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GROUND VIBRATIONS: A NEGLECTED EXTERNAL COST IN THE LIFE CYCLE OF TRANSPORTATION INFRASTRUCTURE?

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Abstract. External costs, which are usually taken into consideration during cost-benefit analysis of different variants of a transportation problem solution, are traffic accidents, noise, and emissions of pollutants including effects on climate changes and congestion. Sometimes some other costs can be included. The effects of ground vibrations during the life-cycle of transportation infrastructure are very often neglected. The most threatening sources of vibrations are blasts and drilling during tunnel construction, vibrations caused by construction machines during road construction and pavement maintenance and vibrations caused by heavy road traffic. During the construction of the motorway in southeastern Slovenia, all these effects were measured and analyzed. The results can help ministries responsible for spatial planning, environment and transportation, to solve some major problems about: i) how to decide about variants of future infrastructure in which external costs are gaining in importance and damage caused by ground-borne vibrations was one of the most neglected criteria in the past and ii) how to decide about requirements about financial compensation to inhabitants affected by transportation infrastructure.

Keywords: external costs of transport, ground vibrations measurement, blasting of tunnels, vibrating rollers, heavy traffic.

1. Introduction

There are two strategic motives behind research work about the impact of ground vibrations on health of exposed human bodies and buildings. Densely populated countries are still developing its transport infrastructure system, particularly motorways and high speed railways. Ministries responsible for spatial planning, environment and transportation are faced with two major problems:

- How to decide about variants of future infrastructure in which external costs are gaining in importance? Damage caused by ground-borne vibrations was (and still is) one of the most neglected criteria in the past. The major problem is the missing evidence about effects of building, maintaining and exploitating transportation infrastructure on the built environment (including people).
- How to decide on requirements about financial compensations of inhabitants affected by transportation infrastructure?

The external costs, which are usually taken into consideration during cost-benefit analysis of different variants of transportation problem solutions, are traffic accidents, noise, and emissions of pollutants including effects on climate changes and congestion. Sometimes other externalities, like sealed soil, visual intrusion etc. are also taken into consideration (Maibach et al. 2008; for example). The effects of ground vibrations during the life-cycle of transportation infrastructure are very often neglected.

The opportunity to study effects of ground vibrations was given during the construction of a new motorway in Slovenia. An old building was situated very closely to the new motorway construction site where during a short period of time blasting, vibrating and heavy traffic were present. This real life situation was studied and compared with reports from experiments in a laboratory.

2. Ground vibrations

During the life-cycle of a motorway a lot of vibration are produced. These, in general, propagate from the source through:

- air, where noise-like vibrations are produced and
- ground, where earthquake-like vibrations propagate.

Ground-borne vibrations will be studied in the continuation.

There are several sources of ground vibrations which may cause structural damage, particularly in urban areas. Focusing on the life-cycle of motorways, the most threatening sources of vibrations are:

- tunnel blasts during construction including drilling,
- vibrations caused by construction machines during road construction and pavement maintenance and
- vibrations caused by heavy road traffic.

The effects of these vibrations on buildings, as well as on their occupants, are complex and have been studied a lot in the past. The fact that human body senses and responds to vibrations in a different way than sophisticated scientific measurement equipment makes the task of reducing the negative impact even more difficult (Hume 2010). The impact of railway traffic has been studied the most (ISEV 2005). There is also a lot of evidence on damage caused by road traffic (Watts 1988) and the measurement and prediction of (airborne and ground-borne) vibrations (Hunaidi 2000, Crispino et al. 2001). Some recommendations and evidence can be also found on countermeasures against road traffic vibrations (Tokunaga et al. 1999, DfT 2010). Suppressing the ground vibration effects generated by blasts of commercial explosives in tunnel construction on buildings in the surrounding area is important. The same problem, namely to achieve the greatest possible effect of vibrations and the least possible mitigation, is to be solved also during the implementation of (compressing, vibrating) construction machinery. The intensity of ground vibration is influenced by numerous factors studied on a lot of specific sites (Kuzu et al. 2008, for example).

