Geosynthetics - 7th ICG - Delmas, Gourc & Girard (eds) © 2002 Swets & Zeitlinger, Lisse ISBN 90 5809 523 1

Geosynthetics in dynamically stressed earth structures of railway lines

K. LIEBERENZ, Prof. DSc., GEPRO Ing.gesellschaft mbH, Germany
U. WEISEMANN, DSc., GEPRO Ing.gesellschaft mbH, Germany

ABSTRACT: Since the beginning of the 1970s geosynthetics have been increasingly used in railway substructures and in earth structures of railways. At first they were elements of drainages and of protection layers of railways with filtering and separating functions. Later geosynthetics were developed to protect, reinforce and seal the track formation. It is necessary to research the stresses and the behavior of embankments and geosynthetics under dynamic loads. Geosynthetics with reinforcing functions are an important static and constructive part within the whole reinforced earth building. That's why both their continuous stability and the interface between geosynthetic and soil are very essential. In connection with the reconstruction of railways there are two interesting areas of application: supporting structures and/or steep slopes of geosynthetic-reinforced soil, e.g. for the extension of embankments and geosynthetic-reinforced supporting layers above pile-like supporting elements, e.g. for embankment foundations on soft layers in the subsoil. With the help of 2 examples these two areas of application are explained. This paper contents the quasi-static and the dynamic assumed loads of calculation, details about the construction phases, the experiences during the railway operation and the results of measurements.

1 INTRODUCTION

Geosynthetics have been increasingly used in railway substructures and in earth structures along railway lines since the beginning of the 1970s. While, at the beginning, they were mainly designed as separating and filtering elements in drainage systems and for protection layers, they were later used as protective, sealing and reinforcing elements.

Specific conditions in railroad systems consist in

- static and dynamic loads from railroad operation, with dynamic stresses much higher than on roads due to the unsprung mass between the wheels and the rail,
- the high influence of water, since the ballast superstructure, contrary to road structures, constitutes an upwardly open system with direct infiltration of surface water,
- an always possible contact between the ballast material and the geosynthetic materials during maintenance work and
- the high safety requirements of the railway operator with regard to the reliability of systems with geosynthetics, because restrictions in performance capability and any necessary repair work would considerably affect railroad operation.

More research is still required with regard to the dynamic stresses and their effects on structures as well as the geosynthetics and their functioning.

As reinforcing elements, geosynthetics are included in the earth structure as static and constructional elements, and interaction with the soil and long-time durability are of specific importance. Two areas of application are particularly interesting with regard to the modernisation of railway lines. These are:

- supporting structures or steep slopes of geosynthetic-reinforced soil, e.g. for embankment broadening and
- geosynthetic-reinforced supporting layers above pile-like supporting elements, e.g. for embankment foundations on soft layers in the subsoil.

2 DYNAMIC STRESSES RESULTING FROM RAILROAD OPERATION

When rail-bound vehicles move along the track, stresses are caused consisting of static and dynamic components.

The vibrations caused by the interaction of vehicle and track are considered in different frequency ranges. Fig. 1 shows these frequency ranges depending on the travel speed and typical distances.

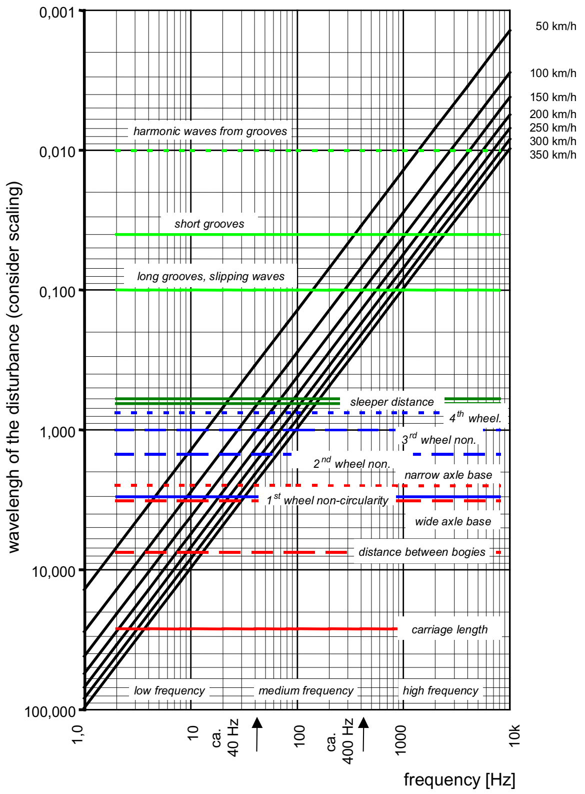


Figure 1Typical frequency ranges (MÜLLER-BORUTTAU & BREITSAMTER (2000))

