Characterization of Road Vehicle Induced Soil Vibration

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Abstract

An original method to evaluate vibration levels due to road vehicles is proposed. A measurement campaign has been carried out to individuate vibration acceleration levels for different typologies of vehicles. Each vehicle passage has been considered as a single event. Vibration levels due to each single event have been measured by means of a data acquisition system. Measurement results allowed to individuate the relations among vibration levels, typology of vehicle, vehicle velocity and soil characteristics. Thus, acceleration levels may be estimated at different distances from the vibration source by adopting a propagation model which has been previously proposed for train induced soil vibrations [1].

1. Introduction

Environmental impact assessments require the prediction of vibration induced by moving loads like trains and road vehicles. Actually, no suitable handy tool is available to predict road vehicle induced vibration for environmental impact assessment. Vibrations are very often predicted without a mathematical method but simply describing possible macroscopic effect induced by vibration.

In this paper a useful simple method for road vehicle induced vibration prediction is proposed. The method is based on a vibration source model (VSM) combined with a propagation model (PM); it allows to predict vibration levels due to a road by traffic fluxes and vehicles velocity data. VSM input data are vehicles typology and velocity: output data are vibration r.m.s. acceleration and level due to a single event (vehicle passage). Acceleration levels due to a single event have been individuated for three different vehicle typologies (cars, vans and trucks) by means of measurement results led along an Italian road. PM allows to determine vibration levels at different prediction point-road distances by taking into account soil absorption and divergence effects. Model results are given in terms of soil r.m.s. acceleration and vibration level. A measurement campaign has been carried out to compare measured levels at different prediction point-road distances with the ones attained with the proposed method. Measurement results have shown estimation errors due to the proposed method are less than 1.5 dB.

2. Theoretical Formulation

In order to estimate soil r.m.s. acceleration levels at a prediction point both vibration source and propagation phenomena must be modeled.

2.1. Vibration source model (VSM)

Energy transferred from a single vehicle (vibration source) to soil is an instantaneous quantity which is governed by complex mechanism the behavior of which is difficultly identifiable. The following simplifying hypothesis is introduced: each vehicle passage is considered as a single event. R.m.s. acceleration due to a single event and single event vibration level (SEVL) at an evaluation point depend on vehicle typology, vehicle velocity and soil characteristics. SEVL dependence on soil characteristics may be neglected if a near road-prediction point distance is considered [1]. For a road centre line – point distance $d_0 = 3$ m (see Fig. 1), energy absorbed by a typical compressed high density soil during the source-prediction point path is less than 3% (see Eq.3).

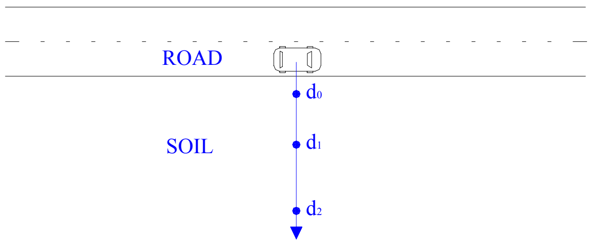

Figure 1: Model reference scheme.

Thus, r.m.s. acceleration at d_0 distance may be represented by the following statement:

$$a_0 = a_0\,(TYP, v_v) \tag{1}$$

SEVL at d_0 distance may be written as follows [2]:

$$SEVL_0 = 10 \cdot \log\left(\frac{a_0}{a_{ref}}\right)^2 = SEVL_0\,(TYP, v_v) \tag{2}$$

2.2. Propagation model (PM)

Vibration waves propagation has been modeled adopting the following hypothesis:

1. Road is considered to be an emitting source the length of which corresponds to vehicle length [3].
2. Vibrational energy is transported only on soil surface by means of Rayleigh waves since their amplitude exponentially decreases along a vertical direction, perpendicular to soil surface. Primary, Secondary and Love waves are not kept into account [4].
3. Each source is characterized by a superficial omnidirectional vibrational energy emission [1].

