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A Review of Current Ballast Bed Assessment Practices Across the Nordic Countries

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Abstract

This study systematically reviews the current practices of railway ballast bed assessment across the Nordic countries, benchmarking Norway against Sweden, Denmark, and Finland. The primary assessment methods focus on regular visual inspections and alignment measurements, supplemented by additional sampling when necessary. The principal methodology typically involves non-destructive assessments to identify defects such as mud pumping, ballast shortage, and vegetation growth, primarily through visual inspections. These are confirmed via track alignment analysis, sampling, and Ground Penetrating Radar (GPR), though GPR is only used in Denmark and Finland. The study highlights varying regional criteria for ballast fouling and cleaning. There is a significant reliance on visual inspections which, while quick and non-intrusive, can be subject to inspector bias and may be challenging to verify. This underscores a potential area for the adoption of more advanced technological measures, which could lead to more precise assessments and more effective maintenance, ultimately optimizing the lifespan of railway infrastructure.

Keywords: railway ballast, Nordic countries, fouling, visual inspection, ground penetrating radar, sampling.

1 Introduction

The importance of the ballast bed for the overall performance of the track system is widely known. The ballast bed acts as the intermediate layer connecting the sleepers to the subgrade, key to the even distribution of traffic load while keeping the track in place. Shi et al. [1] describe the most important properties of the ballast bed, including ballast fouling. Indraratna et al. [2] describe how loading characteristics influences ballast behaviour and breakage. While Guo et al. [3] describe how tamping may increase ballast breakage. Ballast maintenance involves reprofiling and ballast cleaning, the latter having a cost of around 5,000 kr/m as a rule of thumb in Norway.

The ballast bed should be minutely assessed to initiate necessary maintenance for optimized performance. Corrective to detect deficiencies, or preventive to detect trends. Recent studies [4, 5] focus on non-destructive testing like Ground Penetrating Radar (GPR), but too little attention has been given to current practices, making comparisons between what could be done and what is actually done difficult.

Ballast assessment in Norway mainly focuses on regular visual inspection. About 36,100 inspections conducted between 2014 and 2024, detected about 3,400 defects. However, additionally 1,500 defects were reported in the same time by others (shown in Figure 2). 1,700 defects were reported without cause (shown in Figure 1). Inspections are conducted for each object in the asset management database, which may vary in length. One inspection might cover several kilometers while others may cover just a few meters. The same applies to reported defects. Unfortunately defects are only reported with a single distance value, so that both severity and extent has to be described for each defect. There is then a question whether the practices of the railway infrastructure manager Bane NOR SF's is sufficient to detect ballast deficiencies. Comparisons with practices from other countries could provide improved solutions.

The aim of this first article is to establish a framework for reviewing current practices in ballast assessment and benchmark the Norwegian practises against practices from the other Nordic countries. To investigate the research question: What are the current practices for ballast bed assessment in the Nordic region? This review will focus on main lines, excluding switches, bridges, tunnels, and stations, and will not cover aspects like sleeper condition, drainage, and vegetation growth.

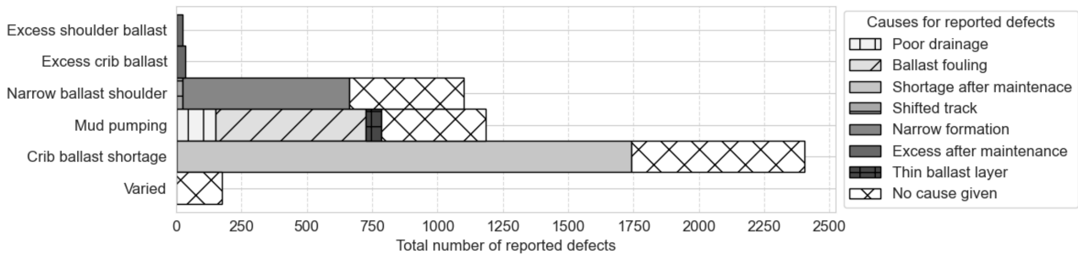

Figure 1: Ballast defects in Norway for main lines (2014-2024), excluding switches.

