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Modelling and abatement of ground-borne noise of a new underground rail line

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This paper provides a case study of assessing and mitigating the environmental effects of ground-borne noise from a new underground rail line. The West Metro line is an extension to the current Helsinki metro, and runs through densely built city and suburban areas. In Finland, the environmental effects of ground-borne noise from rail lines are emphasized, as the local bedrock is very solid, and its surface is close to the ground level. Rail tunnels are commonly constructed directly into the bedrock. This forms an efficient propagation path for ground-borne noise inducing vibration to surrounding buildings, which are established close to the bedrock surface. The ground-borne noise assessment and the design of reduction measures were made during the planning phases of the West Metro line. A custom propagation model was used to calculate the areas and buildings around the metro line that would be affected by various levels of ground-borne noise. The model is a based on physical source and propagation modelling and calibrated with extensive empirical measurement data from the surroundings of the current Helsinki metro line. The modelling approach enabled accurate dimensioning of isolation for each part of the line, depending on the vicinity of individual sensitive buildings, such as homes, offices, schools, high technology facilities, churches and halls. The designed isolation consists of a total length of over 40 km of ballast mats that will be installed into the track bed. The first part of the metro line started operating in 2017, the second part is under construction.

1 Introduction

The Helsinki metro line is being extended to the city of Espoo by the West Metro line. The extension is built in two phases, the first of which started operating in 2017. The second phase is currently under construction and is planned to open in 2023. The total length of the West Metro line is 21 km, including a total of 13 new metro stations, shown in Figure 1. The whole line is built into underground tunnels blasted in bedrock. The tracks run in twin tunnels, that extend together at the station platform halls and track crossings.

Along the metro line there are hundreds of current buildings for housing, schools and office spaces, that are prone to the ground-borne noise caused by the metro trains. There are also numerous special facilities and premises that are very sensitive to noise or vibration, such as churches, theatres and research facilities operating highly sensitive scientific equipment. In addition, the city of Espoo is planning to establish several large new areas of housing in the immediate vicinity of the new metro line.

This paper presents a short description of the ground-borne noise assessments made for the West metro project, together with the noise abatement solutions that have been planned, built and taken into use. The purpose of the assessment has been to ensure, that ground-borne noise from metro traffic does not cause disturbance in the currently built and planned housing areas above and surrounding the metro line. The work has consisted of several phases: research and approval of acceptable design limits for ground-borne noise levels in dwellings and other spaces, the identification of individual areas and buildings susceptible to noise issues, the assessment of site specific ground-borne noise levels, and the planning and dimensioning of the required structural solutions for ground-borne noise mitigation.

Figure 1: The West metro line, shown in orange, extends from Helsinki to Espoo. The first phase from Ruoholahti to Matinkylä is already in operation. The second phase from Matinkylä to Kivenlahti is under construction. [image source: https://www.lansimetro.fi].

2 Background

2.1 Ground-borne noise as a phenomenon

Ground-borne noise is caused by vibrations coupled through the bedrock to building foundations and structures. The amplitude of the vibrations is so small that they cannot be sensed as vibration. However, the vibrating surfaces of a room space emit airborne noise and cause an audible low frequency rumble in the room.

Ground-borne noise from rail traffic is typically limited to a frequency range of 50–200 Hz. At frequencies lower than this, the sensitivity of hearing is low enough to limit noise annoyance. At higher frequencies the attenuation in bedrock and structural coupling increases rapidly, causing a low pass filtering effect.

A general description of rail system induced ground-borne noise as a phenomenon, its effects, metrics, measurement techniques, and prediction model principles can be found in [1].

2.2 Propagation of ground-borne noise

Rail traffic running in a tunnel blasted into bedrock can cause ground-borne noise immissions in the areas above and surrounding the tunnel. The bedrock in Finland is one of the oldest and hardest on the Earth, and vibration causing the ground-borne noise propagates particularly well through the rock. The attenuation at higher frequencies is considerably less than for softer types of rock and soil, such as those found in Central Europe and many other parts of the world. Due to the ice ages, the bedrock surface is exposed in many areas, or there is only a small layer of soil on top of it. The bedrock surface forms a very solid base for building foundations, so it is common for buildings to be in almost direct contact with the bedrock surface.

