Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Key aspects on the behaviour of the ballast and substructure of a modern railway track: research-based practical observations in Finland*

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Received Sept. 7, 2012; Revision accepted Sept. 25, 2012; Crosschecked Sept. 7, 2012

Abstract: This paper presents an overview on the wide-ranging track structure studies at the Tampere University of Technology (TUT), Finland dealing with the key aspects of track geotechnics related to high-speed passenger traffic on ballasted tracks. Special attention is paid to ballast and sub-ballast, while also considering frost action, embankment stability, track stiffness, track geometry and transition zones. As a result, this paper states that understanding the ballast degradation mechanism and its consequences and assessment of its condition occupy an important role in the construction and maintenance of a smooth high-speed rail line. The choices related to building the sub-ballast also have a dramatic impact on later track deformations and maintenance needs. In cold climate, especially where seasonal frost occurs, understanding and taking into account the frost action mechanism is crucial. Especially in the maintenance and rehabilitation planning of existing tracks, high-class analyses of ground penetrating radar data and its integrated analysis with other data can yield considerable benefits.

Key words: Railway, Track, Ballast, Sub-ballast, Substructure, Subsoil, Frost action, Life cycle, Ground penetrating radar
doi:10.1631/jzus.A12ISGT1 **Document code:** A **CLC number:** TU4; U23

1 Introduction

1.1 Finnish rail network

The Finnish rail network is, except for a few industrial sidings, publicly owned. It is managed by the Finnish Transport Agency, which also purchases the related maintenance and construction services, and consequently has great interest in track research.

Finland is a sparsely populated country (16 persons/km^2) where the distances between cities are of medium length. Therefore, the rail network is characteristically a mixed traffic network serving both freight and passenger traffic. Most railway lines consist of just a single track. The current maximum axle load on nearly all sections of the network is 22.5 t; on some lines 25 t is allowed. The maximum speed for passenger trains is 220 km/h and 200 km/h prevails in the trunk network of passenger transportation, as shown in Fig. 1. Some additional lines are currently under extensive renovation in order to allow speeds of 200 km/h. Riding quality and safety perspectives demand great smoothness from a high-speed track. That sets high requirements for track construction and maintenance especially on mixed traffic lines, where rather heavy freight trains are also loading the track. Humid and cold Finnish winters and the often very weak subsoil conditions in many areas are special challenges. In the areas of cold climate, as in Finland, a key factor influencing railway construction is the seasonal frost. To prevent frost-heave susceptible subsoil from freezing, a sub-ballast layer of 1.5 to 2.0 m is required. Moreover, there is considerable need for embankment stability improvement in many areas.

1.2 Railway track research at TUT

In order to manage the above-mentioned challenges and reduce track life-cycle costs, Finnish

* Project supported by the Finnish Transport Agency

Transport Agency together with Tampere University of Technology (TUT) have been running an extensive research program on the behaviour of track and its structural components. TUT's Railway Track Research Group comprises about 15 researchers and operates with annual research volume of over one million Euros. TUT's research activity also covers wheel-rail interaction, rails, sleepers and bridges, but the geotechnical features of the track structure still occupy a key position. This paper presents TUT's track geotechnics research and its results with the emphasis being on the high-speed passenger rail lines.

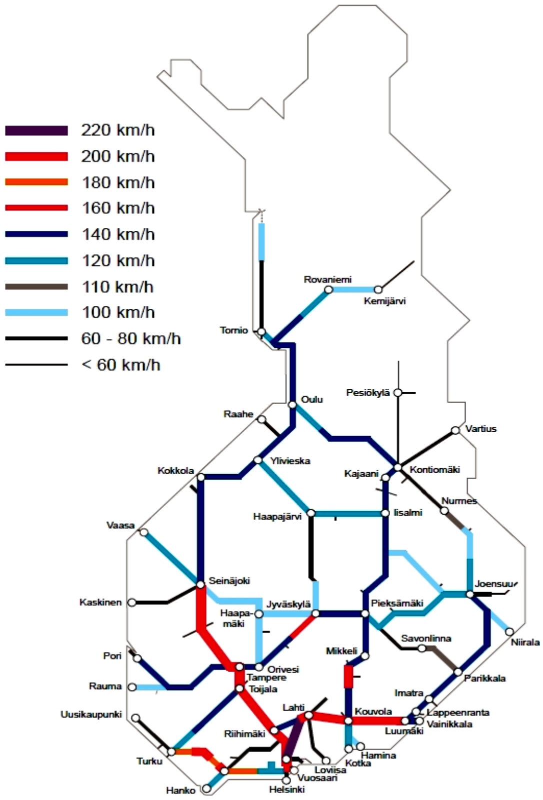

Fig. 1 Operation speeds on Finnish rail network

2 Ballast degradation (fouling)

2.1 Functions of the ballast bed

The ballast bed of a traditional track structure consists entirely of coarse-grained and uniformly graded crushed rock aggregate (Fig. 2). The primary functions of the ballast bed are: (1) to support the track in order to maintain its vertical and horizontal geometries; (2) to enable correction of track geometry errors; (3) to provide appropriate resiliency together with other track components; (4) to provide efficient drainage of track; and (5) to distribute traffic loads from sleeper to a level allowed by lower structural layers.

