Residential Vibration Exposure from Railway Traffic in Sweden

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ABSTRACT

Ground borne vibrations generated by train passages cause annoyance and sleep disturbance when the vibration velocity is too high in dwellings close to railway lines. In order to estimate how many people that are exposed to certain vibration velocities from railway traffic in Sweden, data almost 3 000 measurements of vibration have been used and classified according to geology at the receiving building and at the point on the railway line closest to the receiver. For 7 classes of geology the measurement results at the building foundation was used to estimate a simplified mathematical model, and by using 575 measurements of responses from foundation to indoor vibration velocity the weighted indoor levels could be predicted. Based on geological maps and a database of all properties close to railways the total number of exposed individuals in Sweden could be estimated. The results show that approximately 14 000 people are exposed to an rms-weighted maximum vibration velocity of 1.0 mm/s in their home in Sweden, which is about 65 percent higher than previous estimates.

Keywords: Ground-borne vibration I-INCE Classification of Subjects Number(s): 43.2.3

1. INTRODUCTION

The railway system in Sweden that is administered by Trafikverket, the Swedish Transport Administration, is about 14 700 km long (1). At the moment (2016) the accepted load per axle is between 22 tons and 25 tons, except on the northern railway Malmbanan, where the accepted load per axle is 30 tons (2). The trend is for even heavier loads per axel and there is also a demand for acceptance of both longer and faster freight-trains. The traffic load for passenger trains is also increasing, both regarding journeys and passenger kilometers travelled (3).

Nocturnal vibrations in dwellings cause sleep disturbance and annoyance among the people exposed (4). In laboratory sleep trials vibration exposure have been shown to cause awakenings, increased heart rate and sleep stage shifts if the vibration velocity is higher than approximately 0.4 mm/s.

Trafikverket has been measuring ground borne vibrations from railway traffic since before year 1980. The standard used to measure indoor comfort values is SS 460 48 61, which states that measurements should be performed in the room where the vibration levels are highest and where the vibration problems seems most annoying, in three directions; vertical, along the track and normal to the track (5). The comfort values are frequency weighted to root mean square (rms) values for evaluation. A geophone mounted on the foundation of the house is often used to trigger the comfort measurement geophone. The foundation geophone only need to measure in one direction and is used as a reference for the vibration events.

In year 1989 an investigation was made concerning the vibration situation in Sweden and estimations were made about people and railways affected by ground-borne vibrations (6). The result from the investigation can be seen in Table 1, for the amount of people and railway kilometers affected by vibration levels exceeding 0.5, 1.0 and 2.0 mm/s.

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Table 1 - Estimations of the amount of apartments and railway kilometers in Sweden affected by vibration levels exceeding 0.5, 1.0 and 2.0 mm/s in year 1990 (6).

>mm/s	Mainline network for freight trains		Total railway network	
	railway km	apartments	railway km	apartments
0,5	61	3300	141	6560
1,0	54	2340	80	3260
2,0	26	920	26	920

The purpose of the research presented in this paper have been to make up a model to estimate the amount of people exposed to certain vibration levels. Each axel of a train is modelled as a point source. The data used to estimate the amount of people affected by ground borne vibrations are extracted from a database of measurements performed for Trafikverket.

2. THEORY

2.1 Ground borne vibrations

All buildings included in the model are dwellings. We assume that the vibration in the ground close to the dwellings can be described by the simplified relation

$$1/r^n \tag{1}$$

where r is the radius of the circle or the distance to the point of the force and n is an attenuation constant (7). For the theoretical case of a point source on an infinite half-space n will be 0.5 far from the source for Rayleigh waves. If any damping is introduced n will be higher than 0.5.

In soft soil types vibrations occur at a frequency of 3.5-6 Hz in Sweden and in stiff soils, like till, the frequency of the ground-borne vibrations are higher than 15 Hz, often around 25-30 Hz (8).

Guidelines for ground-borne vibrations are valid in the frequency-span 1-80 Hz (9). An average for when vibrations can be felt by people is at velocity levels between 0.1-0.3 mm/s (weighted rms) for vibrations in the frequency range 10-100 Hz (8).