The annoyance of ground-borne noise is generally limited to a span of 100 m around the tracks in areas where buildings are founded close to the bedrock surface. For buildings that are founded on soil or on piles without contact to the bedrock, the coupling of ground-borne noise vibrations from bedrock to building structures is strongly attenuated: in this case a ground-borne noise area may not exist even directly above a train tunnel. At track switch and crossing areas the vibration stimulus includes impulses caused by the discontinuities of the rail surfaces. These have a considerable effect, but it is geometrically limited to small areas.

2.3 Temporal and local variance of ground-borne noise

Ground-borne noise from metro traffic appears only momentarily during a train bypass. On the other hand, the traffic density of the metro line is considerable: when considering traffic in both directions, there are about 50 train bypasses per hour.

Measurements have shown a large variance in the vibration emissions from the bypasses of individual metro train units. This is due to the differences between the various metro models, the speed of the train as well as the individual condition of wheelsets and tracks. The ground-borne noise levels vary also inside a building, due to the differences in distance from the tracks, variations in bedrock and building foundation conditions, the number of floors beneath, and room acoustical conditions. For these reasons, largest ground-borne noise levels appear only in a limited amount of buildings and room spaces, and only from certain train bypasses.

2.4 Target levels

There are no official limits for ground-borne noise from rail traffic in the Finnish legislation. The Technical Research Centre of Finland (VTT) has published a recommendation for ground-borne noise level limit value [2]. These are in close agreement with the design limits that have been used in the 2000's for new rail lines in Finland [3, 4].

The design limits for the West Metro line (Table 1) agree with the VTT recommendation. The abatement measures specified for the various track sections have been dimensioned to fulfil these limits. The limits for sensitive facilities such as churches have been individually set with site specific assessments. The design objective has been that the ground-borne noise from metro traffic does not considerably stand out from the normal background noise levels.

Table 1: Ground-borne noise target values used for the West Metro.

room type	L_{ASmax}, dB
sensitive facilities	≤ 20…25 dB
dwellings	≤ 30 dB
schools, meeting rooms	≤ 35 dB
offices	≤ 40 dB

3 Ground-borne noise assessment

3.1 Propagation modelling

The spreading, propagation and coupling of ground-borne noise has been assessed by using a calculation model, developed by Akukon Oy and Vibkon Oy [3-7]. The calculation model can be used to assess the ground-borne noise areas around both open air and underground rail lines. Possible traffic types include not only metro trains, but also trams, commuter and long-distance passenger trains as well as freight trains. The model takes into account the properties of the track structure, the bedrock attenuation and the coupling from the bedrock to the foundations and structures of buildings (see Figures 2 and 3). The model also includes factors for the length and type of trains or trams, as well as the effect of a double bypass from meeting trains.

The calculation model has been used and continuously developed over the last decade during the design of several new rail lines in the Helsinki area: the Vuosaari Harbour tunnel (freight trains, in operation), Kehärata/Ring Rail line (commuter trains on open track and in tunnels, in operation), Pisararata/City Rail Loop (commuter trains on open track and in tunnels, waiting for construction), Kruunusillat (tram line, under planning) and the West Metro line (phase 1 operating, phase 2 under construction).

The calculation modelling is made in the Matlab environment, enabling a full 3D modelling of the rail line, bedrock, soil and buildings, together with a wide range of tools for visualising the spreading of the ground-borne noise stimulus to the surroundings of the rail line. Calculations of land areas affected by structure borne noise also take into account the ground and bedrock surface meshes, soil information and building information, including location, foundation type, possible underground floors, and category of building use (dwellings/education/office/etc.). The modelling enables assessments not only for rail lines before they are built, but also for investigating the effects on new buildings and areas in city planning.