The following lengths and frequency ranges are to be considered for the vehicle:

Table 1 Decisive distances and frequency ranges for the vehicle

Excitation	Decisive size (length) and frequency range
Carriage distance	Passenger car: 26.4 m
Bogie distance	7.4 m
Axle bases	Passenger car: 2.5 m ICE driving unit
Wheel non-circularities (1st and higher), wheel flats	Wheel diameter = 0.8 m to 1.2 m
Vehicle movements (galloping, rocking or tail motion	< 10 Hz (mostly low amplitudes)
Perpendicular bending vibrations of the stressed wheel sets	45 Hz to 90 Hz
Perpendicular heaves of the wheel sets on elastic tracks	45 Hz to 90 Hz (frequency-determining: unsprung wheel set unsprung wheel set weight and track stiffness

The following decisive lengths and frequency ranges are to be taken into account for the track:

Table 2 Decisive distances and frequency ranges for the travel path

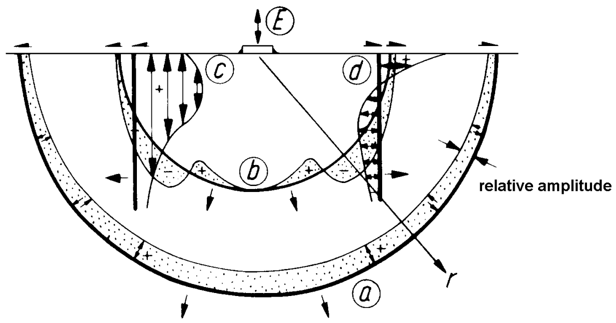
Excitation	Decisive size (length) and frequency range
Hollow positions of sleepers, welded joints and straps	Pulse-type excitation (axle base frequency
corrugations on rails	< 8 cm
Sleeper distance	50…60 cm

Low-frequency excitations (0 – 40 Hz) are thus the carriage distance, the bogie distance, the axle bases, vehicle movements, hollow positions of sleepers, welded joints and fish-joints.

Medium-frequency excitations (40 – 400 Hz) and high-frequency excitations (> 400 Hz) are wheel non-circularities such as wheel flats, perpendicular bending vibrations of the stressed wheelsets, perpendicular heaves of the wheelsets on elastic tracks, corrugations on rails and the sleeper distance (cf. Fig. 1).

These vibrations generated when vehicles drive on the rails basically spread

– in the permanent way, the subgrade and the subsoil
  – with compression waves as well as
  – with shear waves and
– on the ground surface with Rayleigh waves.



Displacement field of shaft types in the halfspace for v=0.25
E exciting circular foundation
a compression wave
b shear wave
c Rayleigh wave, vertical component
d Rayleigh wave, horizontal component

Figure 2 Spreading of compression, shear and Rayleigh waves in the isotropic half-space (KLEIN (1990))

Shear waves are considerably more energy-intensive than compression waves. They have an unfavourable stress effect on soil structures.

Rail-dynamic calculations can be used to calculate the dynamic stresses of the subgrade depending on

– the properties of the subgrade and the permanent way,
– the vehicle properties and
– the speed of the vehicles

for the relevant dynamic excitations shown in Tables 1 and 2. Wheel non-circularities are dominant for the subgrade and subsoil stresses.

The results of a rail-dynamic calculation are

– shown in Figure 3 for dynamic pressures on subgrade upper edge for ideal wheel treads (dotted line) and for non-circular wheels (continuous line) and
– in Figure 4 using the third spectra of the effective pressure on subgrade upper level for the drive of an ICT train with two different speeds (v = 160 km/h and v = 230 km/h).