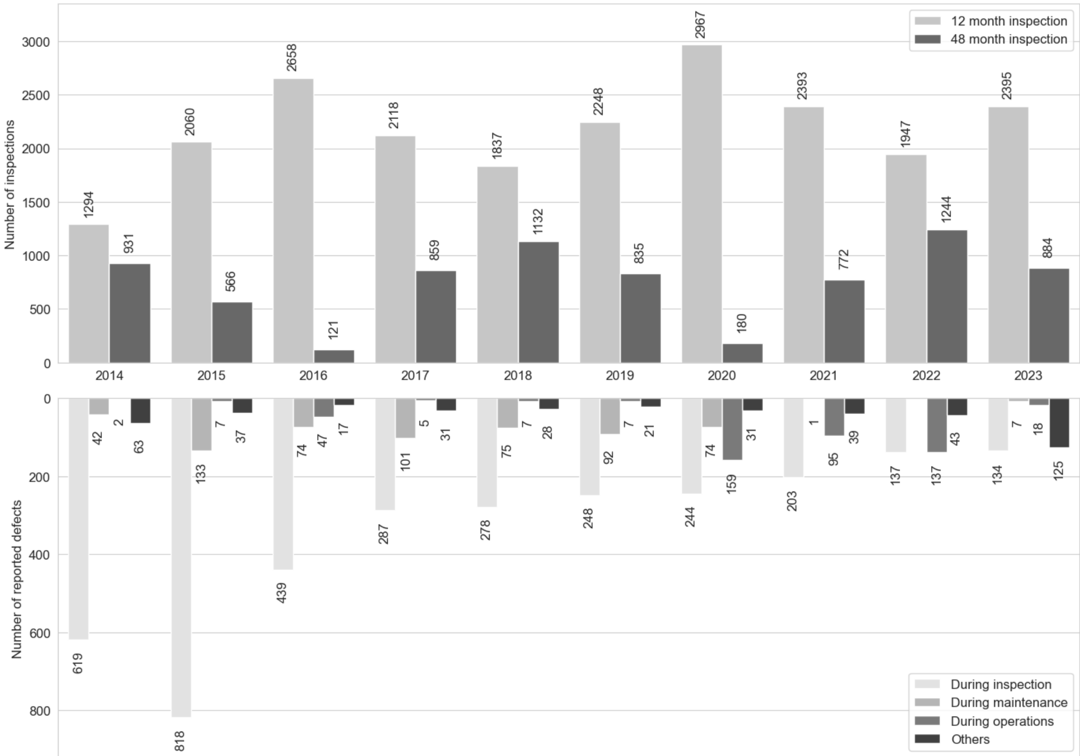

Figure 2: 12 months and 48 months ballast inspection for main lines in Norway with reported defects (2014-2024), excluding switches.

2 Methodology

The review is conducted on publicly available technical regulations and guidelines for ballast assessment as primary sources. Supplemented with secondary sources, i.e. scientific papers and reports, referenced or provided by the railway infrastructure managers. Personal communication is also included. The focus is on what triggers ballast assessments, how they are conducted, their frequency, and use of their results. The review is limited to the Nordic countries with railways due to their shared climate, geology and culture, and proximity.

Using official regulations and guidelines (primary sources) ensures that methods for ballast assessment are accepted and deemed adequate by the infrastructure managers. Only focusing on the primary sources may however lack detailed descriptions, limitations and experiences with the current methods and other emerging technologies. Also methods that have been implemented without updating regulations and guidelines could be missed. On the other hand, focusing on methodologies from scientific papers and reports (secondary sources) may lack the endorsement an infrastructure manager would provide as they may be unused, unfeasible, or unrealistic. Without affiliation with the infrastructure manager, giving the infrastructure manager no say with the method. This latter issue is overcome by only selecting papers and reports that either are refereed to by the infrastructure manager as secondary sources. Nevertheless, the lack of official approval makes the methodologies found only in these works less accurate when trying to answer the research question, and are therefore seen as not officially practised. A clear distinction between methodologies described in primary and secondary sources thus increases the reliability of this study.