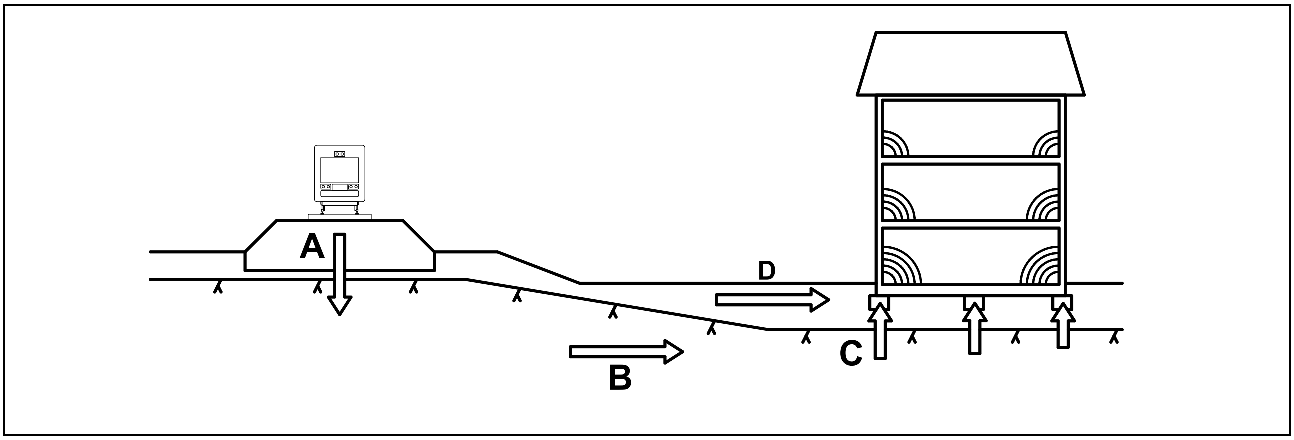

Figure 2. Paths of vibration coupling from the track structures to the bedrock, soil and to buildings.

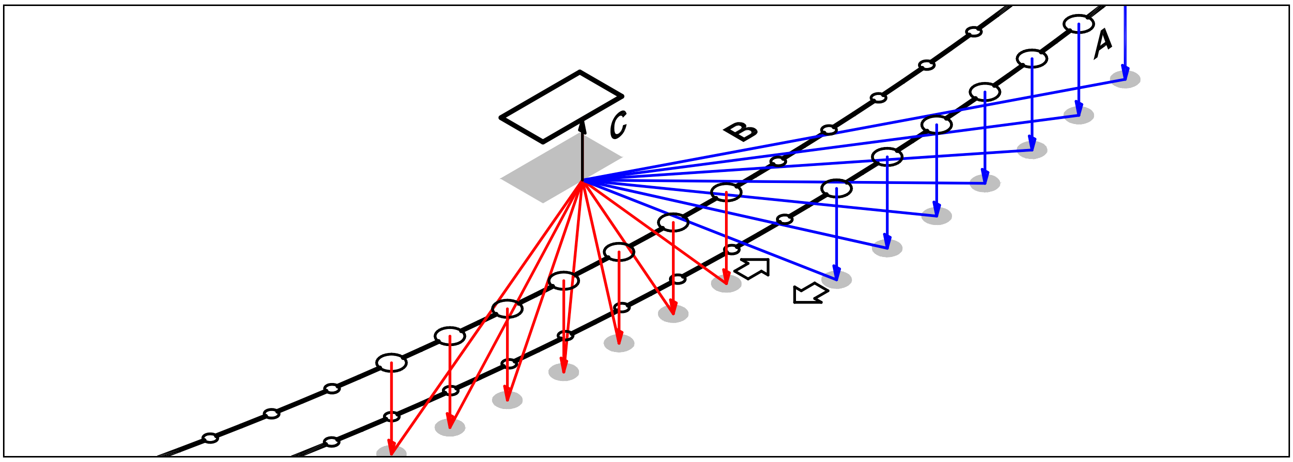

Figure 3. The rail line is modelled as point sources set at given distances from one another. A train passing stimulates a number of point sources: the vibration transfer is first calculated individually from each source point to the location of interest, then summed together for the whole train length. The maximum levels from train pass-byes are calculated using a sliding average. Using superposition, the method also enables the calculation of the total effects from several trains running on a number of adjacent tracks.

The calculation of ground-borne noise levels is based on an equation that is based on both theoretical and empirically determined terms. Equation (1) is given using decibel level quantities:

$$L_{pA}(r) = L_{vA}(r_0) - R\log(r/r_0) - k\,(r - r_0) - K_A - K_C + K_{p-v}\text{ , where} \tag{1}$$

$L_{pA}(r)$ is the ground-borne noise level at the location of interest [dB],

$L_{vA}(r_0)$ is the A weighted vibration velocity level at a reference distance r_0 (determined by measurements) [dB],

r is the radius from the closest point of track to the bedrock surface beneath the location of interest [m],

k is the attenuation due to internal losses in bedrock [dB/m],

K_A is a factor depending on the track structure and possible isolation structures (underballast mats) [dB],

K_C is a factor related to the coupling between bedrock and a building [dB], and

K_{p-v} is a transfer coefficient between the structural vibration velocity level and the noise level it causes in a room [dB].