When a not dissipative media is considered, vibrational energy transported by Rayleigh waves through soil surface decreases proportionally to 1/d. According to hypothesis 1, 2 and 3, time average intensity at a generic prediction point P may be found by calculating power which passes through a P centered unitary diameter circle [1]:

$$J_d = \frac{W_d}{2 \cdot \pi \cdot d} \qquad (3)$$

W_d represents the total power produced by an elementary source which is available at d distance from the elementary source itself. W_d may be determined as follows [1]:

$$W_d = W_0 \cdot e^{-\alpha \cdot d} \qquad (4)$$

Thus, time average intensities relative to a generic d distance and d_0 reference distance are:

$$J_d = \frac{W_0 \cdot e^{-\alpha \cdot d}}{2 \cdot \pi \cdot d}$$

$$(5)$$

$$J_o = \frac{W_0 \cdot e^{-\alpha \cdot d_0}}{2 \cdot \pi \cdot d}$$

Thus, the following relation may be written:

$$\frac{J_d}{J_0} = e^{-\alpha \cdot (d - d_0)} \cdot \frac{d_0}{d} \qquad (6)$$

Absolute value of r.m.s. acceleration is attained by the following equation [4]:

$$\frac{J_d}{J_0} = \frac{a_d^2}{a_0^2} \qquad (7)$$

Thus:

$$a_d = a_0 \cdot \sqrt{e^{-\alpha \cdot (d - d_0)} \cdot \frac{d_0}{d}} \qquad (8)$$

and:

$$SEVL = 10 \cdot log \left(\frac{a_d}{a_{ref}} \right)^2 ; \quad a_{ref} = 10^{-6}\, m/s^2 \qquad (9)$$

3. Measurement Method

A measurement campaign has been carried out in order to:

- individuate $SEVL_0$ values relative to different vehicle typologies;
- compare SEVL given by the proposed method to the measured ones for different vehicle typologies, vehicle velocities and prediction point-road distances.

Three vehicles typologies have been individuated:

A) Cars;
B) Vans;
C) Trucks.

Measurement points have been placed along a straight part of a street sited close to Terni in Italy; no bridge, crossroads, bends and ditches are located near the measurement points. Vibrations have been measured for different vehicle velocities at the following prediction point- road centre line distances:

- 3 m for $SEVL_0$ individuation;
- 6, 7 and 10 m for prediction method-measurement results comparison.

Soil particles acceleration components have been measured by means of accelerometers (model PCB 393C, see Fig.1). Accelerometric signals have been acquired and processed by means of 01dB Symphonie acquisition data system. Signal processing allowed to calculate a_x, a_y and a_z r.m.s. acceleration components from the vehicle-induced instantaneous accelerations time history. Measurement site soil is composed by compressed high density sands the characteristics of which are $E=90 \cdot 10^6$ Pa and $\upsilon=0.2$ [6].

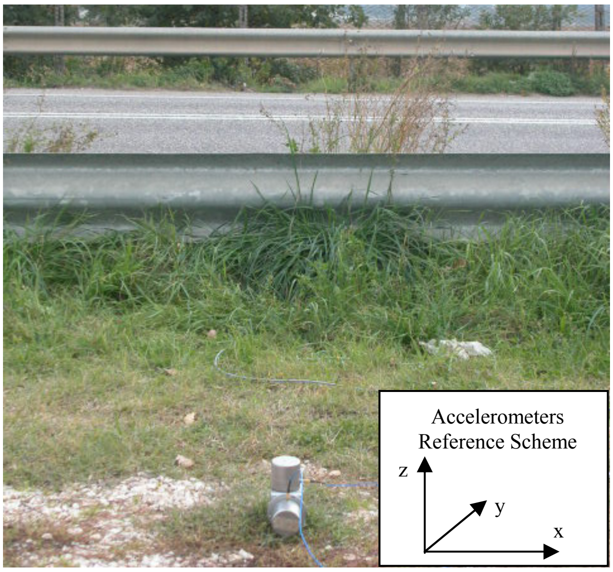

Figure 1: Picture of the measurement site

SEVL due to a single event (vehicle passage) has been calculated as follows:

$$SEVL = 10 \cdot log\left(\frac{a}{a_{ref}}\right)^2 = 20 \cdot log\left(\frac{\sqrt{a_x^2 + a_y^2 + a_z^2}}{a_{ref}}\right) \quad (10)$$

4. Measurement Results

4.1. SEVL$_0$ Individuation

Measurement results relative to 3 m prediction point-road centre line distance are reported in Table 1 for A, B and C vehicle typologies. Table 1 shows measured r.m.s. acceleration and SEVL$_0$ values for different vehicle velocities.