3. Physical characteristics of vibrations caused by blasting

Seismic waves resulting from blasting cause movements of soil which are manifested by non-stationary periodic fluctuations. When seismic waves reach the facility, part of the energy fluctuations in soil transfers to the foundations of the building. Dynamic forces in these structural assemblies cause stress. High intensity of seismic waves can cause stresses which can result in permanent deformation and local destruction of the building. The intensity of the earthquake as a result of blasting and the impact on the surrounding buildings mainly depend on:

- physical and mechanical properties of soil,
- geological composition of soil,
- the quantity and type of explosive,
- type of blasting and
- distance from the blast fields to facilities.

Slovenia does not have its own standards for vibration measurements, so the following foreign standards are used in the Slovenian construction industry:

- DIN 4150 Vibrations in buildings which has three parts, Part 1: Prediction of vibration parameters, Part 2: Effects on persons in buildings and Part 3: Effects on structures,
- ÖNORM S 9020 Building vibrations; blasting vibrations and comparable emissions of impulse shape, and
- SN 640 312a Swiss Standard on vibration effects on buildings.

DIN 4150, for example prescribes the maximum oscillation velocity as follows:

- 3 mm/s for monumental buildings protected,
- 5 mm/s for residential buildings and
- 10 mm/s for industrial facilities.

The oscillation velocity is given as the limit value as a function of frequency. DIN 4150 is the most restrictive standard compared to others as it actually intends to minimize perceptions and complaints (Kuzu et al. 2008, Siskind 2000).

4. Physical characteristics of vibrations caused by construction machinery

Many earthworks, such as driving piles, vibrating compaction of earth materials, and driving heavy construction machinery, cause vibrations which may be transmitted to nearby earth facilities. Due to these vibrations and resulting dynamic forces damage may be caused on the structure. In the design and planning activities on the site it is necessary to assess the potential effects of vibrations, and adjust the operation of vibration causing machinery so as to minimize the effects on adjacent buildings (Achmus et al. 2005). The effects of vibrations which are caused by construction machinery depend on many factors such as:

- intensity of the source of vibration,
- different composition of the soil between the source of vibrations and the facility,
- quality of implemented foundations,
- dimensions of a building and
- quality of construction materials.

Duration, frequency and number of vibration events have a considerable influence on the effect of vibration intensity. The effect of vibration caused by construction machinery can:

- excite users of buildings,
- affect facilities, since there is a shake and movement of structures, and
- threat the structural integrity of buildings.

5. Physical characteristics of traffic caused vibrations

Vibrations caused by traffic are common concerns of society, because they very often cause problems to individuals and structures. Vibrations caused by traffic represent an external source and result from heavy traffic caused by buses and trucks. Cars and light trucks rarely cause vibrations that are discernible in buildings. Road transport usually causes vibration frequency in the range between 5 and 25 Hz and a speed variation of soil from 0.05 to 25 mm/s (Hunaidi 2000). Vibrations caused by road traffic are generated if a vehicle strikes an irregularity in the road surface, such as:

- construction irregularities,
- humps for traffic calming,

- dilatations,
- drainage covers or
- a very rough road surface.

All these are intentionally constructed to improve traffic safety and functionality of road infrastructure. Vibrations are also caused by a damaged road surface. Vibration characteristics depend mostly on:

- a vehicle suspension system and
- allowed speed and weight of vehicles.

A construction engineer has no direct influence on the reduction of intensity of vibration sources. This depends on traffic and vehicle regulations.

6. The site and the measurement procedure

Fig 1. The old caste of Trebnje

The measurements were performed on the castle of Trebnje in Slovenia. The building is historically protected. It was built around 1000 A.D. and was first mentioned in written sources in 1386. The castle retains some of its ancient parts: the square tower which has Roman foundations, the round tower with a secret exit from the period of Turkish raids, and the left and right wings of the building from the beginning of the 16th century. We performed measurements of vibrations during the construction of the above road section from May 2008 onwards. In the immediate vicinity of the castle blasting was performed from June 2008 until October 2008. From December 2008 vibration compaction of earth materials by vibrating rollers was carried out in the vicinity of the castle. Measurements of vibrations were performed to protect the building from potential damage. The nearby castle is located along the old motorway creating heavy traffic. In 2009, the effects and response of the building to vibrations caused by daily traffic were measured. In parallel to measurements of vibration, the following was also measured:

- movements in all three orthogonal directions with retro targets and
- movements of cracks in load-bearing structures.