The source level $L_{vA}(r_0)$ coupled to bedrock from the track structure, as well as the attenuation factors, have been determined empirically. These parameters may be further optimized using case specific measurement data. The effects of train type and speed have been built into the source level. The source level is measured empirically at a distance of 30…50 m from the tracks (r_0) being the typical range at which most affected buildings are situated. This yields smaller errors in calculation than using measurement points situated very close to the tracks.

The effects of bedrock attenuation are the most accurately known part of the propagation path, due to the wealth of actual measurement data available to the authors. The attenuation with distance comprises of geometrical attenuation $R\log(r/r_0)$ and loss related attenuation $k(r - r_0)$. Many of the other factors in the equation include uncertainties that may only be decreased with field measurements made at a representative location. The total number of factors affecting the ground-borne noise levels caused by a train pass-by to a given room space is so large, that the noise levels contain a built-in random variance even when measured under the same conditions. This makes it necessary to always include a certain safety margin in the dimensioning of ground-borne noise abatement measures.

3.2 Evaluation of the attenuation requirements

The needs for ground-borne noise mitigation were assessed by first calculating the spreading of ground-borne noise levels into the areas and buildings above and in the vicinity of the planned tracks. The ground-borne noise areas and building specific ground-borne noise levels were first calculated for unisolated tracks (see Figure 4). This shows the affected areas and buildings and forms a basis for the evaluation of attenuation requirements. The calculation portrays the areas where the ground-borne noise levels on the ground floor of buildings exceed given limits (30 dB and 40 dB in this case). The modelling enables the assessment of ground-borne noise levels and mitigation needs also for areas that have not yet been built. This way it has been possible to take into account the possibilities of city planning for new housing areas close to the metro line, long before either have been built.

All current buildings in the vicinity of the new metro line were assessed. The buildings were listed, and ground-borne noise limits were set according to their intended use. Next, the building specific ground-borne noise abatement requirements were calculated by comparing the limits with the calculated ground-borne noise levels for each building. The effects of building foundations and underground floors were taken into account according to the information available.

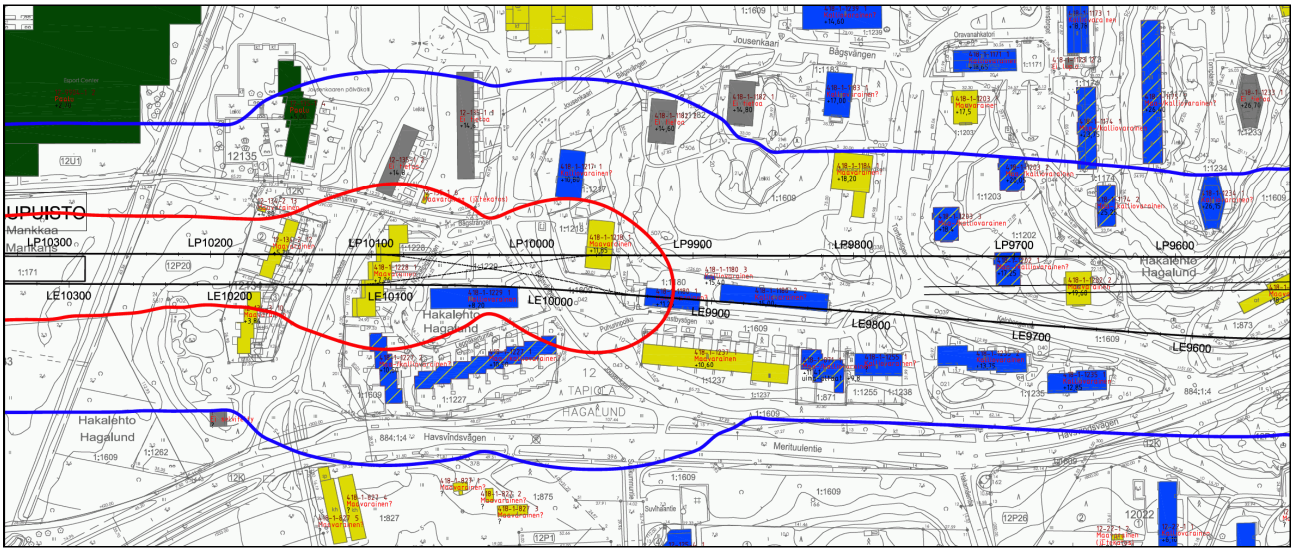

Figure 4. An example of calculated ground-borne noise regions without abatement. A large number of current dwellings are located inside the blue lines that represent the limits of the 30 dB ground-borne noise area. The red line represents the 40 dB ground-borne noise area.