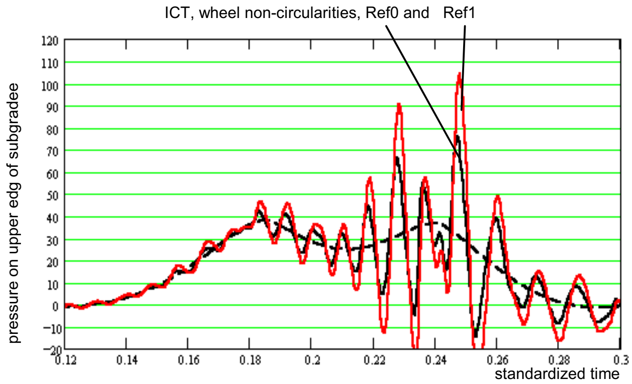


Figure 3 Variation in time of pressures on subgrade top edge for ideal wheels (dotted line) and for non-circular wheels (continuous line) for v = 160 km/h and v = 230 km/h, passage of ICT train

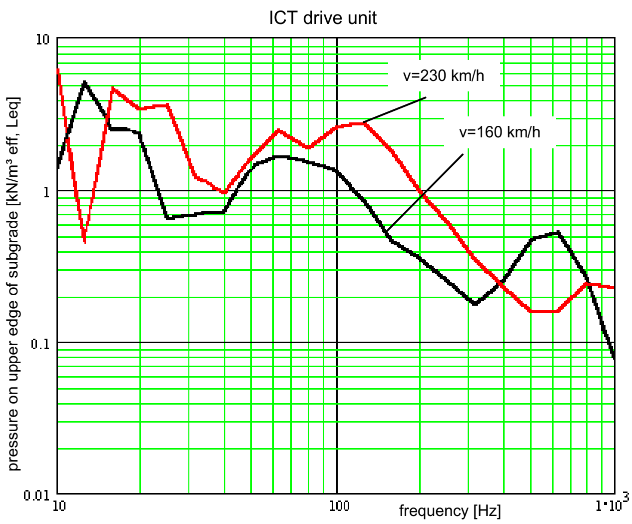


Figure 4 Effective pressure on subgrade top edge for v = 160 km/h and v = 230 km/h during passage of ICT train

Figures 3 and 4 show that in addition to quasi-static loads (circular wheels), large additional dynamic excitations occur for instance due to non-circular wheels. Increasing the speed will considerably enhance these additional excitations. This means that stresses on the soil become greater. Consequently, this also results in an increase in vibration speeds in the soil layers (Figure 5).

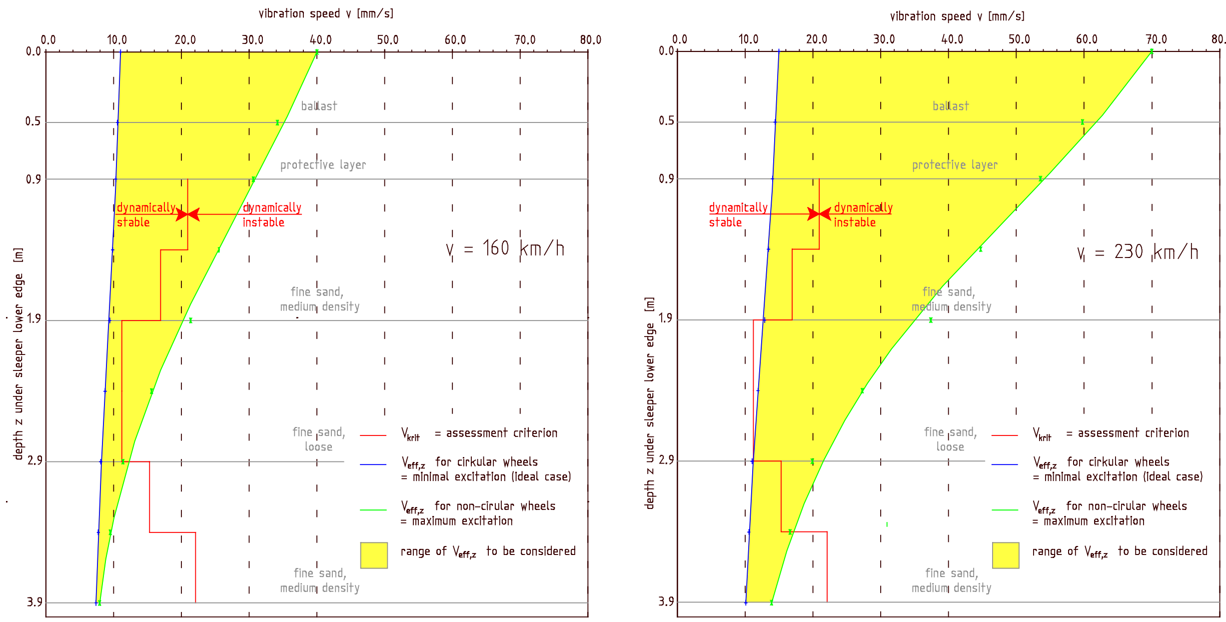


Figure 5 Vibration speeds in the rail substructure for circular and non-circular wheels during an ICT train passage with v = 160 km/h and v = 230 km/h