2.2 Ballast degradation mechanism

The loading environment of the ballast bed has been well described already by Simon *et al.* (1983) who stated that the ballast, in particular, is subjected to the heaviest stress levels and environmental loading of all aggregates used in construction. In an extremely severe loading environment, breakage and attrition of ballast particles are inevitable. As fouling proceeds (Fig. 2), finally ballast cannot meet its functions, and the so-called ballast cleaning limit is reached. An extensive literature review by Nurmikolu (2005) showed that many studies dealing with the degradation of ballast have been published.

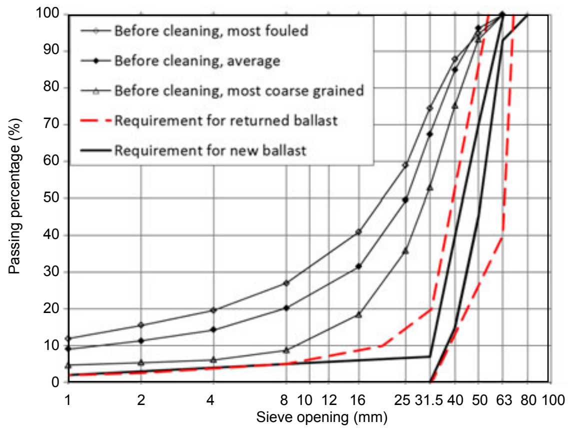

Fig. 2 Finnish grading requirement for new (fresh) ballast (EN 13450, class E), ballast that is to be returned to track after ballast cleaning, and examples of fouled samples taken from the Toijala-Turku and Kuopio-Siilinjärvi railway lines before ballast cleaning

In Finland, the magnitude of fouling has been studied based on sampling of most of the railway lines of the network, primarily for the needs of rehabilitation planning, between 1995–2012. Thus, the grading data of more than 1500 ballast samples has been available for examining the degradation mechanism and rate. The degree of ballast fouling is evaluated on the basis of a degradation number which is determined from ballast samples as the sum of the percentages passing 1 mm, 8 mm and 25 mm sieves. The economical cleaning limit of the ballast bed is seen to be reached when the average degradation number of the railway line exceeds 88. Background for this cleaning limit and its correspondence to other limits introduced in literature is analysed elsewhere (Nurmikolu, 2010).

To assess the quality and harmfulness of generated fines, as well as the degradation mechanism of ballast, it is necessary to examine degradation in an actual loading environment. This was carried out by running an extensive series of laboratory tests on degraded ballast bed samples, which had been in service for 10–40 years and subject to 100–350 million gross tonnes of train loading. A wide range of typical ballast aggregates was covered by doing sampling at far distant points of the railway network. Laboratory analyses of the samples were conducted in order to determine the manner and extent of degradation and, especially, the quality of the resulting fines, as well as variations related to the different aggregates typically used in the ballast bed. Grading, impact (Los Angeles test) and abrasive (micro-Deval test) strength, water absorption, freeze-thaw resistance and frost-heave susceptibility of the samples were tested. Grain size distribution (Sedigraph equipment), mineralogy (X-ray diffraction), specific surface area (nitrogen adsorption), pore size distribution (mercury porosimeter), water adsorption, humus content (ignition method) and surface texture (scanning electron microscope (SEM)) of the fines of the samples were also examined.

In general, most of the fines in the ballast samples consisted of the most common rock minerals, quartz, feldspars and amphiboles, whose average share in the mineral fines of the samples was established at about 80% (Fig. 3). Distinct chemical weathering after crushing could be observed only in one ballast bed sample, where opaque minerals and mica had weathered, resulting in deposits of iron compounds on grain surfaces. This was a positive finding. Despite the thousands of times larger specific surface area of fines in comparison to coarse grains, hard minerals appear resistant to chemical weathering in the structure even in the form of fines. The findings support the idea (Nurmikolu, 2005) that degradation of ballast aggregates in the Finnish railway network is mainly the result of mechanical fragmentation and attrition caused by traffic loads and tamping (maintenance), or in a few cases possibly by frost weathering. Detailed results from field and laboratory tests are presented in (Nurmikolu, 2010).