2.2 Data used for the method

The authority Geological Survey of Sweden (Sveriges geologiska undersökning, *SGU*) has a map covering most parts of Sweden’s surface, showing the type of soils and ground properties (10). Except for soil types, the maps show where there are visible rock. The ground properties are divided according to formation and grain size. In general the maps agree well with reality and the maps are more precise in southern Sweden and close to densely developed areas. The soil type or geological formation can though, according to SGU (10), sometimes differ with 25-100 m.

According to the authority Statistics Sweden, living in a detached small house is the most common way of living in Sweden with 2.7 people in average in each dwelling (11).

3. METHODS

Two collections of data have been used to make estimations of the amount of people affected by ground borne vibrations above certain velocity levels. The first collection of data is measurement data from a database used by Trafikverket that have been used to make a model of damping of vibrational energy as a function of distance. The second collection of data contains information about all buildings situated closer than 200 m to the railway system in Sweden. This collection have been compiled to a file, which will be called the nationwide collection of data throughout this paper. Only buildings close to the railways administered by Trafikverket are included in the two collections of data.

3.1 Data used for the model

The data compiled from the database are for buildings where the distance between the building and the railway is less than 500 m. The information for this collection includes the ground property below the building and below the railway, shortest distance between the railway and the closest point on the building as well as the type of building according to *Lantmäteriet* (the Swedish mapping, cadastral and land registration authority). The highest vibration level registered in the foundation of the building as well as a comfort value registered indoors is also included for each building.

All buildings stated as *unspecified* by Lantmäteriet have been checked if they are or could be a dwelling.

The different soil types or bedrock types represented in the database have been sorted into a total of ten groups with similar ground properties. So has been made with the nationwide collection of data. The soil types have been sorted according to their sensitivity for propagation of ground borne vibration. If a soil class could be sensitive for vibrations it would be sorted as that.

The vibration level at the foundation was plotted as a function of distance between the railway and the building. All plots have been analysed for outliers. For many outliers the ground property have been assumed as set wrong by SGU due to the resolution of the map and therefore changed into a more probable soil class, so has been done with buildings situated on *water* or *till alternating with sorted sediments*. Errors or data that have seemed to be wrong have been deleted or corrected.

3.2 Modelling a attenuation curve

The vibration level is assumed to decrease when the distance between the vibration source and the building is increased and only surface waves, i.e. Rayleigh waves, are assumed to cause ground borne vibrations that affect buildings, as described above. With energy losses included, the constant n in Equation 1 is increased to the constant, k, and the velocity level, v, at the distance, d, can be calculated by

$$v = m \cdot d^{-k}. \qquad (2)$$

where m is related to the source strength. By making the Equation 2 logarithmic and by using linear regression, the constants k and m can be found as a mean of all the input data.

To be able to use the model for as much data as possible the standard deviations have been calculated for the input velocity levels. Multiplying the mean velocity function with two standard deviations will result in a function for which 95 % of all probable results will end up below.

$$v_\sigma = 2 \cdot \sigma \cdot v_m \qquad (6)$$

3.3 Inserting input values to the model

Buildings along railways in Sweden are in general spread out with the same density at all distances from the railway according to the nationwide collection of data.

Results from the database with foundation vibration levels in the range 0-0.2 mm/s are set to the vibration level 0.1 mm/s for the model, since the result show there have at least been some problems with vibrations. When writing the amount of buildings with a foundation level registered, buildings with a velocity level set to 0.1 mm/s are included.

To make up for the loss of "low-vibration buildings" not represented in the database, input values have been made up and included among the data that the curves are based on. The area where vibrations are investigated (within 200 m from the railway) is divided into five equally wide spans. The total amount of buildings in a span is assumed to be equal to the amount of buildings situated within the span closest to the railway, n_{span1}, with registered velocity levels in the foundation. The other spans will consist of the quantity of buildings with a registered value in the foundation as well as an amount of input values. The amount of input values is the difference between n_{span1} and the amount of buildings, with registered foundation levels in the specific span, n_{spanX}. The input values are set to a vibration level of 0.05 mm/s. The distances for all input values within a span are set to a random distance within the specific span, using the command *rand* in MATLAB. The velocity as a function of distance has been calculated based on the measurement data and input values for each soil class group. As shown in Figure 1.

