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Measurement, prediction and modeling the impact of vibration as the possibility of protection cultural heritage objects

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This article describes the possibility of using prognostic equations and the theory of fuzzy logic to predict the intensity of vibrations resulting from the use of construction machinery and heavy traffic. Vibrations from construction machinery can be particularly dangerous if they affect heritage buildings. By analyzing the measured results of vibrations at various facilities, we found that using the theory of fuzzy logic and appropriate modeling we can well predict the intensity of vibration caused by heavy traffic and vibration compaction with vibratory rollers.

Key words: Fuzzy logic, ground vibrations, vibrations monitoring, vibrations prognosis, neural networks.

INTRODUCTION

Experts in sustainable planning of roads are facing the problem of how to prepare their proposals for the authorities so that they will be able to support their decisions with numbered facts. A typical example of such a problem is erecting traffic infrastructure in locations where only part of factors can be shown quantitatively and costs estimated accordingly (mainly construction and maintenance costs). Contrary to this, we tend to show numerous consequences, both costs and benefits, qualitatively, which means descriptively, or we completely ignore the obvious consequences of an intervention in space which may cause social harm or benefits, damage to cultural heritage buildings or create the need of displacement. We are not able to adequately quantify costs and benefits not estimate costs. Another problem of sustainable road design is a deficient judgment of benefits and consequences of road's total life cycle from "ideas" and "construction" to "preservation" and "degradation".

In this paper we focused on and analyzed two very common phenomena occurring during the construction and operation of roads and ancillary facilities: vibrations arising from construction machinery and vibrations arising from freight traffic. The vast majority of construction machinery used in earthworks produces harmful vibrations. Many earthworks, such as piling and vibratory compaction of materials cause vibrations that can be transmitted in soil to nearby facilities. Because of vibrations, generated dynamic forces can cause damage to nearby structures. Old buildings are the most vulnerable of all structures.

An adaptive network fuzzy inference system (ANFIS) is used for predicting the intensity of vibration. ANFIS is considered to be one of the intelligent tools to understand

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the complex problems (Jang, 1993). Therefore, ANFIS is being successfully used in many industrial areas as well as in research (Faravelli and Yao, 1996; Provenzano et al., 2004; Gokceoglu et al., 2004; Rangel et al., 2005; Kayadelen et al., 2009). Khandelwal (2012) predict the blast induced ground vibration using different conventional vibrations predictors and artificial neural network (ANN) at a surface of coal mine and it was found out that the ANN model based on multiple input parameters have better prediction capability than conventional vibration predictors.

PHYSICAL CHARACTERISTICS OF CONSTRUCTION MACHINERY AND FREIGHT TRAFFIC

Slovenia has no standards of its own in the field of vibration measurements. By joining the European Union, we could take over the well established European standards in this field, such as DIN 4150, Swiss Standard SN 640 312a, British Standard (BS) 7385 and BS 6472. In Europe the standard DIN 4150 is most commonly used for measuring and assessing effects of vibrations on buildings. This standard prescribes the maximum ground vibration velocity which is 3 mm/s for heritage buildings, 5 mm/s for residential buildings and 10 mm/s for industrial facilities. The maximum ground vibration velocity is given with special curves depending on ground vibration frequency.

Many earthworks, such as driving pilots and sheet piling, vibratory compaction of earth materials as well as operation of heavy construction equipment, cause vibrations that can be transmitted to nearby buildings. Dynamic forces generated by these vibrations can cause damage to the buildings. When designing and planning activities at the site we need to assess possible effects of vibrations, and adjust work of vibratory machines so as to minimize their effects on the surrounding buildings (Achmus and Kaiser, 2006). The effects of vibrations caused by construction machinery may vary depending on numerous factors, such as the intensity of sources of vibration, different soil composition and its quality between the sources of vibration and the building, the quality of foundations, building dimensions and the quality of built-in materials. The effects of vibrations are enhanced by the intensity and duration of vibrations and by the frequency and number of vibration events. The effects of vibrations caused by construction machinery may interfere with users of a building and damage the building, since there is shaking and moving that can change structural integrity of the building to such an extent that its stability is at risk. In vibratory compaction of loose soil layers we dynamically compact upper soil layers. In these construction processes vibrations are transmitted through the soil to neighbouring buildings causing damage to them. When planning construction, possible impacts of vibrations should thus be assessed and resulting risks and building machines selected so that their impact on surrounding buildings is prevented or at least minimized.

Since 2002 the Slovene statistical office has been performing research about environmental costs arising from different environmental purposes in accordance with the European statistical classification of activities relating to the protection of the environment (CEPA). Data are being collected on investment in environmental protection, current expenses for the environment and income from environmental protection activities. CEPA is a general, multi-purpose and functional classification which is used for classifying the activities for environmental protection. According to this classification the protection against noise and vibrations is also recorded. This protection covers the reduction of noise and vibrations caused by road and rail transport, as well as air transport and shipping. According to the above criteria, activities are foreseen, such as monitoring, traffic management, and erection of sound barriers or anti-vibration devices (Statistical Office, 2009). Traffic vibrations are common concerns of society because they often cause problems to people and structures. They constitute an external source and result from heavy traffic such as buses and trucks. Passenger cars and light trucks rarely cause vibrations that are discernible in buildings. Road transport usually causes vibrations in the frequency range from 5 to 25 Hz and ground vibration from 0.05 to 25 mm/s (Hunaidi, 2000). The frequencies and the vibration velocity depend on numerous factors, such as pavement conditions (especially damage and roughness), the speed and weight of vehicles, a vehicle suspension system, the type of soil, the season, the distance between the road and the building and the type of the building.