All of the infrastructure managers, except BaneDanmark, maintain open databases containing scientific papers, commissioned reports, thesis and etc. A literature search is conducted with these libraries and databases for works since 2010 that include the search words "railway ballast", "ballast bed" in the respective languages. Sources deemed relevant by title and abstract are included.

Using material only publicly available from the infrastructure managers could limit this review as details with different practices may be found elsewhere. Such as other scientific databases, databases and maintenance systems belonging to the infrastructure managers, work descriptions found in contracts between the infrastructure managers and track maintenance contractor, or work procedures defined by the track maintenance contractor. This is mitigated by mainly focusing on the overall practise, while also highlighting missing information.

Personal communication verifies current practices and also provides further details on practical conventions not mentioned elsewhere. Contacts are established with national representatives in the European Rail Infrastructure Managers (EIM) association. Personal communication reduces the study's reliability because the information depends on the bias of the respondents, the questions, and the questioner. Additionally, information may be lacking as answers are not received to questions not asked. There is also a question whether the most suitable person at the infrastructure manager provides answers. Lastly, since personal communication is personal, received information cannot be peer-reviewed to the extent as a scientific paper would. To increase the reliability this study clearly states when personal communication contradicts other sources and exclude biased information.

3 Results

3.1 Norway

Visual inspections are the basis of ballast assessment in Norway, carried out regularly at set intervals, resulting in maintenance work orders to be rectified immediately, within one month, one year, or postponed [6]. The ballast bed is deemed to have a low safety risk, meaning that skipping inspections has a low likelihood for causing serious incidents. Ballast profile geometry (shoulder width, height and slope, and crib) is assessed annually through visual inspections, more frequent at sharp curves and high-risk areas [7]. Ballast fouling and plant residues that could reduce drainage are evaluated visually every fourth year, also noting sections with mud pumping [7]. Visually assessments, though easy, fast and non-intrusive, are influenced by the bias of the inspector and are difficult to verify. Clean ballast over a layer of fouled ballast may give the wrong impression when only inspecting the surface. However obvious deterioration such as mud pumping and vegetation growth will be detected.

Ballast profile measurement is done by the SMV3 - track recording car every third year using a LiDAR system, see Figure 3.

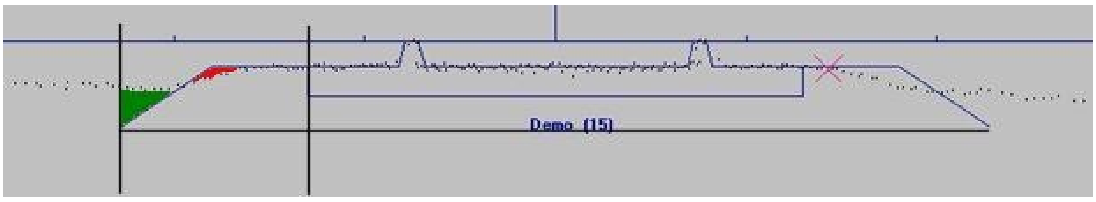

Figure 3: Measurements for ballast shoulder profile in Norway. Missing area are categorizes as adequate for <8 cm^2, with small discrepancies for 8 - 75 cm^2, or inadequate for >75 cm^2 [8].