The intensity of earthquakes as a result of blasting was measured by seismographic instruments. The measuring equipment manufactured by Instantel - Minimate Plus was used for the measurement. The Minimate Plus seismograph is a measuring instrument used for recording blast vibrations on quarries and construction sites. The Minimate Plus seismograph consists of an Instantel seismic data acquisition module and a Siemens remote-controlled consultation system. During measurements of blasting the apparatus was set to automatic actuation of the oscillation velocity of 0.3 mm/s. The event was measured for 3 seconds. We measured the response operation of construction machinery and vibrations caused by traffic with a manual actuation of instruments. The measurement time was 15 seconds.

7. Results of seismic effects measurements

Fig 2. Blasting in the tunnel

The measurements of vibrations and air shock wave pressure on the castle of Trebnje were performed at two measuring points (Fig 3a, b). Both geophones and a linear microphone were located perpendicularly to the location of the blast field. The results of the measurements are the values of individual components of soil fluctuation in all three orthogonal directions. Measurements are presented graphically with the seismogram of individual components of measured oscillation velocity of the soil.

Fig 3. The measuring point ((a) soil at the base of the southeastern part of the building, (b) soil at the base wall at the main entrance to the building)

In the time period from 9.6.2008 to 18.10.2008, the blasting was carried out at the facility near the castle of Trebnje. The results of five control measurements are shown in Table 1, where Q = amount of explosive charge used for detonation, MP = measuring point, R = distance between measuring point and blasting field, f = frequency at maximum oscillation velocity, ν = maximum component oscillation velocity (L-longitudinal, V-vertical, T-transversal) and PVS = (peak vector sum) resultant vector of oscillation velocity.

Table 1. Measurements of seismic impact

Date and time	Q (kg/int)	MP	R (m)	f (Hz)	ν (mm/s)	PVS (mm/s)
20.06.08;	260/30	a	257,5	37	1,76 L	1,94
12:10:51	260/30	b	208,2	43	1,49 T	1,60
23.06.08;	2000/30	a	383,4	51	0,81 T	0,99
14:09:37	2000/30	b	379,7	12	1,32 T	1,64
24.06.08;	2500/20	a	374,2	11	1,10 L	1,28
12:10:51	2500/20	b	371,3	26	3,21 L	3,32
7.10.08;	1140/20	a	301,5	34	1,84 T	1,86
11:24.29	1140/20	b	283,1	21	2,65 T	2,97
14.10.08;	1340/26	a	332,6	17	4,06 T	4,10
11:14:39	1340/26	b	326,8	21	2,44 T	2,74

The set of measurements results presented in Table 1 shows that the security criteria of maximum oscillation velocity of soil were exceeded twice (on 24.06.08 and 14.10.08). The maximum oscillation velocity of soil should be 3 mm/s. The typical seismic records and their analyses based on DIN 4150 standard are presented in Fig 4. Because the distance from the blast fields to measuring points was large, a very low air shock wave pressure was recorded, namely about 12 Pa. These values are not given. The graph in Fig 5. illustrates the maximum components resultant vector (PVS) of ground oscillation velocity at various distances from the blast fields, caused by various blasting.