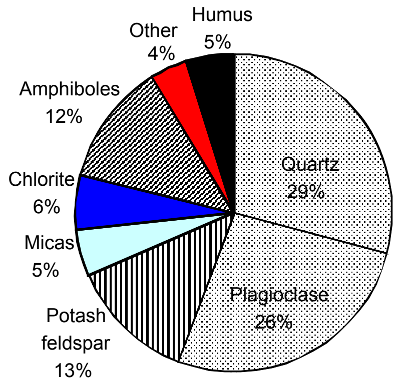

Fig. 3 Indicative average mineral content of the fines of 36 degraded ballast bed samples based on X-ray diffraction analyses

The SEM images of ballast fines did not show significant weathering either. Instead, the high porosity and water retaining properties of some gravel and sand reference materials indicated slight weathering. The differences in surface properties were clearly revealed by the SEM images in Fig. 4. There seemed to be considerably more deviation in particles' surface properties in the case of gravels and sands than with crushed rock aggregates. The environmental loading on the particles of naturally sorted coarse-grained soils over millennia is of a different magnitude than the loading on crushed rock aggregate particles over the few decades since their crushing.

2.3 Effects of ballast fouling

The smoothness requirement of high-speed railway tracks is extremely high and is getting tighter with increasing train speeds. Even relatively small deviations in track geometry limit rail traffic as travel times increase and traffic capacity diminishes. The degradation of the ballast bed is a determining factor in track geometry deviations. In many cases ballast has degraded especially under rails and at the ends of sleepers. Besides for track geometry, such uneven degradation can be critical for stresses in concrete sleepers. Extensive research at TUT has shown that ballast gets fouled due to accumulation of fine-grained material resulting in an increase in: (1) frost-heave susceptibility (Nurmikolu, 2005; Nurmikolu and Kolisoja, 2008); (2) water retention (Nurmikolu,

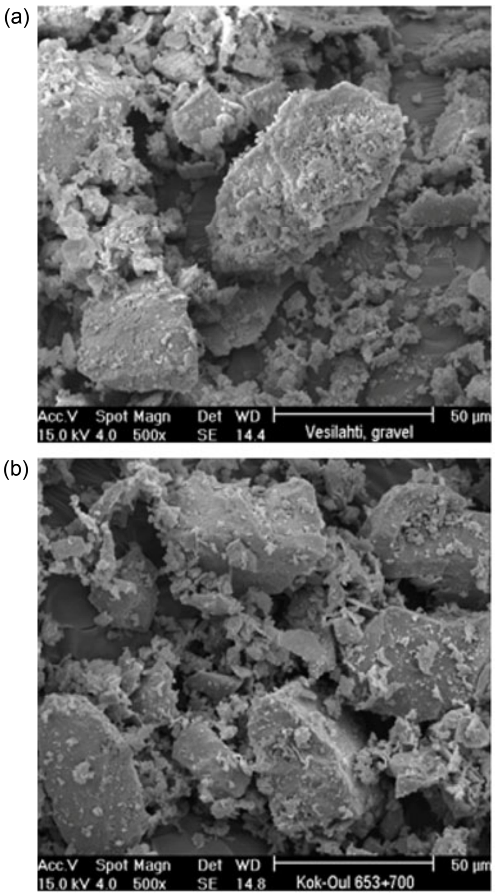

Fig. 4 SEM images of the fines of weathered gravel (a) and a sound ballast bed sample (b)

2005; 2010); (3) resilient and permanent deformations (Nurmikolu and Kolisoja, 2011); (4) stresses on sleeper due to centre binding (Nurmikolu *et al.*, 2010); and (5) need for tamping and track maintenance in order to keep track smoothness at an acceptable level (Silvast *et al.*, 2013).

Ultimately, the effectiveness of the maintenance done to maintain acceptable track geometry decreases to the extent that, instead of tamping, the most economical alternative is to clean the ballast with a large-scale rail-travelling sieving machine. Thus, fouling is the factor that determines the service life of a ballast bed. Degradation depends considerably on traffic density. Nurmikolu *et al.* (2001) presented the Finnish concept of selecting the most life-cycle economic grade of ballast when procuring new ballast. The criteria used include dependence of the ballast service life on its strength, rehabilitation costs of the ballast bed, and differences in purchase prices of ballasts of different grades.

2.4 NDT assessment of the fouling of ballast

In ballast bed condition assessment during the life cycle, the need for sampling has been substantially reduced due to great advancements in ground penetrating radar (GPR) analysis gained in collaboration with Roadscanners Ltd., TUT and Finnish Transport Agency. Currently, the ballast bed fouling index can be reliably calculated from the GPR signal by using a special frequency spectrum analysis algorithm. The results from GPR analysis have been calibrated using hundreds of laboratory analysed ballast bed samples. As a result of persistent algorithm development of GPR data analysis, a very good correlation was revealed in the comparison of the laboratory sieving test results of ballast bed samples and the fouling index from GPR data. Fig. 5 presents an example of this correlation in a certain railway line. The GPR fouling index is calculated as an average value from a 5-m long window. More details are provided in (Silvast *et al.*, 2010).