Sampling, with sieve analysis, is used to determine ballast fouling and the need for ballast cleaning. Sampling could be carried out where it is difficult to get track adjustments to hold, and where settlements after track adjustment can not be attributed to subgrade or embankment faults, or at track sections with mud pumping or frost heaving within the ballast bed [9] Sampling methodology is not specified, but the requirement refers to ERRI [10], and the methodology for newly laid ballast (crib ballast down to the sleeper underside). When sampling an excising track, the material underneath the sleeper at the rail seat would be most interesting as it is subjected to the highest repeated load. However, retrieving this material could compromise the sleeper support and require additional tamping. As fouling rises from the bottom, sampling too high may not give an precise enough evaluation of the entire ballast bed.

Ballast fouling is determined by the 22.4 mm sieve and used to evaluate the need for ballast cleaning, which should be considered when ≥30% of the sample mass passes the 22.4 mm sieve. There is an except for the Ofoten line where ballast cleaning should be considered when ≥18% of the sample mass pass the 16 mm sieve, as it is a heavy-haul line [9]. The fouling criteria [10] was defined by whether the stability of the track could be improved by track adjustment or not. However, only a few of these sections were sampled in the study. The sampling method used when determining the fouling criteria required either sampling directly under a shifted sleeper or core drilling. The criteria was found to be when ballast fouling exceeded about 30% measured with the 22.4 mm square hole sieve, reached after 30 years on low traffic lines or after 400 million gross tons for high traffic lines. The criteria considers a single sieve size, not the entire particle size distribution (PSD). Which may reveal aspects regarding frost heaving [11], or drainage, shear strength and deformation resistance [1, 5], or shape and surface characteristics that could influence track settlement [12].

The implementation of EN 13450 has changed what is considered acceptable ballast material. For instance, in Norway, the acceptance limit for the smallest sieve was

$\leq 10\%$ for the 25 mm sieve [13] while the new limit requires $\leq 3\%$ for the 22.4 mm sieve [14]. Obviously restricting the initial permissible fouling. Lastly, as none of the Nordic countries were included in the study, the result becomes more questionable as aspects specific to the Nordics, such as geology and climate, were not included.

A methodology to determine if and when track adjustments would be deemed difficult to hold is not specified, and it is up to the experience and discretion of the regional track manager. Track alignment measurements are carried out by track recording car 1-6 times per year depending on maximum permissible speed. Track adjustments are made immediately, as soon as possible, or before the next measurement run when measurements exceeds threshold values for twist, longitudinal and lateral level, or track quality (Q-number). The latter is a combination of the standard deviation of the cant, longitudinal and lateral level [15].

Fractal analysis has been implemented in recently to determine local substructure faults such as blocked drainage culverts and overgrown ditches with long wavelength fractals. Mid wavelength fractals has not yet been utilized to assess ballast bed quality. However, both mid and long wavelength fractals has been used to estimate the overall need for track renewal. The methodology [16] uses fractal analysis on track alignment data to distinguish between track irregularities caused by mid wave or long wave faults originating from the superstructure (sleeper and ballast bed) or the substructure (subgrade, subsoil, and drainage). Verified on the Austrian and Swiss rail network, this method attributes a low mid wavelength fractal value to poor ballast bed performance and a low long wavelength fractal value to unsatisfactory drainage.

Ballast thickness is not evaluated in Norway. While GPR has been tested successfully [17], it is currently not in use for any purpose.

3.2 Denmark

Visual inspections of the ballast bed is undertaken, 1-4 times a year by walking and 6 times a year from a rail-going vehicle, to find and evaluate track defects such as poor track alignment and inadequate ballast profile (missing shoulder, missing crib, and ballast on the sleeper surface). The inspection interval may be shortened due to local conditions or events that may reduce the tracks' integrity such as extreme weather. The inspections by walking could be replaced by ballast profile scanning and video recordings [18]. Ballast condition is to be assessed visually annually, by video recordings of the track or inspections by walking, to determine the need for vegetation control, adequate drainage, the durability of track adjustments and ballast profile geometry [19].

Ballast profile measurement is also carried out continuously with a LiDAR system to measure shoulder width and estimate ballast shortage annually as informed by J. Johansen (Track System Supervisor, BaneDanmark, by e-mail 23. April 2024).