3.3 Dimensioning of the attenuation

The abatement for individual track segments was dimensioned so that the given limits were fulfilled, taking into account all buildings and areas affected by the segment in question (see Figure 5). In areas planned to be built later, building specific ground-borne noise levels were calculated alongside the tracks assuming that the new buildings may be founded down to the bedrock surface at that point. The individual track isolation areas and isolation requirements for the under-ballast mats were then optimized in calculation.

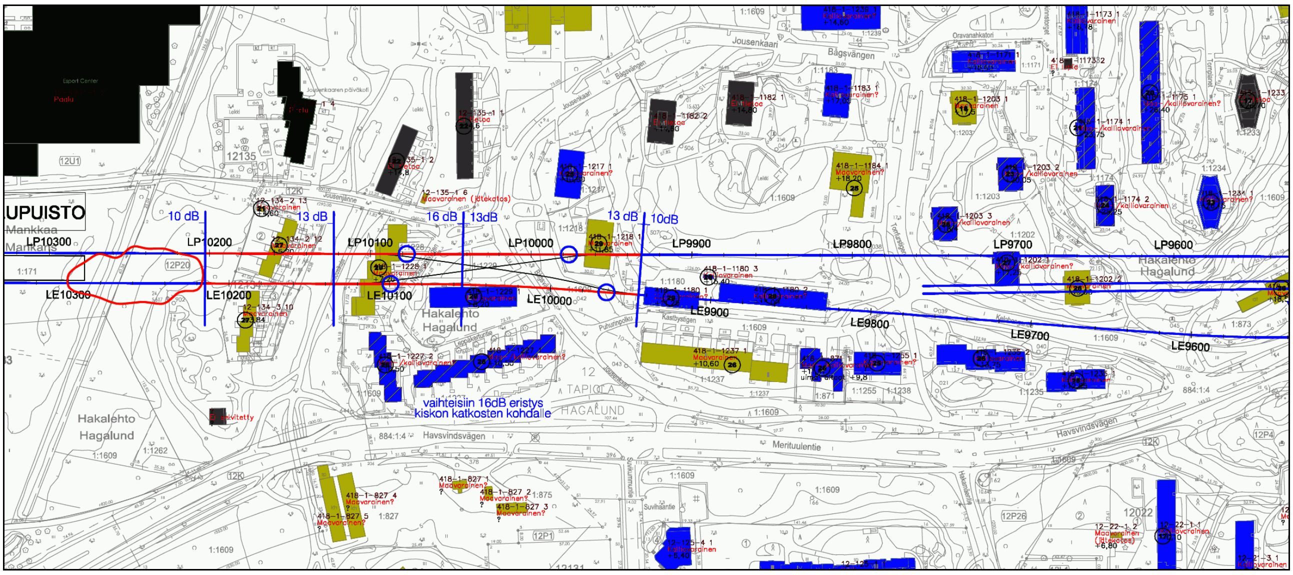

Figure 5. An example of ground-borne noise attenuation dimensioned on the tracks. The 30 dB ground-borne noise area (red line, limit for dwellings) now meets the bedrock surface only at a small area on the left.

4 Structural attenuation solutions

Under-ballast mats built into the track structure were used for mitigation of ground-borne noise. The location of the mats in the track structure is depicted in Figure 6. Three isolation classes were used: 10 dB, 13 dB, and 16 dB. The decibel values of the isolation classes portray the insertion loss ΔL_A to the ground-borne noise levels.

The tracks of the West Metro line are isolated for their almost complete length. The total length of isolated track is over 42 km, when taking into account the twin tunnels, track crossings and service tracks. The total requirement of under-ballast mats is around 170 000 m^2. The material costs of the ground-borne isolation are millions of euros. This is well worth the investment, as the risks of redeeming dwellings in the city areas due to exceeding ground-borne noise levels would be impedingly more expensive.

The dimensioning values and test results given by isolation material manufacturers vary in their background assumptions and basis and are thus seldom truly comparable with one another. For this reason, specific numerical criteria were set for the static and dynamic stiffness requirements of the isolation materials, and these were set as part of the technical approval criteria for the purchasing of isolation products. The fulfilment of the requirements was ensured by requiring each manufacturer to have these properties of their products tested according to DIN 45673-5 [8] at given independent testing institutions. The static and dynamic stiffness of materials can also be comparison tested to a good precision by the authors, using a special test rig developed for this application. On-site samples from product lots to be installed have been tested, providing the client with a third-party quality control during the construction phase.