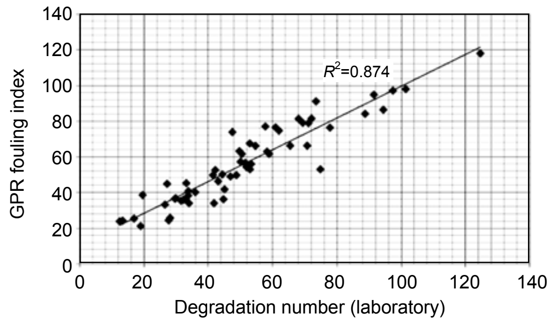

Fig. 5 Correlation chart of ballast bed degradation number (sum of passing percentages in 1 mm, 8 mm and 25 mm sieves) analysed from samples by sieving in the laboratory and calculated from GPR data

3 Sub-ballast considerations

3.1 Functions of sub-ballast

The structural layers below the ballast bed, the sub-ballast, are commonly constructed either of coarse-grained natural soil (gravel, sand) or of crushed rock aggregate. In areas of cold climate, sub-ballast consists of two layers: the intermediate and frost protection layers. Sometimes, a separate filter layer is also used against the subsoil, i.e., under the sub-ballast. The primary functions of the sub-ballast are: (1) to provide a load-bearing base for the ballast bed (primary task of intermediate layer); (2) to prevent frost heaving in track structure (primary task of frost protection layer); (3) to provide appropriate resiliency together with other track components; (4) to prevent mixing of ballast and other structural materials (intermediate layer); and (5) to prevent mixing of frost protection and subsoil material (filter layer).

3.2 Compaction and bearing capacity of sub-ballast

The density of an unbound material layer is one of the most important factors affecting the deformation behaviour of the material (Kolisoja, 1997). Thus, successful compaction of the layers during construction is of the highest importance in gaining the required bearing capacity and preventing undesired train load-induced permanent deformations later on. Efficient compaction, and especially the related quality control, of coarse-grained and rather uniformly graded granular materials have been found difficult to implement.

TUT has studied proper compaction practice, methods and quality control methods by constructing two (one on soft subsoil and the other on stiff subsoil) full-scale test embankments about 200 m long each. The embankments comprised 14 different sections built of both crushed rock aggregate and natural sand (Fig. 6). Sections were compacted with varying practises. For example, the layer thickness was varied between 300–750 mm total height of the embankments being always 1.8 m. Density and deformation modulus were monitored extensively in various stages of the compaction. Density was measured by a water volumeter and the Troxler nuclear density gauge. Deformation modulus was measured by a plate loading test (PLT), a falling weight deflectometer (FWD), and a light-weight deflectometer. Besides standstill measurements, continuous compaction control was also applied. The arrangements and the results are presented in more detail in (Kalliainen *et al.*, 2011).

In general, the best compaction result was achieved when the layer was constructed by bulldozing, the material was properly wetted, a proper layer thickness considering the size of the roller was selected, and compaction was finished before the fines from the upper part of the layer began to move deeper into the compacted layer. The use of a layer thickness above 500 mm, with some material types just a 300 mm layer, significantly reduced the resulting degree of compaction and deformation modulus. Additional compaction did not remedy the situation.

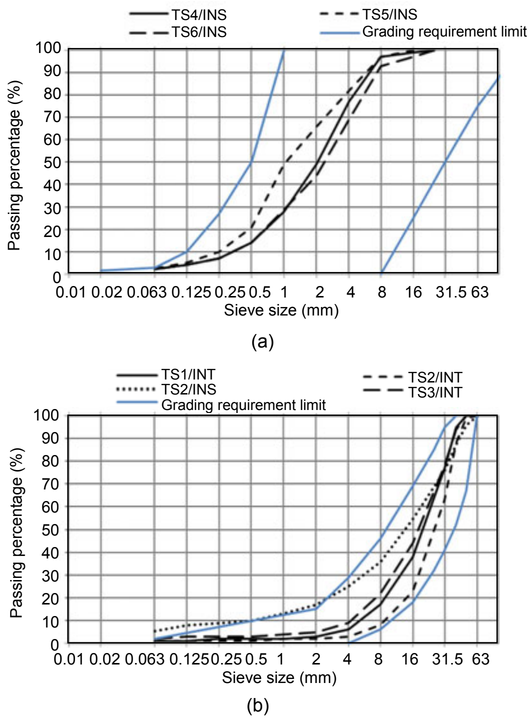

Fig. 6 Natural sand/gravel aggregates in the insulation (INS) layers (a) and crushed rock aggregates used in the insulation and intermediate (INT) layers (b) of test embankments

Rather uniformly graded crushed rock aggregate has been used in Finland (Fig. 6b) to prevent fouling and, thereby, prevent the material from becoming frost-heave susceptible during its life cycle. However, aggregate of this type was found difficult to bring to the required degree of compaction or PLT value. Consequently, the recommended grading for crushed rock sub-ballast was adjusted slightly towards more broadly graded from that as shown in Fig. 6b.