3 EFFECTS OF DYNAMIC STRESSES ON GEOSYNTHETIC REINFORCED EARTH STRUCTURES OF RAILWAY LINES AND CURRENT IMPLEMENTATION OF THESE RESULTS IN STRUCTURE DESIGN

In the situation to be considered here, geosynthetics are installed as reinforcing elements under the rail in the compression area of the loads from railroad traffic. They are laid in gravel sand or natural soil as supporting layer or filling material and subjected to varying ground tensions and vibrations from static and dynamic loads.

In addition, stresses occur due to hydraulic processes caused by seepage water and ambient soil water, which are very much characterised by local conditions.

Critical vibrations occur e.g. in geosynthetic-reinforced supporting elements in accordance with NIMMESGERN & LIEBERENZ (2001) in the medium-frequency range.

The following parts of the geosynthetic-soil system can be influenced by vibrations / shocks:

Geosynthetic:
– Affecting the material property durability by material fatigue and/or damage

Soil:
– Effect on shear strength and stiffness by subsequent compaction / loosening / change in pore water pressures / particle destruction

Soil/geosynthetic composite system:
– Affecting the friction characteristics / the interfacial shear strength between the geosynthetic material and the soil and thus the pull-out resistance or the anchoring length.

In the design and static calculation of geosynthetic-reinforced earth structures in the effective area of railway traffic loads, these findings are at present only considered in a quasi-static way via the reduction in resistance or the increase in impacts.

This means that only increased soil pressure tensions are accounted for while vibrations/shocks are not taken into consideration.

Thus, for instance, they were taken into account for the geosynthetic-reinforced earth structures described in Sections 4 and 5, using the following approaches:

1. Determination of a reduced friction coefficient between the geosynthetic and the soil, e.g.

   $f_{sg} = 0.67 \cdot 0.80 \cdot \tan \phi$

   Explanation of factors:
   $0.80 \cdot \tan \phi$ Determination based on the basis of laboratory tests
   0.67 Consideration of the dynamic effects in the compression area for reinforcing layers up to 3.0 m under the sleeper upper edge with a reduction to 2/3 of the static value in accordance with HEROLD (1999)

2. Applying an additional reduction factor A_{dyn} to the design value of the tensile strength
   In the design of the steep slope from geosynthetic-reinforced earth in Hennigsdorf the first time an additional reduction factor A_{dyn} was developed in co-operation with the German railway authority “Eisenbahn-Bundesamt”. The reduction factor A_{dyn} is used in the following way for reinforcing layers within the compression area of railway traffic loads (Figure 6):
   – Geogrids located at a distance of < 1.5 m below the sleeper upper edge, must not be taken into account for the calculations
   – Geogrids located at a distance of 1.50 m and 3.0 m below the sleeper upper edge, are reduced as follows:
     → A_{dyn} = 1.50 at a distance of 1.50 m below the sleeper upper edge and
     → A_{dyn} = 1.00 at a distance of 3.00 m under the sleeper upper edge.
   The values in between are interpolated in a linear way.
   – Geogrids located at a distance > 3.00 m under the sleeper upper edge, are not subjected to any additional reduction.