Ballast fouling is also determined by the 22.4 mm sieve, and ballast cleaning should be considered at sections with rapidly reduced track quality and need for frequent track adjustments attributed to fouling (exceeding 30%). Expected after 37.5 years or when the accumulated load reaches 700 equivalent million gross tons (EMGT). EMGT being the gross tonnage adjusted for speed and rolling stock wear, about 1.2-1.8 times the actual gross tonnage [19]. A special criteria is set for renewal at underpasses and bridges where the existing ballast bed must be replaced if fouling exceeds 22% [20].

Track recording cars measure all lines 0.5-6 times a year depending on maximal allowable speed and annual gross tonnage. Track adjustments are made immediately or within 3-12 months depending on the quality class of the line when threshold values for cant, twist, and absolute and standard deviation of the longitudinal and lateral level are exceeded [21]. J. Johansen (by e-mail 11. March 2024) informed that the both the running standard deviation for 50 m sections and the standard deviation over 200 m is calcualted and used to locate sections with further investigations. A frequent need for track adjustment would be if change in standard deviation of the longitudinal level for 200 m is equal to or higher than to the values given in Table 1.

Maximum permissible speed [km/h]	**Need for track adjustment**	**Change of SD over 1 year [mm]**
$200 < V \leq 250$	Every third year	0.10
$160 < V \leq 200$	Every third year	0.14
$120 < V \leq 160$	Every third year	0.18
$80 < V \leq 120$	Every third year	0.26
$V \leq 80$	Every third year	0.37

Table 1: Frequency for track adjustments in Denmark [19].

Ballast thickness measurement with GPR (accuracy ± 10 cm) or probe sampling (accuracy ± 5 cm) would in most cases be sufficient for assessing ballast bed condition, in addition to surveys considering cross-section and drainage, track behaviour and alignment measurements. Ballast thickness is measured with GPR for every meter, or by probe sampling at an interval of at least 50 m or 100 m depending alignment. The probing interval increases at underpasses and overpasses. Calibration of GPR is done with probing 1-2 times per kilometer [22]. By use of frequency analysis, GPR also allows for indications of fouling and moisture [23]. This could be done by calibrating the received signal with ballast fouling (<22.4 mm) and moisture content for the calibration samples from a survey. Making the indicated ballast fouling and moisture content relative to the calibration samples. J. Johansen (by e-mail 23 April 2024) informs that currently GPR is in limited use. Compared to probing GPR, is more imprecise, but detects fouling better. Analysis by track measurement and adjustment needs is normally adequate to determine precisely sections for further exploration where probing is used for the best result.

Sampling could be carried out for quality control of determined thickness (accuracy ± 2 cm) or for sieve analysis. At least 1 sample per kilometer when probing, and minimum 3 per 10 kilometer with GPR. Ballast samples should be taken by defined volumes, either the core sampling drill or the steel frame as described in EN-13450 [14]. Fouling is only considered for the mass underneath the sleepers [19] so the sampling depth is used to estimate ballast fouling using the equation (1) [22]. Quality control of the ballast cleaning is carried out by surveying the track cross-section every 5 - 100 m depending on the cleaning process. With at least 1 sample per kilometer that must be in accordance with the requirements for PSD for cleaned ballast [19].

$$v = \frac{v_t - (100 - v_t) * \frac{h}{d} * 0.04) * 100}{100 - (100 - v_t) * \frac{h}{d} * 1.04} \tag{1}$$

v : Adjusted percentage of ballast fouling (<22.4 mm) beneath the sleeper

v_t : Sample percentage of ballast fouling (<22.4 mm)

d : Total sample depth, measured from the ballast surface

h : Height from the sleeper underside to the ballast surface

BaneDanmark also provide a non-normative method of estimating remaining service life by assuming a linear relationship between traffic load and fouling, it is estimated that fouling (<22.4 mm) increases yearly with equation (2) [19]. However, the usefulness of so simple models may be questionable as fouling varies by geography, climate, traffic, tonnage, ballast quality and nearby structures [4].