MEASUREMENTS, DESCRIPTION OF THE EXPERIMENT AND THE RESULTS

Vibration measurements were performed separately for three types of vibrations. We have measured the impact of the vibrating roller on the residential and on heritage object, where motorway was under construction. The second segment of monitoring comprised the measuring of effects at the residential building, during driving and pulling of sheet piling when the round about and the access to a new motorway was under construction. In the third case we measured the impact of heavy traffic on the residential building.

Earthquake intensity, which results from operation of construction machines or traffic, can be measured with seismographs. Seismographs are portable devices that can be placed wherever it is necessary to measure the intensity of vibrations. They measure vibrations which are transmitted to the seismic mass of a geophone and then to three perpendicularly mounted electromagnetic coils.

Table 1. Technical characteristics of dynamic rollers.

Variables	HAMM 3520	AMMAN AC 110
Operating weight (kg)	12480	12100
Rear axle load (kg)	7320	7140
Vibration frequency (Hz)/amplitude (mm)	30/1,19	28-35/1,8-0,8

Vibration components induce voltage and hence electrical impulses in the winding. These impulses are transmitted to the electronic recording with a built-in microprocessor with a certain memory. Measurement values recorded in the memory can be processed analytically with the software. For vibration measurements, we used the measurement equipment of the manufacturer Instanel from Canada, namely the four-channel device Minimate Plus and the eight-channel device Minimate Plus with the associated linear microphone and the geophones. The impact of construction machinery, whose operation causes vibrations, and the impact of road freight transport are also measured by ground vibration velocity. Geophones can be used for these measurements as well as for assessing a building response to vibrations. Ground vibration velocity is usually measured at the source of vibration – on the ground in the immediate vicinity of a construction machine, on the ground in front of the foundation of the building observed, and at the foundation of the building. The results of measurements present the measured components of vibration velocity in all three orthogonal directions.

Effects of vibration from trucks

Heavy vehicle traffic was monitored in two cases during earthworks for the construction of the parking house. We measured vibrations on the gravel road caused by trucks with a total weight of 20 tons in the phase of driving off, and vibrations on the asphalt road caused by trucks with a total weight of 20 tons and running at a speed of 40 km/h.

Effects of vibration from a vibrating roller

The constructor of the motorway section used two types of construction machinery which causes vibrations. In compaction of road section the dynamic roller HAMM 3520 was used. The second dynamic roller was AMMAN AC 110. The following technical characteristics are presented in Table 1. We have measured the effects of vibrations during the operation of one vibrating roller and two synchronously operating rollers HAMM. The second measuring with vibrating roller AMMAN has ben measured the imapct of surface dynamic compaction, deep dynamic compaction and static compaction.The measuring instruments – Instantel Minimate Plus measuring station were activated manually, with a time interval between individual measurements of 10 s.

Effects of vibration from driving/pulling sheet pilling

The measurement of vibrations during the construction of new bridge in the old kernel of town was performed at 17 measuring points. Vibrations were measured at facilities, which are protected cultural heritage structures. The second part of measurements was performed on the residential building during the construction of a road roundabout. In both cases the sheet piling was used to protect the excavation or construction pit, respectively.

Prognosis of vibration

The prognosis of vibration based on vibration measurements, which were measured and the use of empirical equations by various authors. The use of prognostic equations as an option for reducing the negative effects of vibration.

Prognosis of vibration velocity from trucks

The measurements were analyzed with a model for predicting the intensity of vibration proposed by Watts (1990). The presented model is based on local degradation of the roadway surface, along which vehicles run with a certain speed, and the distance between the moving vehicle and the measuring point. The model is expressed as:

$$PPV = 0.028 \cdot a \cdot (v/48) \cdot t \cdot p \cdot (r/6)^x . \quad (1)$$

Where: PPV = the peak particle velocity (mm/s), a = the maximum degradation of a surface or a defect (mm), v = the measured speed of a vehicle (km/h), t = the coefficient of soil supporting a roadway structure, p = the wheel index, which is over 0.75 for heavy vehicles when one wheel crosses a damaged spot, or 1 in other cases, r = the distance between the measuring point and the moving vehicle.