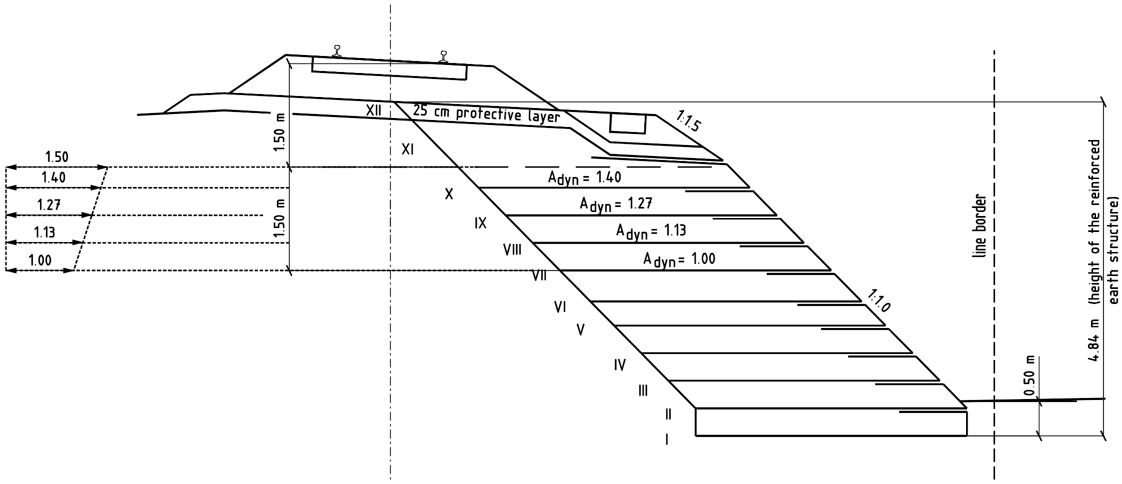


Figure 6 Geometric derivation of the reduction coefficient A_{dyn} in the static calculation of the steep slope made of geosynthetic-reinforced soil in Hennigsdorf , developed in co-operation with the German railway authority

3. Raising static traffic loads by the dynamic factor k_{dyn}
   A quasi-static consideration of the effects from train operation, practised currently for higher travel speeds, is the increase in static loads by the dynamic factor k_{dyn}. The dynamic factor varies between k_{dyn} = 1.00 for 100 km/h and k_{dyn} = 2.00 for 300 km/h. Subsequently, these increased static traffic loads are used in the unchanged proofs in the common way (MUNCKE et. al. (1999)).

4 USE OF GEOSYNTHETICS IN THE NIEDERUNG HARPER MÜHLENBACH EMBANKMENT UPGRADING PROJECT

Re-starting service on a finished line section made it necessary to broaden the formation and to specifically upgrade the foundation due to a soft layer in the subsoil. Ecological and economic reasons caused planners to decide in favour of a specific solution. This envisaged removal of the top of embankment up to a maximum depth of 3.0 m below the future sleeper upper edge. This was to form the working level from where both the upgrading of the embankment and the embankment foundation ("in downward direction") as well as the broadening of the top of embankment ("in upward direction") were to proceed in such a way that the natural space was not even affected in the area of the footing.
The method used was (Figure 7)

- An embankment foundation made of compacted column foundation of ready-mixed mortar (downwards from the above-mentioned level) under a continuous, horizontal, all-over geosynthetics reinforcement (carrying layer) above the column heads
- A broadening of the top of embankment with vegetated steep slopes on both sides, made of geosynthetic-reinforced earth, in upward direction from the above-mentioned level.

The functional principle of the embankment foundation can be briefly described as follows:

- The stresses resulting from the foundation's own weight and the traffic load are introduced in the compacted column foundations of ready-mixed mortar via the embankment body and the geosynthetic-reinforced carrying layer and dissipated from there into the good bearing subsoil.
- Stresses from the horizontal component of the ground pressure due to its own weight are assigned as expansion forces and dissipated via friction and conversion into the soil.

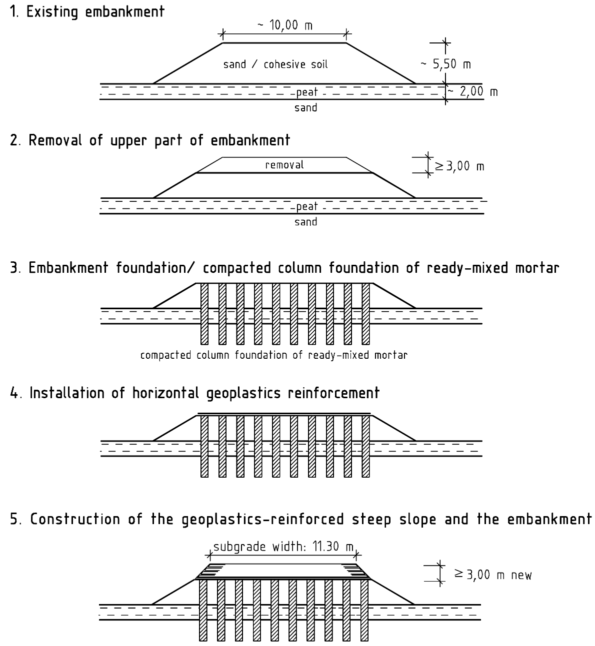


Figure 7 Solution used for the embankment upgrading at Niederung Harper Mühlenbach

Although the geosynthetics of the embankment foundation are in the compression area of the railway traffic loads, their depth is clearly above 3.0 m below the sleeper upper edge. Thus no reduction of the friction coefficient and no additional A_{dyn} value were used in the calculations.