$$R \sim \begin{cases} \frac{v_2 - v_1}{0.64}, & \text{if } T_c \leq 18.67 \\ \frac{v_2 - v_1}{0.034 * T_c}, & \text{if } T_c > 18.67 \end{cases} \tag{2}$$

R : Estimated remaining service life

v_2 : Estimated fouling (<22.4 mm) by the end of service life. Or 30%.

v_1 : Fouling (<22.4 mm). v (Equation (1)) or 6% after cleaning.

T_c : Yearly traffic load in million gross tons

3.3 Finland

Visual inspections are conducted annually according to the tracks' maintenance level, maximum speed, superstructure type and traffic, by track recording car (2-6 times), visual inspection from a moving vehicle (2-6 times), and walking visual inspection (1-3 times). The track recording car measures (longitudinal and lateral level, cant, twist and track gauge). Irregularities are categorized by maintenance level and severity as * (immediate action), D (corrected in near future), or C (to be monitored). The geometric quality (GKPT) is the percentage of kilometers with a satisfactory length of D-errors. >25 m of D-errors per kilometer is unsatisfactory [24].

Visual inspection from a vehicle evaluates ballast shortage and other defects affecting safety and maintenance, while visual inspections by walking evaluate ballast bed geometry and shortage [24] by limits for ballast profile geometry given by maintenance level, track, and superstructure type [25]. Inspections, track alignment measurements, error-classification, and GKPT are used annually to determine the need for track adjustment [25, 26]. H. Seppälä (Specialist Track Superstructure Väylävirasto, by e-mail 20. March 2024) informs that further investigations such as ballast sampling are initiated when repeated track adjustments are needed.

Sampling is carried out in test pits at the low rail at sites typical for the track under evaluation. Normally 1 test pit per kilometer, with 2-3 samples from each determined by visual stratification. A near vertical cut exposes the sleeper ends. Samples (5-10 kg) are retrieved horizontally from the exposed cut between the sleeper ends with a shovel, see Figure 4. An additional shovel is inserted as deeply as possible beneath the sample to capture seeping fines. Deviations may occur when stratification is clearly visible. Upon completion, the excavated bed is restored, and manually compacted and tamped. Samples are documented with pictures of the test pit, location, time, estimation of layer thickness, color, and a description. Laboratory analysis performed on samples may include sieve analysis, shape characteristics, density, resistance to abrasion, water absorption, pollution, and petrographic description [27]. Sample sizes do not meet the recommendations presented in EN 933-1 [28]. It is not described how this would affect the outcome, but one could assume a less precise PSD.

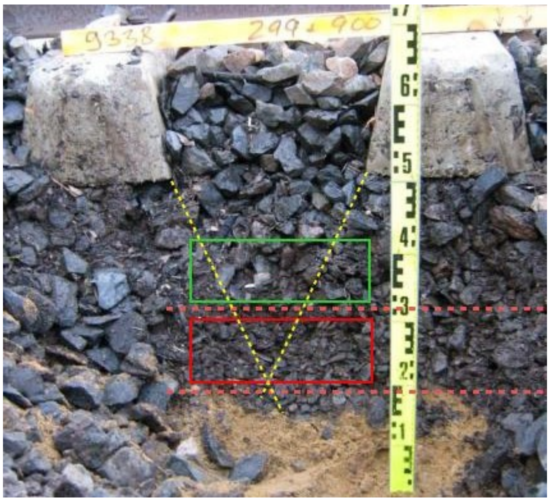

Figure 4: Location for ballast sampling in Finland, from an area 25 cm by 10 cm, 25 cm depth. For concrete sleepers at 13-23 cm beneath the sleeper underside for the upper sample and 23-33 cm for the lower sample [27, 29]