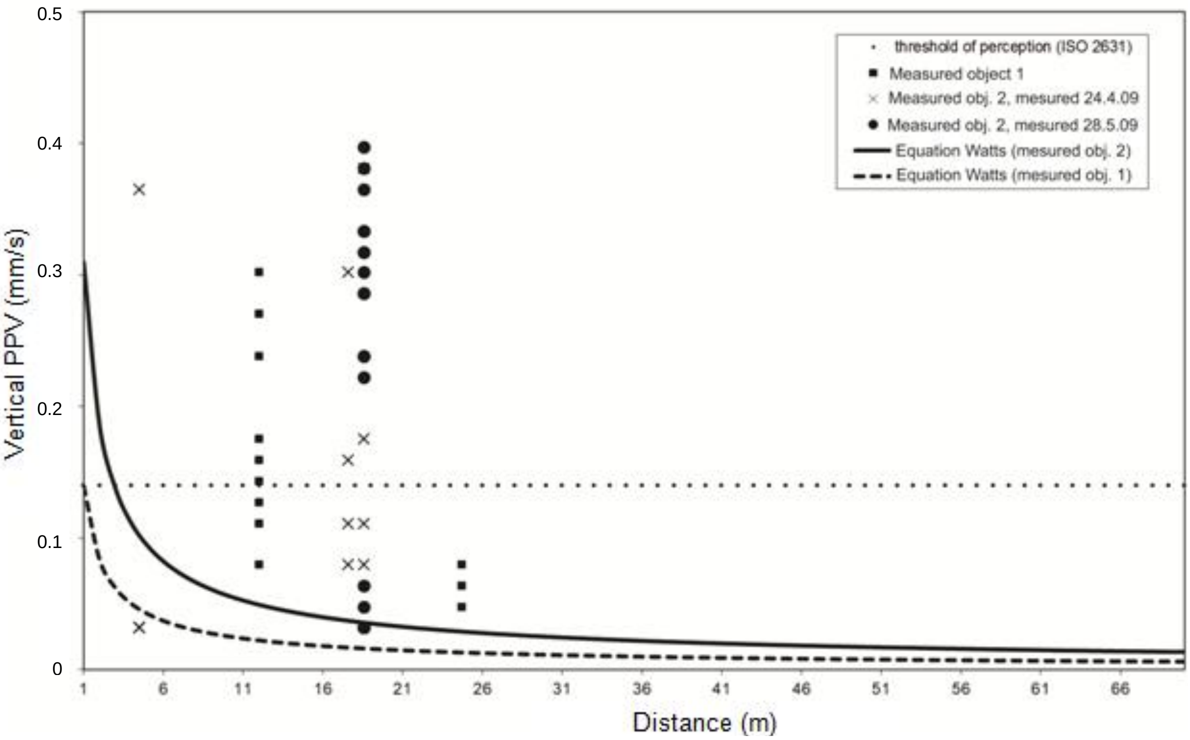

Figure 1. The results of the measured values using the prognostic equation for heavy trucks.

The value of the exponent x determines damping of vibrations and it depends on the site and the distance. The results of the effect of vibrations caused by heavy trucks are given in Figure 1.

Prognosis of vibration velocity from a a vibratory roller

To forecast the potential damage to structures, foundation oscillation velocity, not ground vibration velocity, is used as the base value. Maximum oscillation velocity changes at the transfer to foundations, mainly resulting in the reduction. In the case of resonance, there is a very slight, small increase in oscillation velocity. Due to unknown factors of the transfer of oscillations to the foundations of a building, it is useful to know direct equations to forecast maximal components of foundation oscillation velocity. This is practical because in measuring vibrations measuring devices are placed on foundations and not on the ground, which allows easy calibration of the equations. Such prognostic equations are mainly based on practical experience and are not yet widespread. Since vibratory energy of vibration machines is difficult to assess, a decisive parameter in these prognostic equations is the operating weight of the machine. To predict foundation oscillation velocity arising from vibration rolling we used two equations. The first Equation (2) is suggested by Philipps et al. (2010), and the second Equation (3) by Achmus et al. (2005).

$$v_{Fi,\max} = 1{,}1\frac{\sqrt{G}}{r^{0{,}7}} \tag{2}$$

$$v_{Fi,\max} = K\frac{\sqrt{G}}{r} \tag{3}$$

Where: $v_{Fi,max}$ is the maximum foundation oscillation velocity (mm/s), G is the operating weight of the vibrating machine (t) and r is the distance from the vibration source to the foundation (m).

The coefficient K in Equation (2) is 4.31 for a 50% accuracy of results. We used the results of vertical and longitudinal components of foundation oscillation velocity, which are graphically presented in Figure 2, together with the lines of the prognostic Equations (2) and (3) and the relevant literature data (Achmus et al., 2005).

Prognosis of vibration velocity from driving/pulling sheet pilling

Ground and foundation vibration velocity is also taken as the basic physical quantity to predict the potential damage on buildings. In the transfer of vibrations from the ground to the foundations of the building the vibration velocity tends to decrease, yet it can increase in some

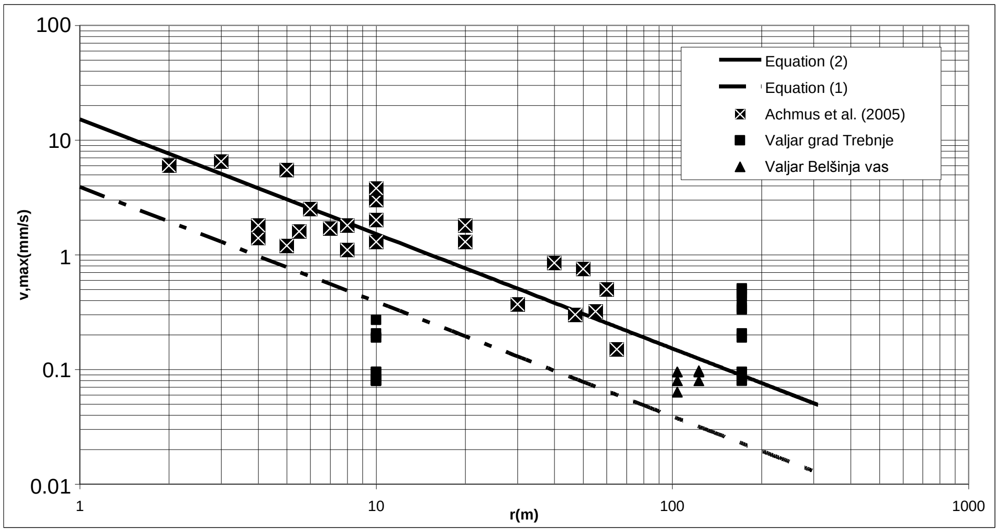

Figure 2. The measured versus predicted values of foundation oscillation velocity.

