
<td></td>
<td>Very critical state of repair</td>
</tr>
<tr>
<td></td>
<td>h_c &lt; 1.50 m</td>
<td>C</td>
<td>Marked / Special expert survey to be obtained at once</td>
<td>V_{eff} &gt;&gt; V_{guideline} Critical state of repair and with little cover</td>
</tr>
<tr>
<td></td>
<td>h_c &lt; 4.50 m</td>
<td>D</td>
<td></td>
<td>Very critical state of repair</td>
</tr>
</tbody>
</table>

The decisive parameter for assessing the stability of semi-flexible or steel-pipe culverts was the maximum compressive force acting on the inside of the pipe cross-section at its abutment. Figure 11 shows the maximum compressive force in the cross-section of the pipe as a function of the load diagram and the height of cover (h_c), again for train wheels with a mean out-of-roundness.

Interpreting Figs. 10 and 11 together reveals that:

- the section forces resulting from the load diagram for a “class D4” railway line with a train speed of 90 km/h are noticeably greater than for the lighter weight-high-speed trains; and
- the resulting section forces in the rigid culvert are reduced where use is made of the elastic Zw 700 rail pad, as is clear from the more pronounced shape of the bending curve.

5 Conclusions and the drawing up of appraisal algorithms

Soil bodies

The soil bodies that must be checked for stability under the influence of railway traffic are embankments and the valley sides of track beds cut into hillsides.

The 10-20 % increase in oscillation velocity resulting from the higher train speed can be seen as tolerable for nearly the whole of the embanked parts of the route, where the embankments are close to a state of normality and provided the soil conditions are not critical. This conclusion is based on the finding that increased train speeds do not cause an increase in the quasi-static load affecting the earth structures compared with the “D4” load diagram.

For soil bodies resting on critical substrata (such as loosely packed sand that may react sensitively to any translocation or soft underground strata with only a thin cover or a water table only just below the surface), it is possible that excessively large oscillation displacements, velocities and/or accelerations could cause significant effects.

Table 2: Categorization of support as regards suitability for increasing train speeds from 160 to 230 km/h

<table>
<thead>
<tr>
<th>Category</th>
<th>Construction year</th>
<th>Effects/Necessary measures</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1983 and later</td>
<td>None /None</td>
<td>Support structure computed in accordance with RIL 836 or DS 836</td>
</tr>
<tr>
<td>II</td>
<td>1982 and earlier</td>
<td>Evident /Special expert survey to be obtained at once</td>
<td>Support structure not computed in accordance with RIL 836 or DS 836</td>
</tr>
</tbody>
</table>

The assessment made for the soil bodies was a linear one, not related to any specific object. The following information about the railway line was used for assessing its suitability for use and its stability for both the existing use situation and the planned future one:

- high elastic deformations, and/or
- high plastic deformations.

In the final analysis, these could affect the track’s suitability for use (positional quality, more intense maintenance of the superstructure and substructure) and consequently its stability.

Increasing train speeds to 230 km/h, however, bring about an increase in the dynamic loads acting on the earth structures, since the faster speeds induce oscillation velocities that are 10-20 % higher and excitation occurs at higher frequencies.

The results of the comparative computations

Comparative computations have shown that increasing train speeds to 230 km/h does not cause any increase in the quasi-static loads acting on the earth structures, given that both the ICE-T with its 14-tonne axle load and the TSI high-speed train with its 18-tonne axle load do not lead to any increase compared with the load diagram for “class D4” railway lines in:

- vertical stresses in the plane of the top edge of the subgrade,
- maximum section forces in the cross-sections of culverts, and
- elastic settlement.

Increasing train speeds to 230 km/h, however, bring about an increase in the dynamic loads acting on the earth structures, since the faster speeds induce oscillation velocities that are 10-20 % higher and excitation occurs at higher frequencies.
Evaluating the stability of existing earth structures

route-layout parameters, and
inhomogeneities, such as old and condemned level crossings, bridge backfills and openings with very little cover.

This information was used as the basis for extracting critical conditions. After that, engineering recommendations were drawn up and coordinated with one another.

Culverts

Generally, culverts can be reckoned to be less sensitive to oscillations. When they are subjected to a permanent load, as is the case with rail traffic, oscillation velocities of less than 6.0 mm/s can be taken as uncritical. This figure of “6 mm/s” should be taken as no more than a guideline, since it is possible for it to be exceeded by up to 30 % (for instance by an extremely eccentric wheel) without any immediate damage being caused. For that reason, culverts are rated as uncritical if they are in very good repair and have an adequate cover.

If structures show signs of dilapidation or damage, such as cracked concrete or masonry, so that they would have to be placed in damage class “D” according to the terms of Module 836.0900, they are not suitable for an increase in speed and ought generally to be surveyed by an expert and, where necessary, remediation work ought to be carried out.

Remediation work is also called for on culverts suffering dilapidation or damage that would place them in damage class “C” according to RIL 836.0900 where the height of cover is less than 1.50 m. For culverts in this group, the guideline value for an oscillation velocity of less than 3.0 mm/s would be exceeded by more than 100 %. The culverts were assigned to categories (Table 1) on the basis of the interrelationships discussed above and also considering:

- the year of their construction/remediation,
- the increase or change in load,
- design details such as type and height of cover, and
- state of repair.

Support structures

Those support structures that must be checked for stability under the influence of rail traffic are those that are located below the traffic load. Those earth structures that can be computed to be in good repair using the methodology of RIL 836 can be considered as uncritical if the support structure is at least 2.50 m away from the sleeper for an increase of 10-20 % in oscillation velocity resulting from higher train speeds, since at this distance the effective oscillation velocities are less than 5.0 mm/s. In curves, centrifugal forces cause an additional horizontal load. Once again, however, these are lower than those caused by the UIC 71 load model for a speed of 160 km/h. For those support structures that were calculated in accordance with RIL 836, it was thus assumed that they possessed adequate stability for a speed increase to 230 km/h. Actually, very few of the support structures had not been calculated in accordance with RIL 836, and so the simple solution was to consider each of them individually.

Literature