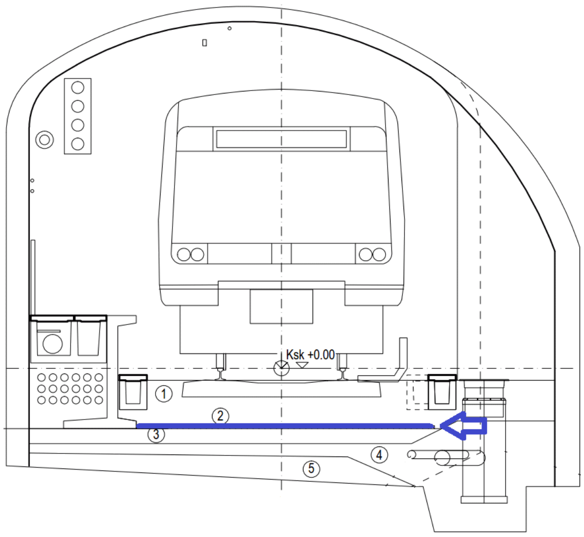

Figure 6. The location of the under-ballast mats in the cross section view of the West Metro tunnel. The isolation layer has been marked in blue.

5 Comparison of modelling and in-situ measurement results

The outcome and performance of the ground-borne noise isolation materials and measures were tested in 2017 during the test runs on the first phase of the West Metro line. A series of verification measurements was performed in quiet room spaces at the lowest floors of buildings founded on bedrock directly above the tracks. Each isolation class and material were measured separately. The measurement results showed that the ground-borne noise modelling and the installed under-ballast mats function as specified, and the ground-borne noise levels from the metro traffic are below the design limits along the line.

An example of ground-borne noise levels measured inside a dwelling is shown in Figure 7. The apartment is located on the first floor of an apartment building directly above the West Metro line, with 10 dB isolation installed in the track structures. The results portray the significant variation in ground borne noise levels from individual metro by-passes. The inherent background noise levels in dwellings (25…30 dB) are typically somewhat higher than the ground-borne noise from the metro traffic. This does help to decrease the subjective annoyance of the ground-borne noise, but makes the accurate measurement and analysis of ground-borne noise immissions more demanding. Typically, the measured noise signals have to be band-pass filtered in order to constrain the effects of background noise not caused by the metro traffic.

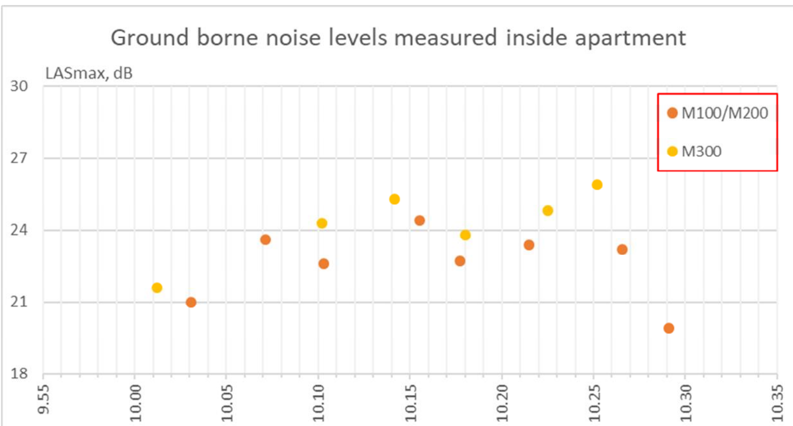

Figure 7. An example of ground-borne noise levels from metro traffic, measured inside an apartment located directly above the metro line. The horizontal axis shows a period of time from 9:55 to 10:35.

6 Summary

Ground-borne noise induced by a new underground rail line West Metro was assessed in the design phase of the line. The noise levels inside dwellings and other noise sensitive properties were estimated using a prediction method designed for various types of railway traffic: passenger and freight trains, trams, and underground trains. The West Metro line runs through densely built city and suburban areas, and the track and majority of buildings are founded on bedrock, so ground-borne noise abatement was needed for most parts of the line. Ground-borne noise design limits inside hundreds of buildings were achieved using under-ballast mats in the track structure. Control measurements have been performed for the first phase of the West metro, and the results clearly indicate that the calculation model and the abatement measures function as intended and the noise criteria are met. The second phase of the West Metro line is under currently under construction, and is planned to start operating in 2023.

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