cases owing to resonance. Especially in pulling sheet piling, sudden changes can occur in vibration velocity in three orthogonal directions. Because of this it is very important to consider the highest measured value in forecasting and evaluating the effect of vibrations. In this case, we used the equation of Achmus et al. (2005), which reads:

$$v_{Fi,\max} = K_F \frac{\sqrt{\frac{W}{f}}}{r}. \tag{4}$$

Where: $\upsilon_{Fi,\max}$ = the maximum foundation oscillation velocity (mm/s), W = the maximum power of the machine in watts, f = the operating frequency of the machine (s-1) and r = the distance from the source of vibration to the measuring point in (m).

The coefficient K_F is 7.9 for a 50% probability of increase, or 18.5 respectively for a 2.25% probability of increase. In analyzing the measured values given in Figure 3, we considered that in driving 7.1 kNm of energy is consumed, while in pulling 2.8 kNm. Vibration frequency is 28 Hz in both cases.

ANFIS MODEL FOR GROUND VIBRATION PREDICTION

The basic structure of the fuzzy inference system (FIS) was introduced by Zadeh (1965). In this type of FIS it is essentially to predetermine the rule structure and the membership functions. Human determined membership functions are subjective and differentiate from person to person. The standard methods, which transform human knowledge or experience into the fuzzy rules and membership functions, do not exist. Usually there is the collection of input/output data, which we would like to use for constructing the FIS model. The effective method for tuning the membership functions and to minimize the output error measure is the Adaptive-Network-Based Fuzzy Inference System (ANFIS). ANFIS (Jang, 1993) uses a given input/output data to construct a FIS, whose membership function parameters are tuned (adjusted) using either a back propagation algorithm alone or in combination with a least squares type of method. This adjustment allows fuzzy systems to learn from the data they are modelling. ANFIS only supports Sugeno-Takagi-Kang (1985) identification models, which should have only one output parameter. Adaptive network is a superset of all kinds of feed-forward neural networks with supervised learning capability (Rumelhart, 1986). ANFIS is a fuzzy inference system implemented in the framework of adaptive networks and uses the advantages of neural networks and fuzzy logic.

One of the most important stages in the ANFIS technique is data collection. The data was divided into training and checking datasets. Training datasets contains measurements of the vibration caused by trucks and vibratory roller. As an interface for mathematical modelling and data inputs/outputs the MATLAB (2010), a high-level technical computing language, was used.

Vibration caused by trucks

In this case, data is collected using noisy measurements, and the training data cannot be representative of all the features of the data that will be presented to the model. In this model, 15 measurements were used to build a model. Among which, 11 evaluations (70%) were used