The geosynthetics of the broadening of the top of embankment are in the compression area of the railway traffic loads. Dynamic effects were considered as described under Section 3.

Considering this earth structure from the perspective of acting vibrations, the following conclusions can be drawn:

- The not yet upgraded earth structure is the typical case of a dynamically sensitive line section, in particular for increased speeds. An embankment of approx. 4.50 m height located on a soft layer with a thickness of approx. 2.0 m is excited in the low-frequency area (approx. 10 Hz). This and possible vibration speeds in the subgrade/subsoil may cause settlements and instabilities.
- The foundation on column-type carrying elements down to the good bearing soil and the high geosynthetic-reinforced

surcharge not only dissipate the static loads without any problems, but also change the vibration characteristics of the embankment. The embankment and the soft layer are practically decoupled, and the embankment is modified due to its connection with the good bearing subsoil. Resonances with critical vibration speeds may no longer occur. Vibration speeds in the subgrade will quickly decrease with depth. Thus dynamic effects on the geosynthetics will be low.

Figure 8 Embankment upgrading in the Niederung Harper Mühlenbach Embankment with inclinometers

The earth structure was built in March/April 1999 (Figure 8). The line was put into service after heavy-load passages in December 1999. To ensure long-term performance capability, a measuring program has been implemented with:

- Geodesic measurements in 3 measuring profiles,
- Inclinometer measurements and extensometer measurements,
- Inspection of the outer skin and grassing and
- Control of the long-term behaviour of geogrids by inserting a material deposit within the reinforced steep slope.

Furthermore it is planned to carry out vibration measurements to be able to evaluate the dynamic behaviour of the upgraded earth structure taking into account the aspects described in Section 2.

Based on the results of the zero measurements and 4 follow-up measurements we can say that settlements occurred mainly due to heavy load traffic. These mainly result from subsoil settlements due to load introduction via the columns, from the embankment's own settlement and to a very limited extent from the settlement of the soft layer. This indicates an activation of tensile forces in the geogrid and a load introduction into the columns.

5 STEEP SLOPE FROM GEOSYNTHETIC-REINFORCED EARTH IN HENNIGSDORF

The reopening of service on a city train line made it necessary to broaden the track formation and to replace a supporting wall which had lost its stability. To comply with the existing railway ground limits, as well as for ecological reasons, planners decided to build a geosynthetic-reinforced steep slope (Figure 9).

Based on the static dimensioning and the maintenance of the line borders, dimensions were found for the geosynthetic-reinforced steep slope of a length of approx. 110 m, a height of approx. 4.0 m, a slope inclination of approx. 51° and 9 to 11 reinforcement layers.

The geosynthetics are in the compression area of the railway traffic loads. Dynamic effects were also considered as described in Section 3 and shown in Figure 6. The geosynthetic-reinforced steep slope was built in 1998 (Figures 10 and 11)