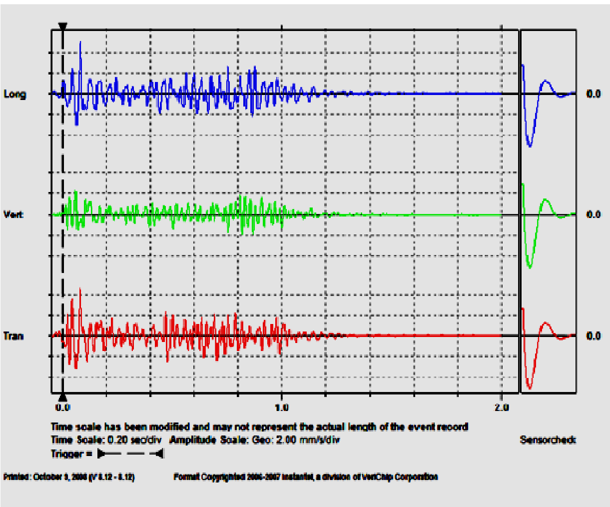

Fig 4. Seismic records and analyses according to DIN 4150 of events on 24.06.08

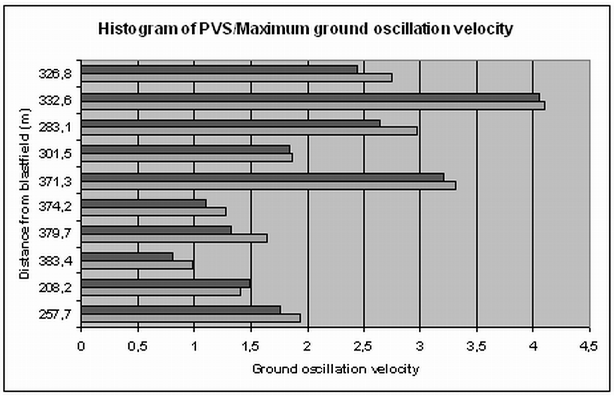

Fig 5. The distribution histogram of ground oscillation velocity and distance from blast fields

8. Vibrations caused by a vibratory roller, results

Fig 6. Two vibratory rollers (3.4.2009)

During the construction of the motorway embankment the roller type HAM 3520 was applied. This machine has the following technical characteristics: the roller operating weight = 12,480 kg, the weight of the rear wheels axle load = 7320 kg, the frequency of vibration = 30 Hz, with the amplitude of 1.19 mm. Vibrations and air shock wave pressure were measured at the location directly below the embankment, at the distance of about 10 m from the center of vibration on the motorway route, where a vibratory roller was used. Figs 7a and 7b show the location of the measuring points with the measuring kit.

Fig 7. The measuring point ((a) soil under the embankment, (b) soil near the basic wall and the basic wall with a mounted triaxial geophone)

Vibrations and air shock wave pressure were measured at standard measuring points of the castle so that one triaxial geophone was placed on the soil while the other was rigidly fixed to the base wall of the pavilion. This measuring point, together with the measuring kit, is shown in Fig 7b. At the site of the castle of Trebnje several measurements of vibration impact were performed. On 22.12.2008 and 2.03.2009, we took measurements of the operation of one vibratory roller, and on 3.04.2009 we took measurements of the operation of two vibratory rollers. When we measured the impact of one vibratory roller both instruments were activated when the roller was the closest to the instrument. A time interval for each measurement was 10 seconds. The results are presented in Tables 2, 3 and 4, where GL = location of geophone, NZ = geophone on the soil under the embankment, Z = geophone on the soil near the castle basic wall, TZ = geophone mounted on the basic wall and T, V, L are transversal, vertical and longitudinal oscillation velocity / frequency, respectively.

Table 2. Monitoring on 22.12.2008 (12:52, 12:55)

T (mm/s – Hz)	V (mm/s –Hz)	L (mm/s – Hz)	PVS (mm/s)	GL
0,270/47	0,206/28	0,397/51	0,417	NZ
0,0957/34	0,0794/85	0,0794/37	0,116	Z
0,0794/39	0,0952/22	0,127/23	0,135	TZ
0,238/51	0,190/26	0,381/43	0,419	NZ
0,0636/85	0,0952/>100	0,0635/>100	0,0966	Z
0,0635/>100	0,0794/85	0,0794/39	0,0870	TZ

Table 3. Monitoring on 2.3.2009 (13:05, 13:06)

T (mm/s – Hz)	V (mm/s – Hz)	L (mm/s – Hz)	PVS (mm/s)	GL
0,333/47	0,19/43	0,381/64	0,434	NZ
0,0635/>100	0,0794/>100	0,0635/>100	0,0855	Z
0,0635/>100	0,0794/57	0,0794/34	0,102	TZ
0,810/51	0,270/57	0,952/57	1,17	NZ
0,0952/34	0,0794/>100	0,476/>100	0,108	Z
0,0794/>100	0,0952/34	0,111/21	0,136	TZ

Table 4. Monitoring on 3.4.2009 (12:22, 12:25)

T (mm/s – Hz)	V (mm/s – Hz)	L (mm/s – Hz)	PVS (mm/s)	GL
0,159/43	0,0952/64	0,222/85	0,226	NZ
0,0635/>100	0,0794/>100	0,0635/43	0,0912	Z
0,0476/>100	0,0794/27	0,0794/34	0,0939	TZ
0,159/26	0,111/48	0,206/57	0,218	NZ
0,0794/24	0,095/>100	0,270/>100	0,272	Z
0,0635/>100	0,0794/57	0,0952/30	0,0979	TZ

The graph in Fig 8 illustrates a typical seismic record according to the standard DIN 4150 caused by the operation of two vibratory rollers.