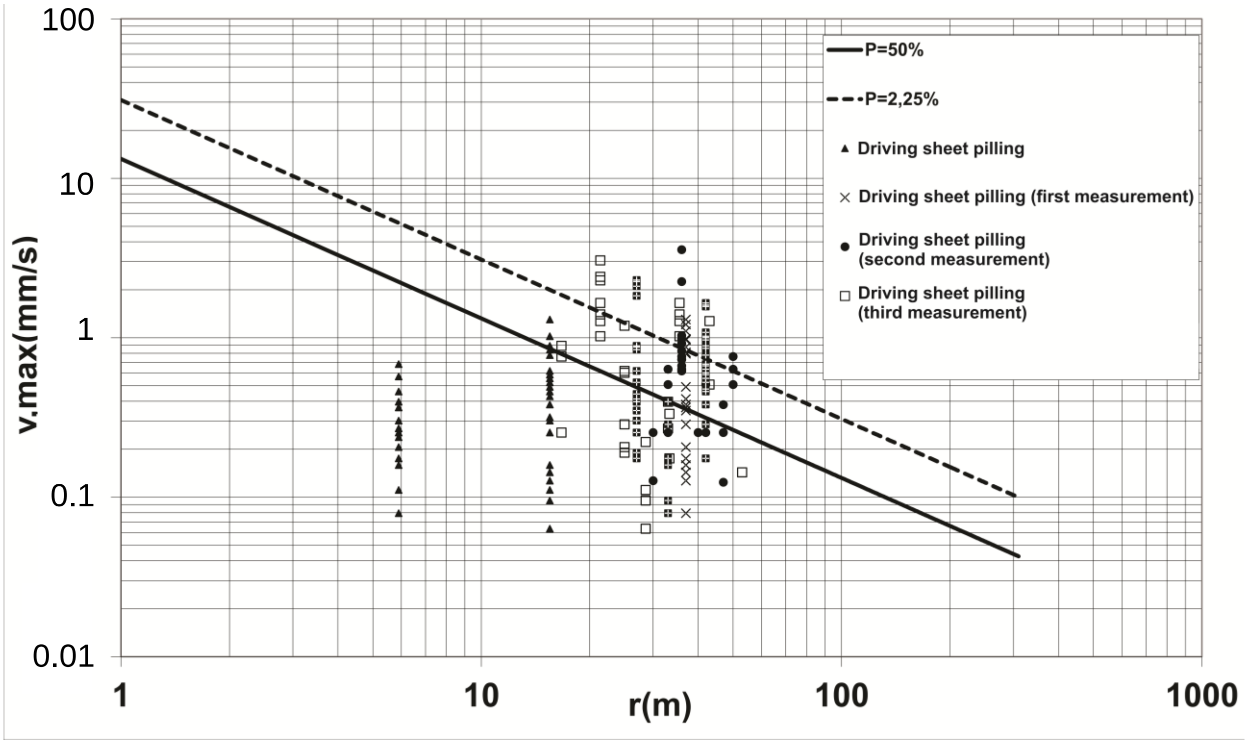

Figure 3. The measured values using the prognostic equation for driving/pulling sheet piling.

Table 2. Training data.

No. measurements	V (km/h)	r (m)	PPV (mm/s)
1	86	7	1.02
2	86	67	0.087
3	71	7	0.766
4	71	67	0.087
5	69	7	0.658
6	69	67	0.092
7	68	67	0.096
8	67	67	0.010
9	65	7	0.809
10	65	67	0.125
11	57	7	0.457

for the training of the ANFIS model, whereas 4 data sets (30%) were chosen for checking the model. Table 2 represents training data and Table 3 represents checking data.

PPV is predicted using ANFIS model based on two parameters (speed of a vehicle and the distance between the measuring point and the moving vehicle). The maximum degradation of a surface is 0.5 mm and the coefficient of soil supporting a roadway structure is 0.1. On the basis of the measured data we build model to predict PPV value for any speed of a vehicle and the distance between the measuring point and the moving vehicle (Figure 4).

ANFIS use a given input/output data to constructs a FIS whose membership function parameters are tuned (adjusted) using either a back propagation algorithm alone or in combination with a least squares type of method. This adjustment allows a fuzzy systems to learn from the data they are modeling. The hybrid algorithm is described in detail (Jang, 1993). The hybrid algorithm can reduce the error between FIS model and the data that we used to build and verify the model. The aim of ANFIS

Table 3. Checking data.

No. of measurements	V (km/h)	r (m)	PPV (mm/s)
1	70	7	0.502
2	70	67	0.094
3	67	7	0.851
4	67	67	0.103

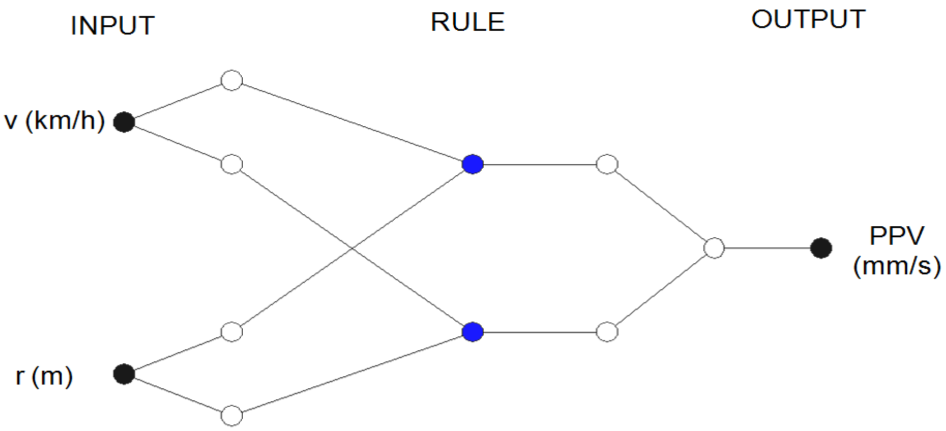

Figure 4. Suggested ANFIS for prediction of ground vibration caused by trucks.

Table 4. The ANFIS structure.

No. of training data sets	11
No. of checking data sets	4
Type	sugeno
No. of input membership functions	2
No. of output membership functions	2
No. of rules	2
And method	prod
Or method	probor
Defuzzification method	wtaver
Implication method	prod
Aggregation method	max

method is to minimize the root mean square error (RMSE) of the model to given attributes. Optimal parameters of the model were achieved when the RMSE is no longer decreasing. ANFIS structure for ground vibration prediction is summarized in Table 4.

Results of ANFIS model - vibration caused by trucks

Results of ANFIS model are shown in Figure 5. Surface shows the influence of speed of a vehicle and the distance between the measuring point and the moving vehicle on the peak particle velocity. ANFIS method is alternative to existing methods for prediction of ground vibration due to heavy vehicle traffic. However, results need to be generalized as present work is valid only for considered data. Comparison of measured and predicted PPV values for training data is shown in Figure 6.