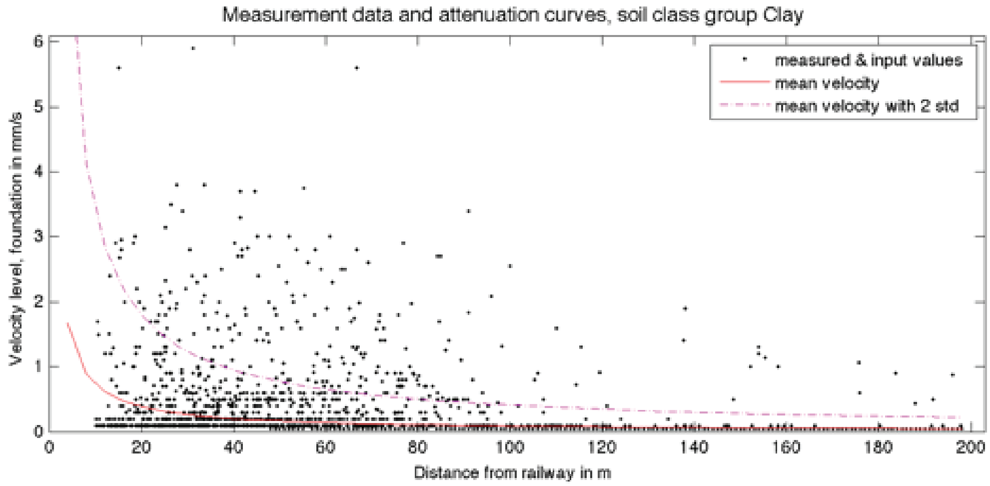

Figure 1 - Measurement data and attenuation curve for the soil class group Clay.

All functions showing the mean velocity including 2 standard deviations can be seen in Figure 2.

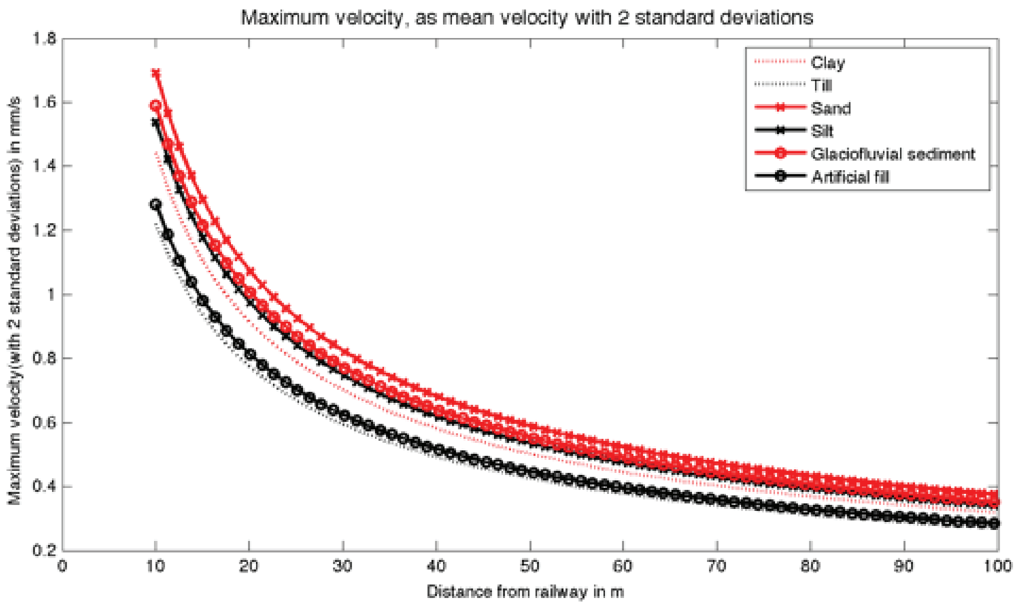

Figure 2 - All attenuation curves shown as mean velocities including 2 standard deviation.

3.4 Making estimations of people and buildings affected by ground-borne vibrations

The transfer factor for transmission from foundation to comfort value, TF_{fc}, is calculated from the vibration level measured in the foundation compared to the vibration level as an rms-weighted comfort value inside the same building. The Transfer factor TF_{fc} can therefore be seen as an indication of the relationship between the two values and is calculated as

$$TF_{fc} = v_{rms,comfort}/v_{foundation} \tag{6}$$

where $v_{rms,comfort}$ is the vibration velocity as a rms-weighted comfort value and $v_{foundation}$ is the vibration velocity level as a peak value in the foundation of the same building. The mean transfer factor, $TF_{fc,\text{mean}}$ has been calculated as a mean of the transfer factors calculated for all buildings, where both a foundation level and an rms-weighted comfort value is registered and where both values are larger than or equal to 0.2 mm/s, regardless of soil class group.