Ballast fouling is measured by the gradation number, the sum of percentages passing the 1 mm, 8 mm, and 25 mm sieves. When exceeding 90, the possibility of replacing or cleaning the track ballast should be evaluated [25]. Kuula et al. [26] estimated that the gradation number would increase by 0.5-2.0 per million gross tons. Sailaranta [29] found that samples collected at the sleeper ends at lower depths had a 33% higher gradation number than samples collected at 30-40 cm below the sleeper surface (the existing guideline at the time). The difference being especially clear for the

25 mm sieve, and concluded that the PSD is significantly affected by the sampling location. Which was as well noted by Nurmikolu [11] who furthermore observed that the gradation number increased at the end of the sleepers, compared to the center, and varied greatly when sampling consecutive kilometers. It was concluded that samples retrieved at intervals of one kilometer or more should only be used to determine average gradation number. A recommendation was made for sampling at levels considering the influence of fines on water retention and frost susceptibility, and the required voids for proper maintenance and deformation. A sample near the formation layer would disregard the possible good condition of the upper levels.

Nurmikolu [11] also commented that the use of only 1 mm and 8 mm sieve are better suited to determine fouling. Since the ballast grading 22/55 mm was used up to 1995 implied a greater initial gradation number compared to the 31.5/63 mm ballast grading used from 1995. Water retention and frost susceptibility would increase with increasing fines content making the 25 mm sieve too coarse for ballast assessment. A new fouling limit of 35 would correspond to the existing limit, at that time, of 88.

Before ballast cleaning, additional samples are taken every kilometer to assess the formation layer. Samples after cleaning ensure that PSD and particle shape requirements are met [30]. Nurmikolu and Kolisoja [31] showed how the percentage of returned material varied in the ballast bed after cleaning. Highest at the bottom and the sleeper ends. The resilient modulus decreased rapidly with increasing gradation number then less so as the material fouled. Resilient modulus with only returned ballast was similar to samples of uncleaned ballast, indicating the importance of fresh angular particles for recoverable deformation [31]. This highlights the importance of sampling methodology when comparing samples from ballast, and an argument could be made for also addressing shape and surface characteristics.

Ballast thickness and frost susceptible material could be determined with GPR, to provide locations for further investigations. With GPR-surveys extended down 3 m below the top of rail, calibrated with 2-5 samples per kilometer [32]. P. Tolla (Senior Geotechnical advisor, Väylävirasto, by e-mail 5. May 2024) informs that a one-time systematic network survey was carried out with GPR about 10 years ago, and after that some sections have been re-surveyed for track renewal projects. H. Seppälä (by email 30. April 2024) supports that GPR is mainly used in track renewal projects or to assess frost insulation needs but not as a part of regular maintenance. Silvast and Nurmikolu [33] describe how GPR could be used to estimate the gradation number. As fouled ballast attenuates the signal more at high-frequencies compared to clean ballast, a correlation between attenuated signal and the gradation number at a known depth could be determined. This correlation could then be used to determine a continuous classification of the network. However, H. Seppälä (by e-mail 30 April 2024) and P. Tolla (by e-mail 5. May 2024) inform that there are no current plans for fouling assessment with GPR.

3.4 Sweden

Visual inspections are either regular or safety inspections, the latter to verify that infrastructure does not reach a state with an unacceptable risk to life and property [34]. With regular inspections annually [35] and safety inspections 1-5 times a year [36] depending on inspection class (maximum permissible speed, annual tonnage, and a risk assessment evaluating defects and other aspects that may affect safety) [37].

Regular inspections determine whether there are conductive objects in the ballast bed, vegetation growth in or near the ballast bed, and the overall cleanliness. Also determination of whether the degree of fouling is unusually high. In addition, the assessment also includes visual inspections of abrasion around sleepers ("white spots") and insulated joints to determine reduced sleeper support [35]. Defects found during regular inspections are to be rectified according to their severity immediately (A), within 14 days (V), within 90 days (M), before the next inspection (B), within three years (Å) or when appropriate (Ö) [38]. A description of how to classify each ballast defect during regular inspection is not given, contrasting safety inspections which have precise description for classification (A, V, M, or B) to ensure that the ballast profile conforms to the standard cross sections [39, 40].