Vibration caused by vibratory roller

The vibratory energy of machines depends on type of compaction. Tables 5 and 6 contains the measurements

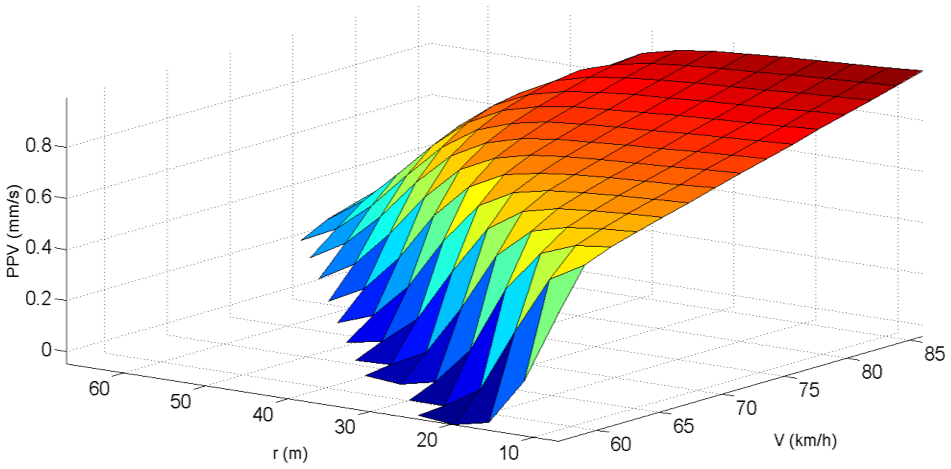

Figure 5. Result of ANFIS model.

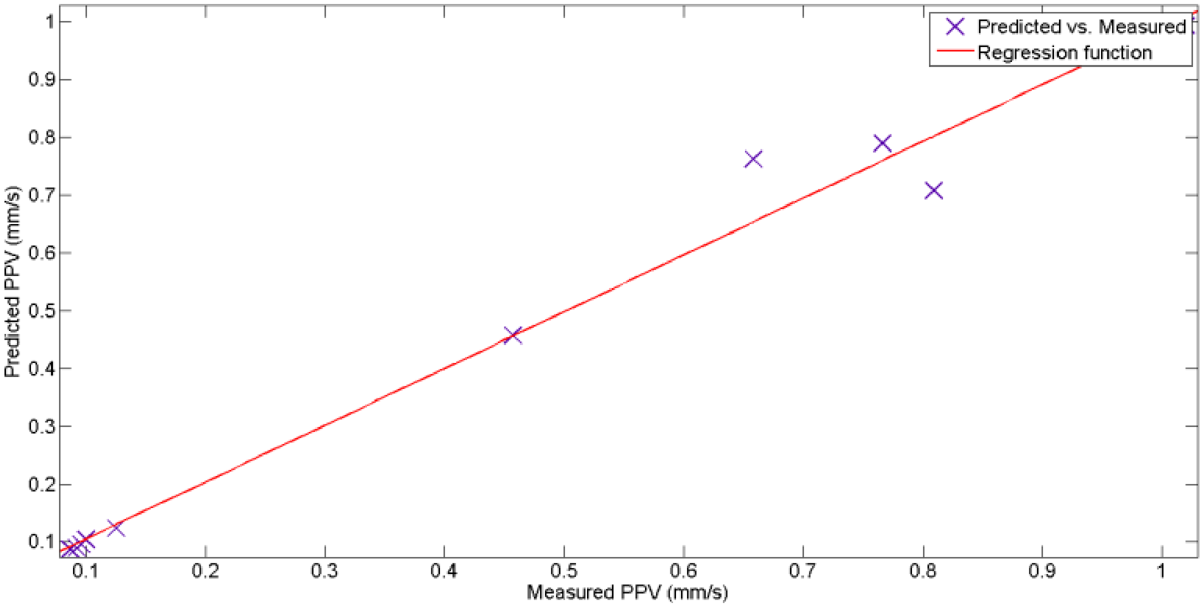

Figure 6. Measured versus predicted PPV values for training data sets.

Table 5. PPV measurement results caused by three types of compaction methods for heritage objects.

Distance (m)	PPV (mm/s) Surface dynamic compaction	PPV (mm/s) Deep dynamic compaction	PPV (mm/s) Static compaction
8.0	3.57	3.51	0.220
8.9	3.28	2.91	0.220
10.7	2.61	1.50	0.311
30.0	2.22	0.93	0.220

of PPV for surface dynamic, deep dynamic and static compaction. Additionally the measurements are obtained on two buildings with different quality of foundations. For each building, type of compaction and various distances

Table 6. PPV measurement results caused by three types of compaction methods for residential objects.

Distance (m)	PPV (mm/s) Surface dynamic compaction	PPV (mm/s) Deep dynamic compaction	PPV (mm/s) Static compaction
5.4	2.01	1.51	0.220
7.1	1.94	1.50	0.220
15.1	0.93	1.26	0.254
16.0	1.02	0.81	0.284

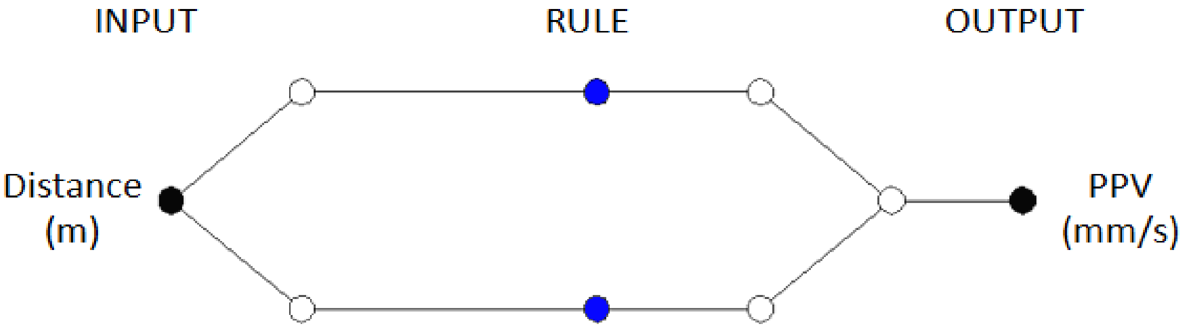

Figure 7. Constructed ANFIS models for prediction of ground vibration caused by compaction.