The buildings presented in the nationwide collection of data include all buildings in the area 0-200 m from the railway. Since the area within 10 m from the tracks have been seen as situated in the near field for vibration propagation and very few buildings are situated in this area the quantity of buildings in the area 10-200 m is assumed to be the same as in the area 0-200 m.

The distance 10-200 m has been divided into 10 m-wide spans. The quantity of buildings in each soil class group has been divided equally in the 19 spans, since the density of buildings in the analysed area is more or less the same at all distances as described above. The maximum expected velocity level, $v_{sigma,spanX}$, in the foundation of a building has been extracted from Equation 6 for the shortest distance (railway to building) in each span and soil class group. This is shown in Figure 3.

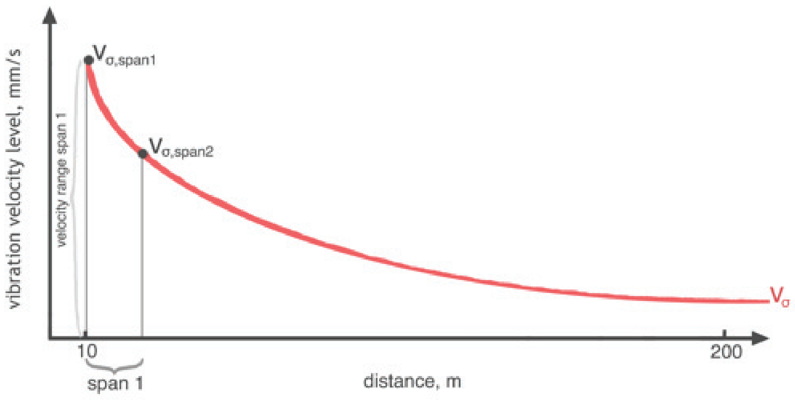

Figure 3 - description of how the velocity levels are found for each 10 m wide span.

All buildings in each span is assumed to have velocity levels in the foundation evenly distributed between the velocities 0 and the maximum velocity level in the span, $v_{sigma,spanX}$ creating a vector with estimated vibration levels in the velocity range of the span, $[0, \ldots, v_{sigma,spanX}]$. To transform the foundation levels into comfort levels, all foundation levels have been multiplied with the mean transfer factor, TF_{fc}. The quantity of values in each matrix has been found for vibration velocity levels exceeding 0.4, 0.7, 1.0 and 1.4 mm/s, which are levels stated in the guideline in used by Trafikverket and for the old estimations. To get estimations of the amount of people affected by vibration levels exceeding the levels mentioned above, the estimated amount of buildings exceeding a vibration level has also been multiplied with the 2.7 average amount of people living in the most common dwelling-type in Sweden.

4. RESULTS AND DISCUSSION

The mean transfer factor for transmission from foundation to the indoors comfort value was found to be 0.86 for all buildings with a registered vibration velocity value both at the foundation of the building and as an rms-weighted comfort value. The average transmission factor, TF_{fc} is based on 575 pair of values.

The *m*- and *k*-values for each soil class group as well as the standard deviation for each soil class group is shown in Table 2.

Table 2 - Constants to model transfer functions for different soil glass groups.

Soil class group	k-value	m-value	std	No. buildings in model
Clay	0.92	5.93	2.33	1 295
Till	0.81	2.67	1.98	404
Sand	1.09	13.52	2.77	642
Silt	1.0	10.82	2.55	262
Glaciofluvial sediment	1.07	10.38	2.58	281
Artificial fill	0.83	3.40	2.04	68

The group *Rock* has been excluded from the model because ground-borne vibrations, experienced as whole-body vibrations, does not propagate in rock. The groups *Clay till* and *Peat* have been added to the group clay. The same has been done with the group *Gravel*, which is included in the group *Glaciofluvial sediment*.

The amount of people and buildings affected by ground borne vibrations exceeding the velocity levels 0.4, 0.7, 1.0 and 1.4 mm/s are stated in Table 2 for each soil class group. The total amount of buildings with values exceeding the same levels and people living in these buildings can also be read.

Table 3 - The estimated amount of people and buildings affected by ground borne vibrations above certain velocity levels (rounded to hundreds).