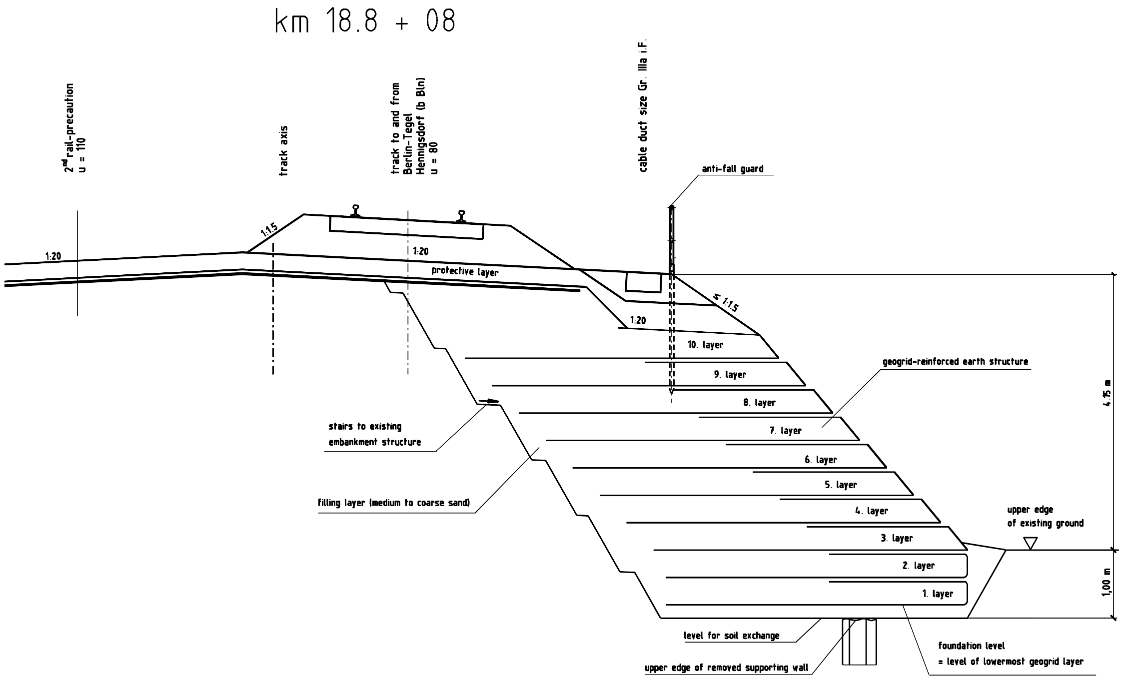


Figure 9 Cross-section of the geosynthetic-reinforced steep slope

Figure 10 Laying and installation of geogrid layers

Figure 11 View of the completed steep slope, still without vegetation

Considering this earth structure from the vibration point of view allows the following conclusions:

- The earth structure reinforced with geosynthetics has a high degree of homogeneity and compactness, thus constituting a compact structure.
- Consequently, critical vibrations may only occur in the medium-frequency range (approx. 30 – 40 Hz), their share, however, is very low during city train operation at 100 km/h.
- Vibration speed will quickly decrease with depth. Thus dynamic impacts on geosynthetics will be low.

Figure 12 Growing of vegetation on the steep slope approx. 6 weeks after the wet sowing

Figure 13 Condition of the steep slope in the year 2001 (approx. 2 years after the re-opening of the line)

The completed, geosynthetic-reinforced steep slope is monitored both visually and with measurements to ensure its performance capabilities and durability. For this purpose, 5 measuring points each have been installed on the ground surface in two transverse profiles. The first measurements were carried out as zero measurements before the railway line was set into operation in October 1998. Up to 2001, 4 follow-up measurements were carried out to study the deformation behaviour of the slope and the long-term characteristics of the geogrids. Furthermore, material deposits were installed in a cross-section at the footing and below the track for future sampling to obtain additional practice- and site-related statements about the long-term behaviour of the reinforcing material.

6 SUMMARY AND OUTLOOK

The aim of the study was to discuss the dynamic impacts on geosynthetics in earth structures and to show how these impacts are taken into account in the design of such structures. It has been shown that stresses from railway operation are currently only considered in a quasi-static way via

- reducing resistance values and/or
- increasing the impacts.

The described behaviour of geosynthetic-reinforced earth structures under dynamic loads with the effects on the geosynthetics constitutes a first interpretation. Further studies and measurements will be necessary to obtain a more profound knowledge of the dynamic impacts and the resistance values required in earth structures with geosynthetics.

To be able to better model dynamic stresses from railway operation and the response of the geosynthetic-reinforced earth structure, it will be necessary

- to use rail-dynamic calculation methods,
- these should be combined with FE programs developed for soil-mechanical problems, first of all for specific objects.