Table 1: measurement results for SEVL$_0$ individuation

Vehicle Typology	Vehicle Velocity (km/h)	r.m.s. Acc. Values (m/s^2)	Measured SEVL$_0$ (dB)
A	72,4	0,001145	61,00
A	84,3	0,001407	62,98
A	87,0	0,001389	63,34
A	94,7	0,001634	64,24
A	96,5	0,001637	64,42
A	101,4	0,001797	64,90
A	102,4	0,001819	64,99
A	105,0	0,001967	65,22
A	109,9	0,001892	65,62
A	115,5	0,002045	66,04
A	127,9	0,002054	66,84
A	142,6	0,002369	67,61
B	65,0	0,003259	70,40
B	70,6	0,003767	71,77
B	72,5	0,003934	72,16
B	78,6	0,004665	73,27
B	84,2	0,005095	74,11
B	85,0	0,005352	74,22
B	91,0	0,005729	74,97
B	95,0	0,006071	75,42
B	101,2	0,006312	76,03
B	115,6	0,007156	77,19
B	120,5	0,007399	77,53
B	125,2	0,007789	77,82
C	55,1	0,003934	72,22
C	61,6	0,005868	74,80
C	65,5	0,006451	75,97
C	70,1	0,006956	77,09
C	71,7	0,007611	77,43
C	77,3	0,008411	78,49
C	78,1	0,008678	78,63
C	80,4	0,008845	78,99
C	86,6	0,009441	79,87
C	88,2	0,009873	80,07
C	90,1	0,010190	80,30
C	100,2	0,011895	81,37

Results allowed to individuate the following relation for SEVL$_0$ individuation:

$$a_0 = K \cdot ln\left(\frac{v_v}{v_0}\right); \quad v_0 = 40\ km/h \quad (11)$$

where

$K = 0.00189$ m/s^{-2} (A typology - car)
$K = 0.00682$ m/s^{-2} (B typology - van) (12)
$K = 0.01275$ m/s^{-2} (C typology - truck)

SEVL may be estimated at different distances by combining Eqs (8), (9) and (11):

$$SEVL = 20 \cdot log\left(\frac{K \cdot ln\left(\frac{v_v}{v_0}\right) \cdot \sqrt{e^{-\alpha \cdot (d-d_0)} \cdot \frac{d_0}{d}}}{a_{ref}}\right) \quad (13)$$

Thus, the proposed model allow to estimate vibration level due to a road at a generic distance by the knowledge of N_i traffic fluxes relative to each vehicle typology:

$$VL = 10 \cdot log\left(10^{\frac{SEVL_{car}}{10}} \cdot N_{car} + 10^{\frac{SEVL_{van}}{10}} \cdot N_{van} + 10^{\frac{SEVL_{truck}}{10}} \cdot N_{truck}\right) \quad (14)$$

4.2. Comparison between model and measurements results

Tables 2, 3 e 4 shows the comparison between measured SEVL values and the ones obtained by the proposed model for different point-road distances.

Table 2: comparison between the proposed evaluation method and measurement results (A vehicle typology)

Road-point distance (m)	Vehicle Velocity (km/h)	Measured SEVL (dB)	Estimated SEVL (dB)	Δ (dB)
6	113,7	62,10	62,77	0,68
7	58,2	53,80	53,16	-0,65
7	62,2	54,31	54,58	0,27
7	75,9	57,56	57,81	0,25
7	86,8	59,34	59,46	0,11
7	88,0	59,96	59,62	-0,34
7	93,6	59,34	60,27	0,93
7	96,6	59,87	60,58	0,72
7	103,0	61,34	61,19	-0,15
7	127,9	62,48	62,98	0,50
10	73,0	55,19	55,58	0,39
10	95,1	58,33	58,75	0,42
10	118,0	59,87	60,68	0,81

According to Tables 2, 3 and 4, maximum estimation error Δ is:

- Less than 1.0 dB (A typology - car)
- Less than 1.2 dB (B typology - van)
- Less than 1.5 dB (C typology - truck)

Absolute maximum estimation errors relative to C typology are greater than A and B ones. This fact is due to the trucks mass which is highly dependent from the load.