Especially with coarse-grained and open graded crushed rock material, direct measurement of the degree of compaction was found to result in high variation, possibly unreliable results and/or required huge efforts. The best option is to use a nuclear gauge, but it requires that the reference density is defined, which may be unreliable especially for coarse-grained materials. Therefore, the control of deformation modulus was recommended for the compaction control. In the PLT, loading is done twice and the modulus from the second loading cycle, E_{v2}, is compared with the modulus from the first loading, E_{v1}. When aiming at compaction control, the appropriate limits of deformation modulus requirements depend slightly on the material. In general, requirements $E_{v2}/E_{v1}\leq 2–3$ and $E_{v2}\geq 160–180$ MPa, were judged appropriate also from the compaction control point of view. Due to the large variation, open graded crushed rock aggregate can be problematic also in terms of E_{v2}/E_{v1}. The highest deformation modulus was achieved from the middle of the embankment. Static rolling before the tests improved the results. The appropriate requirements for the deformation modulus from the bearing capacity point of view are currently under extensive investigation at TUT.

3.3 Effect of embankment width and slope angle

The role of embankment width is another factor in the attempt to restrict permanent deformations of sub-ballast under train loading during the life cycle. In order to reduce investment costs, embankments have typically been made quite narrow with steep slopes. That can result in insufficient lateral support and an excessive rate of permanent deformations accumulating in the embankment structure. The effect of embankment width and slope angle on the accumulation of permanent deformations under repeated loading has been studied at TUT by monitoring a full-scale field test site (Kalliainen *et al.*, 2010), extensive repeated loading tests in an arrangement simulating moving train load on top of model scale (1:4) test embankments (Kalliainen and Kolisoja, 2011), and modelling with PLAXIS software (Kalliainen *et al.*, 2010).

The observations clearly indicated the determining role of subsoil stiffness in the deformation behaviour of the embankment. In stiff subsoil conditions, the embankment dimensions did not seem to affect the accumulated permanent deformations of the embankment, but in more flexible subsoil conditions the effect was remarkable. The widening of the embankment reduced accumulated permanent deformations effectively throughout the embankment in flexible subsoil conditions. Reducing the slope angle ratio of the embankment can have an even greater influence on permanent deformation behaviour. That is also indicated by the results of repeated loading tests with the model scale embankment (Fig. 7) and in more detail in (Kalliainen *et al.*, 2010; Kalliainen and Kolisoja, 2011). Based on the findings, embankment width was made dependent on subsoil stiffness in Finland.

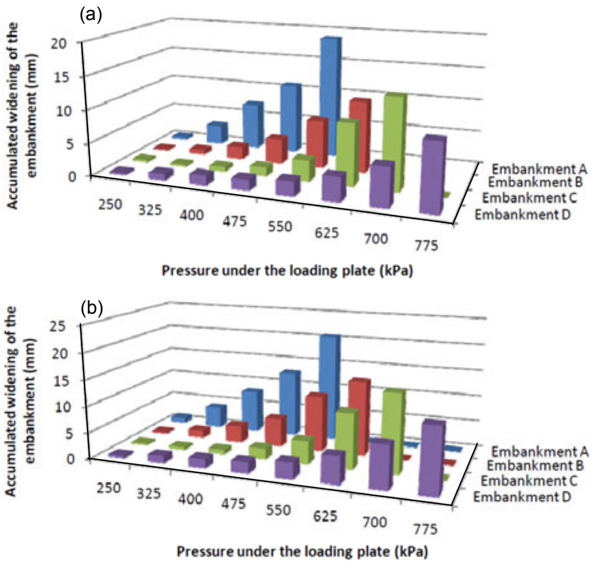

Fig. 7 Accumulated embankment widening at top of slope in the laboratory model scale repeated load test series performed in stiff (a) and flexible (b) subsoil conditions
Each load step comprised 20 000 loading cycles. Embankment A (scale 1:4) is 5.4 m wide with a slope angle ratio of 1:1.5; the corresponding dimensions of the other embankments are: B: 6.0 m & 1:1.5, C: 6.8 m & 1:1.5 and D: 6.0 m & 1:2

3.4 Degradation (fouling) of sub-ballast

As in the case of ballast, attrition and breakage of sub-ballast particles also causes permanent deformation and consequently need for tamping maintenance. Crushed rock aggregates have been used as sub-ballast in Finland only for a decade. Mainly environmental concerns have resulted in a strong tendency to replace gravel and sand with crushed rock aggregates. In the absence of long-term use experience, an effort has been made to estimate the degradation of crushed rock aggregate sub-ballast in cyclic laboratory scale loading tests using a test box. A key point in the development of the test arrangement was to allow the principal stress directions in the aggregate to rotate corresponding to an overhead moving train loading in the real track structure (Fig. 8). The rotation of the direction of loading could be arranged by using three separate loading cylinders in turn to simulate the situation under a track section spanning three sleeper intervals (Fig. 9). The arrangement enabled the simulation of loading cycles corresponding to decades of train traffic in a test lasting a few weeks.