Ballast profile measurements are also conducted annually to every fourth year with the IMV100 - track recording car [41]. A complete ballast profile 2 m from the track center is recorded per meter and per section (100 m or one catenary span) [42], with the difference between measured and standard profile. Missing shoulder area is calculated to 60 cm outside the sleeper ends (75 cm when radius $\leq$500 m), and categorized for thresholds into <40 dm^3/m, 40-80 dm^3/m, or >80 dm^3/m per section.

Ballast fouling (<22.4 mm exceeding 30%) or ballast thickness less than 30 cm determines the need for ballast cleaning [43].

Sampling method is not described [43], but a reference is made to EN 13450 [14] and the fouling criteria by ERRI [10]. Sampling is usually done with the Markundersökningsmaskin (MUM), a rail-going core sample driller, complemented by manual excavation. The machine uses a tube with a 20 cm diameter, capable of retrieving samples down to 1.3 m below the top of rail out to 1.3 m from the center of the track [44]. An experienced geotechnical engineer categorize the retrieved ballast material as "approved" or "not approved", with material in the latter category to be put through sieve analysis. The samples are used with other data sources (earlier surveys, track alignment measurements, and maintenance and inspection reports, etc.) to estimate ballast thickness and condition [45]. The percentage of mass passing sieve 11.2 mm, 22.4 mm and 31.5 mm must be evaluated. Ballast service life is expected to be about 40 years [40]. Additionally, there are requirements [43] for cleaned ballast include PSD and particle shape from 1 sample per kilometer or 1 per 2,000 tonnes depending on the cleaning process.

EL. Olsson and J. Gunnarsson (Geotechnical engineering and Track Engineering Trafikverket, by-email 20. March 2024 and 8. May 2024) inform that sampling is not done regularly, only before track upgrading or renewal. With 4 samples per kilometer and 3 samples per switch with MUM. Weighing about 25-30 kg, samples are analyzed for fouling and pollution to determine need for fresh material for ballast cleaning, besides amount and end use of fouled material (landfill or recycled).

Ballast thickness and moisture may be determined by GPR to be used when evaluating load-bearing capacity and ballast bed quality, especially to determine track sections for further exploration with MUM [45]. However, EL. Olsson (by-mail 8. May 2024) informs that GPR is usually not used to investigate the ballast bed. Instead ballast thickness is visually determined with samples from MUM.

4 Conclusion and future work

A review of the current practices for ballast assessment in the Nordic countries has been done. Currently visual inspections and alignment measurements are used with sampling when needed, although not standardized. Fouling is evaluated by the 22.4 mm sieve, except in Finland where the sum of the 1 mm, 8 mm, and 25 mm sieve is used which may be more suited to emphasize frost-susceptible and water retaining fines. All infrastructure managers, except Bane NOR, determine ballast thickness by GPR, probing, sampling, or core drilling. All countries regularly measure ballast profile geometry, except Finland (Väylävirasto). Assessments are used to determine the need for and effectiveness of track maintenance such as track adjustments, ballast reprofiling, and cleaning.

Future improvements could involve utilizing GPR continuously to monitor ballast thickness, fouling, and moisture content, with fouling and need for maintenance determined by criteria for PSD, particle shape, and surface characteristics due to their influence on water-retention, frost, shear strength, and deformation resistance. With this in mind, Bane NOR could consider incorporating practices from Finland.

Future work is an expansion with state-of-the-art in ballast assessment and practices from other global infrastructure managers with similar climates or comparable network sizes and conditions. This will show gaps between the network wide practices for ballast assessment, and the possibilities for further research. A further review may also extend the scope with station areas, switches, bridges, tunnels, fixed installations in the track, and failure modes affecting ballast bed performance.

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