Table 7. PPV measurements caused by three types of compaction methods.

Number of training data sets	6 x 4
Type	Sugeno
Number of input membership functions	2, Gaussian
Number of output membership functions	2, Constant
Number of rules	2
And method	prod
Or method	probor
Defuzzification method	wtaver
Implication method	prod
Aggregation method	max

from the source of vibrations the PPV were measured. Based on the measurements the simple one parameter ANFIS models were constructed (Figure 7). The PPV value is predicted for two different types of foundations and three types of compaction, therefore six models were constructed with the same structure. Table 7 presents the input data of fuzzy models, which are essential to repeat the calculations.

Results of ANFIS model – vibration caused by vibratory roller

Figure 8 shows the vibration velocity as a function of distance from the source of vibration – based on ANFIS model. Figure 8a shows the graphs for the heritage objects which have generally poorly foundations and have no built-in anti-seismic ties. Graphs on Figure 8b are shown the same physical quantity but for residential objects, which are better quality. A graphical representation of vibration velocity of the distance from the source of vibration indicates that the vibration velocity depends on the type of hardening of soil produced with roller. From the graphs it is evident that surface dynamic compaction and deep dynamic compaction cause almost the same vibration velocity in a small distance from the source of vibration. With increasing distance from the source of vibration surface dynamic compaction leads to

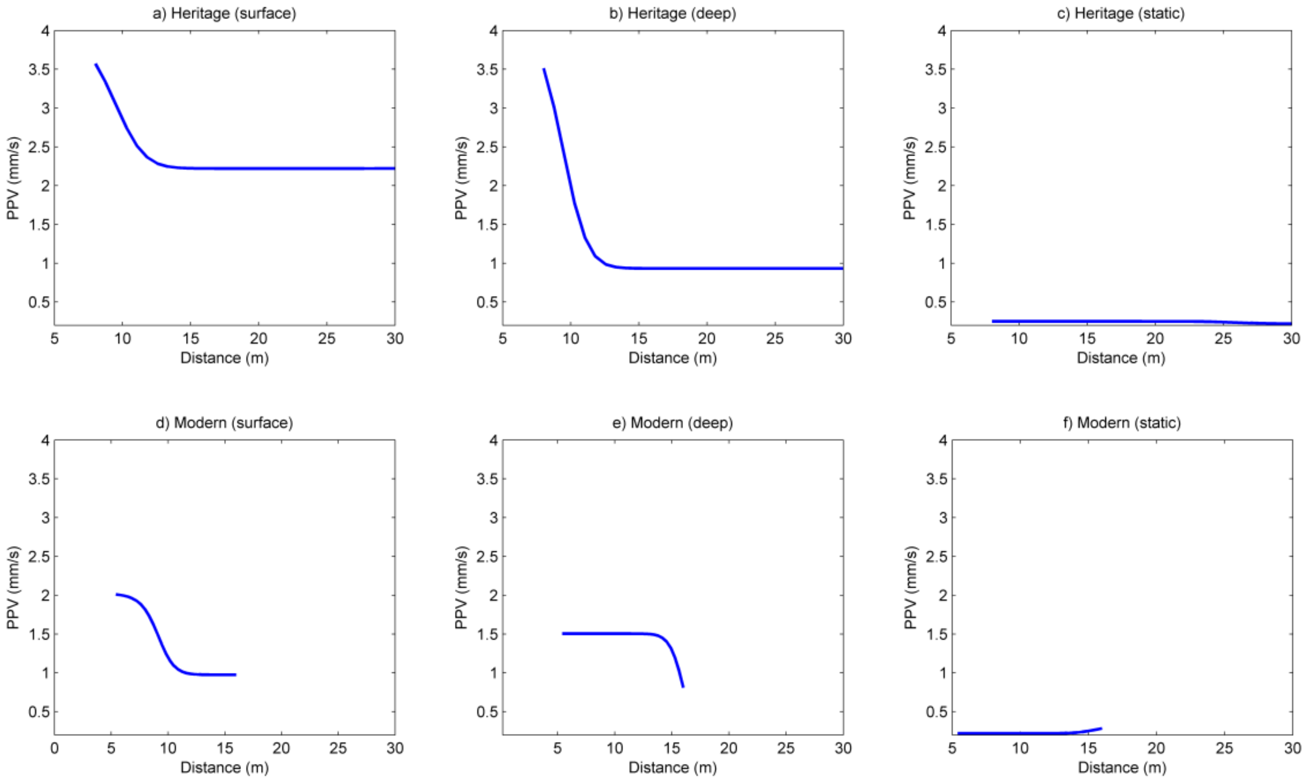

Figure 8. Results of ANFIS model – measuring values which are shown in Tables 5 and 6.