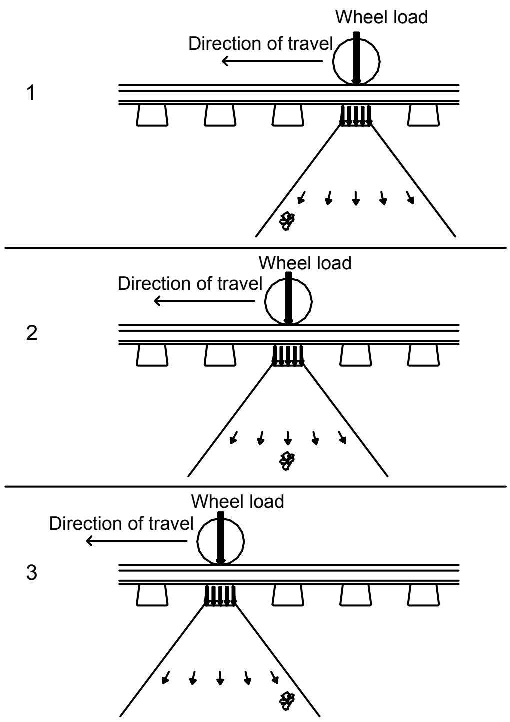

Fig. 8 Principle governing change in the major principal stress direction affecting a given particle group as the train travels forward

A total of 35 long-term cyclic loading tests equivalent to about 150–300 million gross tons were carried out varying grain size distribution, strength of the aggregate, amount of fine material and water in the aggregate, loading level and flexibility of the bottom. The test arrangement and test programme are described in more detail in (Nurmikolu, 2005; 2010).

Considering the correspondence of the equipment to the actual loading situation, the biggest drawback was the problem of the interface between the aggregate and the box that in some cases caused considerable unrealistic degradation. The problems in the simulation of the behaviour of the subsoil are also related to this issue. The movable wall solution suggested by Indraratna and Salim (2003) could be applied in the development of the loading arrangement. Because of these constraints, the loading arrangement can be regarded as a model test with distinct drawbacks, and the obtained degradation results cannot under any circumstances be applied as absolute values to the conditions of the actual track structure. However, it was considered more useful to compare the effects of different variables on the degradation of the aggregate and its ability to distribute loads with the present equipment instead of further development of the equipment.

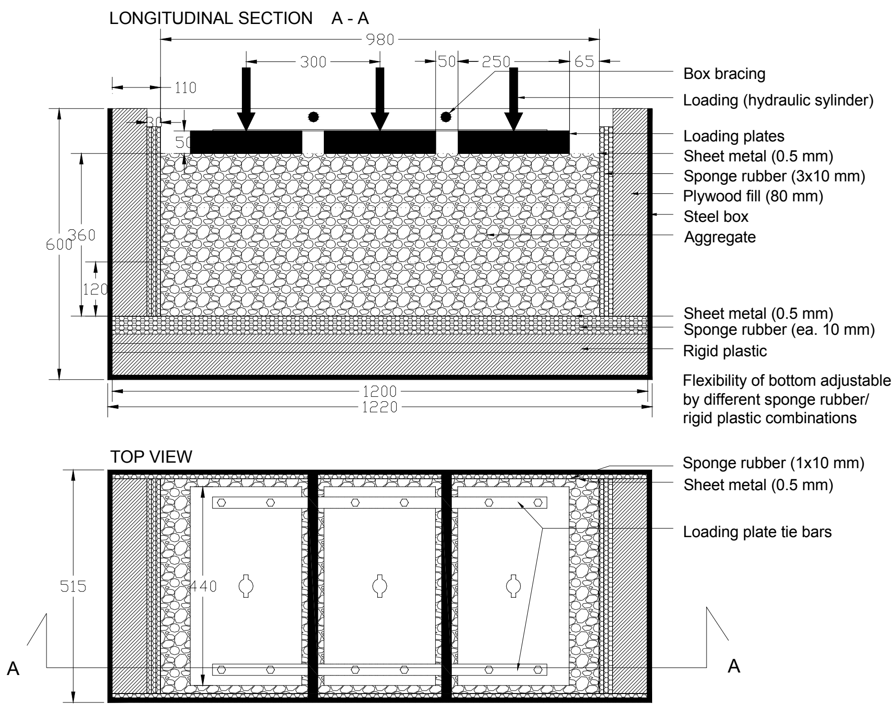

Fig. 9 Test box prepared for cyclic loading tests (unit: mm)

The degradation situation proved most disastrous when the aggregate is in a water-saturated state. In the worst case, the slurry in the water in the pore space between coarse grains starts moving in a constant pumping motion. As observed in the field, this is often referred to as mud pumping. Thus, the functioning of track drainage is of utmost importance in preventing degradation of crushed rock aggregate.

In the cyclic loading test arrangements, the ability of aggregate to distribute loading correlates very closely with its ability to resist degradation. Grading of crushed rock aggregate had a significant impact on the degradation observed in cyclic loading tests. Uniformly graded aggregates degraded clearly more than more broadly graded aggregates. So did the loading level, since increasing it from 150 to 225 kPa increased degradation 3.5-fold to 5-fold in the comparisons.