Table 3: comparison between the proposed evaluation method and measurement results (B vehicle typology)

Road-point distance (m)	Vehicle Velocity (km/h)	Measured SEVL (dB)	Estimated SEVL (dB)	Δ (dB)
6	88,4	70,79	71,52	0,72
6	90,3	71,22	71,75	0,54
6	111,7	72,62	73,77	1,15
7	92,1	72,26	71,25	-1,02
7	95,6	72,38	71,63	-0,75
7	101,4	71,62	72,19	0,57
7	102,3	72,26	72,28	0,02
7	120,4	73,18	73,67	0,48
10	68,0	65,88	65,64	-0,24
10	70,5	65,37	66,21	0,84
10	72,1	66,14	66,55	0,41
10	91,6	68,69	69,51	0,82
10	99,6	70,04	70,35	0,31

Table 4: comparison between the proposed evaluation method and measurement results (C vehicle typology)

Road-point distance (m)	Vehicle Velocity (km/h)	Measured SEVL (dB)	Estimated SEVL (dB)	Δ (dB)
6	62,1	70,94	71,84	0,90
6	110,1	78,78	79,08	0,30
6	73,8	73,30	74,72	1,42
7	69,9	73,51	73,20	-0,31
7	74,8	73,82	74,18	0,36
7	77,9	73,92	74,73	0,81
7	80,1	74,69	75,08	0,39
7	86,6	75,43	76,02	0,59
7	87,3	76,29	76,10	-0,20
7	95,4	76,45	77,04	0,59
10	70,4	70,94	71,62	0,69
10	82,7	73,51	73,79	0,29
10	92,6	74,69	75,05	0,36

5. Conclusions

The proposed method for road vehicle-induced soil vibration prediction furnishes vibration level due to a road by traffic fluxes and vehicles velocity data. The method is based on the determination of single event vibration levels (SEVL) due to a vehicle passage. A vibration source model has been individuated by means of a measurement campaign. Measurement results have shown that r.m.s acceleration values depends on vehicle velocity by a logarithmic relation. SEVL relations at a 3 m prediction point-road reference distance have been individuated for three different vehicle typologies (cars, vans and trucks). A propagation model has allowed to estimate SEVL for different distances [1]. Predicted values have been compared to the ones given by a measurement campaign. Results have shown a 1.5 dB maximum estimation error. The proposed model will be improved by collecting vibration data regarding different soil and vehicle typologies.

6. Symbols

Symbol	Units	Description
a_d	$m \cdot s^{-2}$	r.m.s. acceleration at d distance
a_0	$m \cdot s^{-2}$	r.m.s. acceleration at d_0 reference distance
a_{ref}	$m \cdot s^{-2}$	reference acceleration
a_x	$m \cdot s^{-2}$	r.m.s. acceleration x-component
a_y	$m \cdot s^{-2}$	r.m.s. acceleration y-component
a_z	$m \cdot s^{-2}$	r.m.s. acceleration z-component
α	m^{-1}	soil dissipation constant
d	m	distance between prediction point and vehicle
J_d	$W \cdot m^{-1}$	average vibration intensity transferred by vehicle to surrounding soil at d distance
J_0	$W \cdot m^{-1}$	average vibration intensity transferred by vehicle to surrounding soil at d_0 distance
K	$m \cdot s^{-2}$	VSM calibration costant
N_i	adimensional	Traffic flux due to i-th vehicle typology
SEVL	dB	single event vibration level
$SEVL_i$	dB	single event vibration level due to i-th vehicle typology
$SEVL_0$	dB	single event vibration level at d_0 reference distance
TYP	acronym	vehicle typology
v_v	$m \cdot s^{-1}$	vehicle velocity
VL	dB	road vibration level
W_0	W	power transferred by vehicle to surrounding soil
W_d	W	power transferred by vehicle to surrounding soil at d distance

7. References

[1] Rossi F., Nicolini A., "A simple model to predict train-induced vibration: Theoretical formulation and experimental validation", *Environmental Impact Assessment Review*, Vol.23, Elsevier, 2003.

[2] Beranek L.L., Ver I.L. *Noise and Vibration Control Engineering: Principles and Applications*, Interscience, 1992.

[3] Le Houdec D., "Modelling and Analysis of Ground Vibration Problems: a Review.", *Civil and Structural Engineering Computing*, Chapter 19, 2001.

[4] Hunt H.E.M., *Measurement and Modelling of Traffic Induced Ground Vibration*, Ph.D. Thesis, Cambridge University, England, 1988.

[5] Spagnolo R., *Manuale di Acustica*, UTET Libreria, Torino, 2001.

[6] Pialli G., *Carta Geologica dell'Umbria*, 1995.