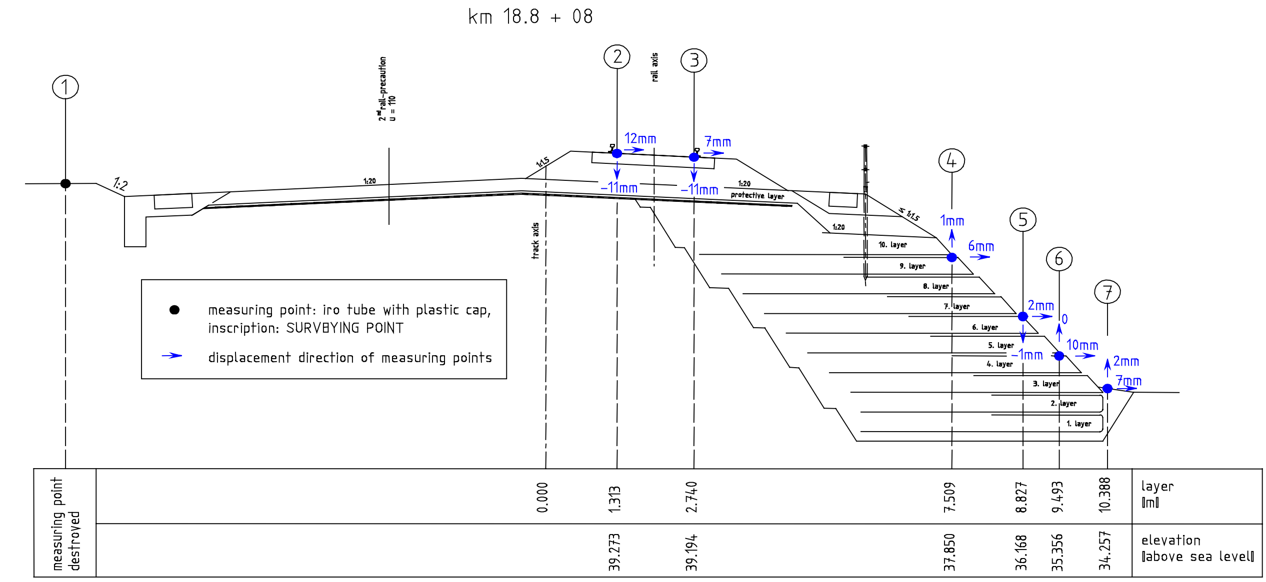


Figure 14 Sketch showing the deformation characteristics of the steep slope (3rd follow-up measurement in 2000)

As soon as a sufficient number of calculation results, verified by measurements, are available, the aim should be to develop a "dynamic dimensioning method" for geosynthetic-reinforced earth structures which, based on present knowledge, should contain the following elements:

- A systematic approach to the stresses on the geosynthetic-reinforced structure caused by railway operation (quasi-static and dynamic considerations),
- Preliminary dimensioning of geosynthetic-reinforced earth structures with conventional methods (quasi-static considerations)
- Proof of the performance capability of geosynthetic-reinforced earth structures with regard to their stress and deformation characteristics using FE programs (dynamic considerations),
- Estimation of the vibration characteristics of geosynthetic-reinforced earth structures, e.g. on the effect of the reduction in vibrations speeds resulting from carrying layers with geosynthetics.

REFERENCES

Klein, G. 1990. Bodendynamik und Erdbeben. In *Grundbau-Taschenbuch Teil 1*. Berlin: Ernst & Sohn Verlag für Architektur und technische Wissenschaften.

Hillig, J. et. al. 1999. Zum Langzeitverhalten von Vliesstoffen im Tragsystem von Eisenbahnstrecken. In *Geotechnik Sonderheft 1999*: 83-88. Essen: Deutsche Gesellschaft für Geotechnik e.V..

Herold, A. 1999. Geokunststoffe unter dynamischer Belastung II. In *Geotechnik Sonderheft 1999*: 69-75. Essen: Deutsche Gesellschaft für Geotechnik e.V..

Lieberenz, K. et al. 1999. Bau der Steilböschung in Hennigsdorf aus geokunststoffbewehrter Erde im Druckbereich von Eisenbahnverkehrlasten. In *Geotechnik Sonderheft 1999*: 77-88. Essen: Deutsche Gesellschaft für Geotechnik e.V..

Lieberenz, K. et al. 2000. Bau eines Bahndammes mit geokunststoffbewehrter Basis und Böschung. In *Vorträge der Baugrundtagung 2000 in Hannover.* Essen: Deutsche Gesellschaft für Geotechnik e.V..

Müller-Boruttau, F. H., & Breitsamter, N. 2000. Elastische Elemente verringern die Fahrwegbeanspruchung. *ETR-Eisenbahntechnische Rundschau* 2000 (49), volume 9: 587-596.

Muncke et al. 1999. Neue Erkenntnisse und Lösungen im Brücken-, Tunnel-, Erd- und Grundbau. *ETR-Eisenbahntechnische Rundschau* 1999 (48), volume 10: 622-638.

Nimmesgern, M. & Lieberenz K. 2001. Geogitterbewehrter Bahndamm – Ausgrabungen nach 10jähriger Beanspruchung. In *Geotechnik Sonderheft 2001*: 173-180. Essen: Deutsche Gesellschaft für Geotechnik e.V..