In the case of aggregate strength properties, the correlation with degradation occurred in the case of dry state cyclic loading tests mainly between the results of tests depicting impact resistance (e.g., Los Angeles value) and in the case of water saturated state tests with results depicting abrasion resistance (e.g., micro-Deval value).

In relation to performance in cold climate, the material becoming frost susceptible also has to be considered. It can be a determining result of degradation, as frost-heave susceptible fines accumulate into sub-ballast material. Based on the results, the strength and grading requirements for the aggregate used as sub-ballast (Fig. 6b) were given.

3.5 NDT evaluation of sub-ballast

The railway track's subsurface layers are difficult to properly inspect just by visual methods. On the other hand, taking samples from the track structure is laborious and costly. GPR is well known to be a very effective tool in evaluating the thickness of the structural layers of track substructure. Roadscanners Ltd., TUT and Finnish Transport Agency have put a lot of effort into making GPR analysis an even better tool for the assessment of the condition of railway track structures. Algorithms have improved as drilling, sampling and laboratory analyses have been used as references. As a result, sophisticated GPR data analyses provide an excellent and reliable tool for versatile track structure investigation. The analyses can reveal, for example, moisture anomalies, ballast pockets, fine-grained materials in the structural layers and locations prone to frost action problems in structural layers and subsoils. The use of integrated analysis software, such as in Fig. 10, enables accurate and thus more economical rehabilitation planning procedures. Modern GPR-based data integration is a design tool that has taken rehabilitation planning to a new level.

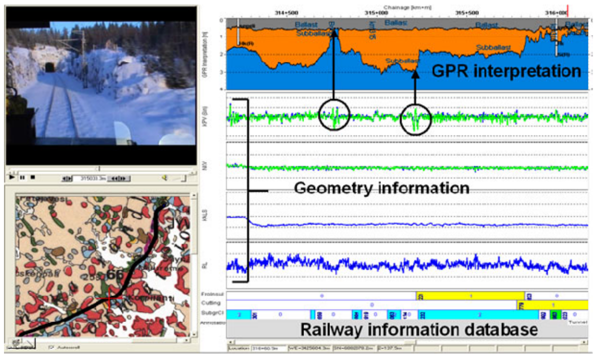

Fig. 10 A data view from Railway Doctor^{TM} software, showing a interpreted GPR profile with drilling data, track geometry information, and the track database showing the locations of special structures. The video window and map show the location of the current view (Silvast *et al.*, 2007)

Silvast *et al*. present more precisely the development and results that enable 3D GPR to be successfully used for evaluation of: (1) Ballast thickness (including ballast pockets, i.e., varying cross-sectional ballast thickness) and fouling (as discussed earlier) (Silvast *et al.*, 2009; 2010); (2) Sub-ballast thickness, fouling, drainage problems, frost-heave susceptibility and existing frost action problems (Silvast *et al.*, 2012); (3) Subsoil surface, soil type, frost-heave susceptibility and drainage problems (Silvast *et al.*, 2012); (4) Level, fractures, sheet ice and drainage problems in the top surface of the bedrock (Silvast *et al.*, 2013); and (5) Concrete slab structures, frost insulation boards and other objects in the substructure (Silvast *et al.*, 2007).

4 Frost action in a railway track

The frost action phenomenon is explained by Nurmikolu (2005). Frost heave can be a determining problem for railway operations in cold climate. High-speed trains require a very smooth track. The acceptable tolerance in level is only a few millimetres depending on wavelength and allowed train speed. At worst, frost action can cause a lift of hundreds of millimetres. Thus, in practice, a high-speed track has to be non-frost-susceptible. Frost action on railway tracks has been studied at TUT extensively for a decade.

Due to track unevenness caused by frost action, depending on the severity of the winter, temporary additional speed limits are needed in Finland in late winter and spring. The problem has been severe especially during the last two winters (2009–2010 and 2010–2011). Frost action has created the need for wintertime speed reductions on 827 km (winter 2011) and 1068 km (winter 2010) of the 5919 km rail network in Finland. During the preceding seven winters (2003–2009), the average length of track subject to temporary reduced speed limits was only about 5% of the level in the winters of 2010 and 2011.

The causes of frost-induced track roughness have been investigated extensively in laboratory tests at TUT. In addition to insufficient ballast and sub-ballast layers, the problems can be caused by discontinuities such as transitions from cuttings to embankments, culverts, level crossings, switches, sheet ice formation in rock cuttings or by the ballast or sub-ballast material itself. It was found that degradation (fouling) of ballast may turn the ballast material frost-susceptible (Nurmikolu, 2005; 2010; Nurmikolu and Kolisoja, 2008). Also, sub-ballast material, which may have been visually judged in the early 20th Century to be non-frost-susceptible, may still actually be frost-susceptible (Pylkkänen and Nurmikolu, 2011). In order to design proper remedies for frost action sites, it is necessary to understand the actual cause behind the problem. Ground-penetrating radar surveys have been systematically conducted as part of field investigations to support the identification and rehabilitation design of frost-affected areas (Silvast *et al.*, 2012).