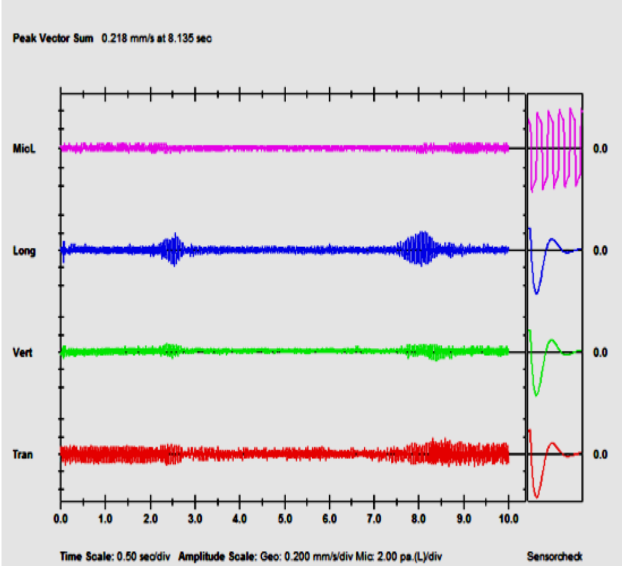

Fig 8. The seismic record according to DIN 4150 of events on 3.4.2009: measurement NZ

9. Vibrations caused by heavy traffic

For the measurement of vibrations caused by heavy traffic, we set three measurement points. The first one was placed on the castle wall at 0.5 m from the ground, the second one was placed in the nearby soil and the third one on the ceiling in the second floor of the castle (Fig 9).

Fig 9. The measurement point on the second floor of the castle

Transport of heavy vehicles can cause similar vibrations as construction machinery (Fig 10).

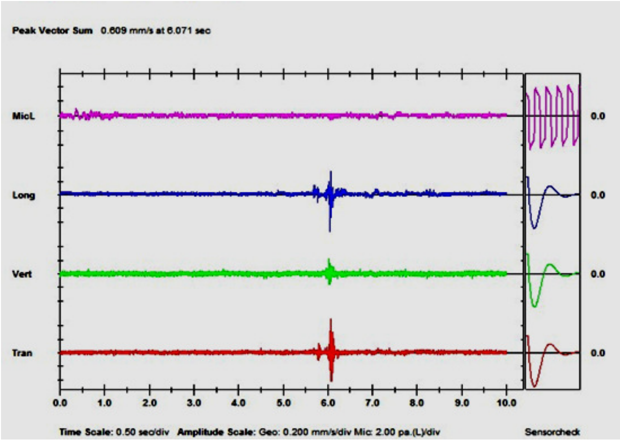

Fig 10. Records of vibrations caused by heavy vehicle traffic

We found that at distances greater than 250 meters the number of heavy vehicles does not substantially affect the intensity of vibration. Even at low levels of velocity oscillation, on the lightweight ceilings in the last floor, vibrations may occur at very low frequencies.

10. Conclusions

The measurements produce a lot of useful data, which might be also used in the strategic transportation planning decision making process. Our experiment shows:

- good coincidence of results with well-known empirical equations (Wieck 2003, Achmus et al. 2005),
- at a distance of between 50 and 130 meters there is practically no difference in the value of velocity oscillation when one or two vibrating rollers are in operation,
- at the distances greater than 250 meters from the motorway, the number of heavy vehicles does not influence significantly the intensity of vibrations etc.

This might lead to the conclusion, that external costs caused by ground vibrations are really limited to the buffer of approximately 250 meters around roads and particularly motorways. This is very similar to the noise (air-borne vibrations). The external costs caused by traffic noise are mostly calculated on the basis of WTP (willingness to pay) method (Banfi et al. 2000, Lep et al. 2004), and ground vibrations are therefore already included in this calculation. On the other hand, damage on historical buildings and cultural heritage in the near surrounding of transportation infrastructure will occur, and this must be taken into account when external costs of variants are assessed.

In the planning of works it is necessary to assess possible effects of vibrations and the resulting risks. It is necessary to select the construction equipment so that the impact of its operation on nearby structures is prevented or at least reduced to a minimum.

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