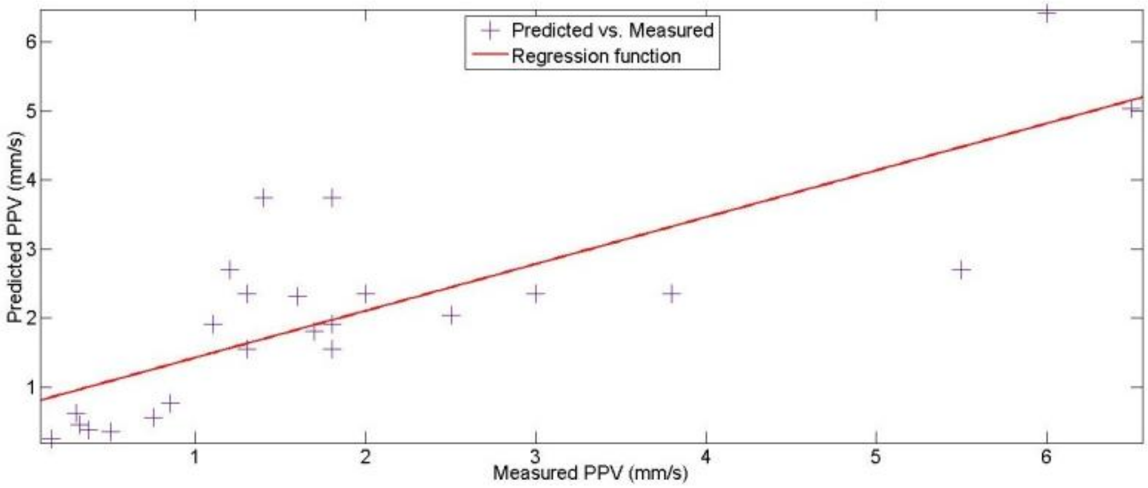

Figure 9. The measured versus predicted ground vibrations due to a road roller activity.

a higher vibration velocity when compared with the deep dynamic compaction. Vibration velocity caused by the static compaction is negligibly small when compared with the vibration velocity induced by surface and deep dynamic compaction. Calculations also confirmed by the fact that the vibration velocity and the distance of the same intensity and the distance of the source are greater then in residential objects. Additionally, we have constructed an ANFIS, based on measurements provided by Achmus et al. (2005). With the developed model we are able to predict the PPV value for any selected distance. Figure 9 shows the measured versus predicted ground vibrations due to a road roller activity.

CONCLUSIONS AND RECOMMENDATION

The measured foundation oscillation velocities presented in Figure 1 correspond very well with the line of the prognostic Equation (3). We can conclude that the prognostic Equation (3) can be used for the preliminary assessment of foundation oscillation velocity within the scope of risk assessment. Based on the calculation with the prognostic Equation (3), the likely value of foundation oscillation velocity is 0.12 mm/s, while the DIN 4150 standard provides an orientation value of 5 mm/s for horizontal components of oscillation velocity. If this value is not exceeded, we do not expect damage to the building and can exclude the likelihood that horizontal oscillations of structural elements would occur on the top floor of the building with the increase of the oscillation amplitude. For vertical oscillation velocities of the ceiling in the building, DIN 4150 provides an orientation value of 8 mm/s. At a frequency of the vibrating roller of 30 Hz there could be a risk of resonance. However, considering that the transfer factor for wooden ceilings kz ≤ 15 (Funk, 1996), we obtain the maximum oscillation velocity of 1.8 mm/s using the prognostic Equation (4), which means that in no event the guideline value of the standard DIN 4150 is exceeded and no damage is expected to the building. According to the prognostic Equation (4), the measured values of driving, and in some cases of pulling, sheet piling correspond very well with the boundary probability line. The results for pulling sheet piling in a direct vicinity of the measuring point present a border case, a very troublesome one, which is difficult to predict due to the proximity of the source. When planning construction works it is therefore necessary to assess possible effects of vibrations and the resulting risks, and select such building machines whose operation does not affect surrounding buildings or is at least minimized. The measurement of vibrations resulting from heavy trucks has shown that the prognostic Equation (4) sets very strict criteria, which are mostly exceeded in our case.

Data scattering of vibrations is very large, therefore conventional vibration predictors are not able to predict the PPV up to an acceptable limit. Many researchers found out that artificial neural network and neuro-fuzzy technique have superiority in solving problems in which many complex parameters influence the process and results, when process and results are not fully understood. Therefore is very important that experimental data are available. The prediction of ground vibrations due to heavy vehicle traffic is also of this type. Speed of a vehicle and the distance between the measuring point and the moving vehicle are two input parameters for ANFIS model. Built model can be improved with more measurements of ground vibrations. Based on engineering judgment, the proper measurements should be selected for training and checking data sets. Prediction of vibration caused by the dynamic compaction of soils with vibratory rollers are in good agreement with calculations by prognostic Equations (2) and (3). The elaborated method using techniques FIS and model ANFIS can be applied to assesment of vibration of buildings. The results of experiments show, that application of this methods are possible.

Conflict of Interest

The authors have not declared any conflict of interest.

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