A rather simple model, with very good coefficient of determination, for determining the frost-heave susceptibility of materials has also been created (Nurmikolu, 2010). But in order to further improve understanding of frost action, TUT in collaboration with the Finnish Transport Agency has developed a field measurement technique for real-time monitoring of frost depth, frost heave, thaw settlement, and moisture conditions in railway track embankments (Pylkkänen *et al.*, 2012). Examples of frost-heave and frost depth monitoring results are presented in Fig. 11. The purpose of the monitoring is to enable modelling of frost heave in the field based on material properties determined in the laboratory and conditions (moisture, temperature) in the field. This will allow site-specific projections of the recurrence interval for speed reductions as well as life-cycle cost analyses for comparison of repair costs and the sum of maintenance and speed reduction costs.

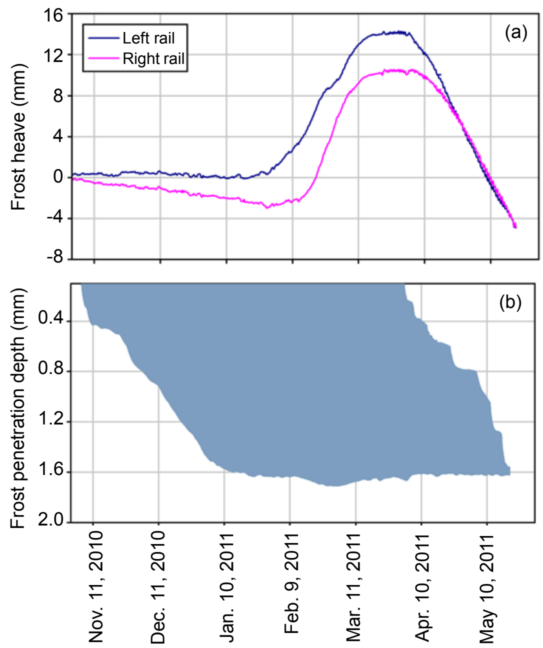

Fig. 11 Example on (a) frost heave and (b) frost depth results from one of the monitoring sites in northern Finland

Currently the main remedy to fix the frost action problems is the installation of extruded polystyrene frost insulation boards, whose long-term durability in track structure has proven (Nurmikolu and Kolisoja, 2005) to be generally good.

5 Other track geotechnical research at TUT

5.1 Improvement of embankment stability calculations

TUT's track geotechnics investigations have focused heavily also on development of embankment stability calculation. The subsoil reinforcement need that depends on the result of the calculation is highly significant as to its cost effects. Sufficient stability, i.e., avoidance of massive shear failure, is the most central safety feature of track geotechnics whose importance is accentuated in high-speed passenger operation.

Stability analysis has been developed continuously concerning both 3D finite element modelling (FEM) and the limit equilibrium method (LEM), which is easier to use in conventional design. Along with the development of calculation methods, alternative techniques of improving stability are being examined. For instance, a full-scale loading test of a heavily instrumented embankment to subsoil failure was implemented (Fig. 12) to help verify the development of calculation methods. Development of stability analysis is described in more detail in (Lehtonen, 2011; Lehtonen *et al.*, 2011; Mansikkamäki *et al.*, 2011).

Fig. 12 Full-scale embankment failure loading experiment
The loading wagon fallen due to the failure on right and extensive soil instrumentation arrangements on left

5.2 Creation of track stiffness measuring devices and the problems at transition zones

Novel rail-travelling apparatus for continuous measurement of track stiffness is being developed at TUT. Existing equipment or prototypes in other countries have been examined as a starting point of development and currently own prototype is under construction.

Standstill stiffness measurement techniques have also been developed and compared. An apparatus utilising acceleration sensor technology has proven to be a simple and the most effective method among camera applications, displacement transducers, geophones and falling weight induced deflection measurements. It has been applied successfully, e.g., in analysing/investigating bridge transition zone problems (Luomala and Nurmikolu, 2012).

5.3 Advancement of track geometry data analyses

The track geometry measurements carried out at least 4–6 times annually provide the best source of information on track performance and its development. More effective utilisation of this information is being studied. It is already clear that it is possible to increase the efficiency of asset management with the help of geometry development trends. A key role is also played by the integration of track inspection data with available track structure data (Silvast *et al.*, 2013).

6 Summary

High-speed passenger traffic sets a high demand for track smoothness. Ability to maintain the smoothness and avoidance of excessive maintenance need over the entire life cycle require optimal consideration of several factors related to ballast and sub-ballast materials, dimensioning and design. This paper summarized observations based on recent research results at TUT on phenomena causing unsmoothness and degradation of track condition as well as the means of managing them. On the other hand, one should remember that it is not worthwhile building a "too good" structure from the viewpoint of life-cycle economy by investing excessive amounts. Cold climate and possible mixed traffic pose special challenges for maintaining smoothness.

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