Above the vibration level (in mm/s)	0.4	0.7	1.0	1.4
Total amount of people	54 100	25 000	14 200	7 300
Total amount of buildings	20 000	9 300	5 300	2 700

The model for estimating the amount of people affected by ground borne vibrations exceeding the guideline levels is based on a large set of data. A few of the data registered in the database are registered in the wrong way. Those data can though be seen as more of an exception especially since the set of data used has been analysed for errors.

The information about soil classes are, for all data, based on SGUs map for soil classes and the topcoat of the soil. The borders between to different soil classes are not extremely exact. Even though the soil classes are shown wrong in some areas, the final result should not be to affected since the soil classes are wrong in both ways, showing a more soft soil class in areas than reality and a more stiff soil class in other areas. Improvements for the model could though be to use more exact soil class data and the soil class below the railway could be investigated as well as the impact of a combination of the conditions under the railway and building.

The soil class group Clay is usually seen as the most sensitive for propagating ground-borne vibrations. According to this work it seems like the clay group is not as sensitive as many other soil class groups. An explanation could be that the soil class group clay contains a lot more data to base the attenuation curve on than any other soil class group.

5. CONCLUSIONS

1. The estimated amount of people affected by vibration levels exceeding 0.4, 0.7, 1.0 and 1.4 mm/s are 54 100, 25 000, 14 200 and 7 300 people respectively.
2. The model could be improved by using more precise soil class information.
3. The model could be used to improve the usability of Trafikverkets database for ground borne vibrations and to simplify analyzes of the probability that a certain vibration level affects a building.
4. The estimated amount of dwellings affected by vibration levels exceeding 1.0 mm/s is 65 % more than the previous estimate.

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REFERENCES

1. Trafikverket. Sveriges järnvägsnät. [Internet]. Borlänge: Trafikverket; [updated 2016-02-23; cited 2016-05-12]. Available from: http://www.trafikverket.se/Privat/Vagar-och-jarnvagar/Sveriges-jarnvagsnat/

2. Trafikverket. Järnvägstermer. [Internet]. Borlänge: Trafikverket; [updated 2016-02-23; cited 2016-05-12]. Available from: http://www.trafikverket.se/resa-och-trafik/jarnvag/sveriges-jarnvagsnat/jarnvagstermer/
3. Trafikanalys. Railway transport 2015, quarter 2. Trafikverket; 2015. 2015:25.
4. Smith M, Ögren M, Persson Waye K. Physiological reaction thresholds to vibration during sleep. Gothenburg: The Sahlgrenska Academy Institute of medicine; 2015. AMM 2015:02.
5. Standardiseringskommissionen i Sverige. Vibration och stöt - Mätning för bedömning av komfort i byggnader. Stockholm: 1992; SS 460 48 61.
6. Pagoldh C, Bähler, S. Godstågstrafikens stambanenät - Vibrationsstörningar från järnvägstrafik i Sverige. Stockholm: Ingemansson AB; 1990. S-5967-A.
7. Auersch L. Wave propagation in layered soils: Theoretical solution in wavenumber domain and experimental results of hammer and railway traffic excitation. Journal of Sound and Vibration. 1994;173(2):233-264.
8. Banverket, Naturvårdsverket. Buller och vibrationer från spårburen linjetrafik - Riktlinjer och tillämpning. Borlänge & Stockholm: Banverket and Naturvårdsverket; 2006. S02-4235/SA60.
9. International Organization for Standardization. Evalutaion of human exposure to whole-body vibration Part 2: Continuous and shock-induced vibration in buildings (1 to 80 Hz). Switzerland: International Organization for Standardization; 1989. ISO 2631-2: 1989 (E).
10. Sveriges geologiska undersökning. Produktbeskrivning - Produkt: Jordarter 1:25 000-1:100 000 (VISNINGSTJÄNST). [Internet]. Uppsala: Sveriges geologiska undersökning; 2015. [cited 2016-05-12]. Available from: http://resource.sgu.se/dokument/produkter/jordarter-25-100000-wms-beskrivning.pdf
11. Statistics Sweden. Villa vanligaste boendeformen. [Internet]. Stockholm: Statistics Sweden. 2014 [updated 2014-03-04; cited 2016-05-12]. Available from: http://www.scb.se/sv_/Hitta-statistik/Artiklar/Villa-vanligaste-boendeformen/