MONITORING AND CONTROL OF THE BUILDING STRUCTURES VIBRATION DUE TO NEARBY AREA CONSTRUCTION WORKS

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ABSTRACT

Construction activity such as driving piles, vibrating compaction of earth materials and driving heavy construction machinery can result in varying degrees of ground vibration, depending on the equipment and methods employed. The operation of construction machinery causes ground vibrations which spread through the ground and diminish in strength with distance. Such vibration can also has a negative impact on security and stability of the structures, facilities performance and peoples should be controlled or monitored by experimental way and achieved results compared with relevant standards prescription values and criteria (Eurocodes, National Standards, etc.). The construction vibrations can be reduced by planed and guided use of construction machinery utilizing of the experimental analysis results, too. The effects of the construction vibration on the Bratislava Airport buildings structure caused by sheet pile driving during the construction work near present operating airport buildings are shortly described in this paper.

Keywords: *dynamic response of structures and soils, experimental analysis, FEM.*

INTRODUCTION

In the case of analysis of construction vibrations caused by sheet pile driving during the construction works sometimes it is need to predict or monitor vibration level of on nearby structures and buildings. In this study the results of the theoretical and experimental investigation of the M. R. Stefanik Bratislava Airport building structures vibrations caused by pilling operations were analyzed mainly from the aspects of the safety of the existing building structures with full operating capacity [1]. The study also includes result of experimental tests for soil dynamic parameters evaluation of geological area of surrounding the pile driving positions.

1. SOUCES CONSTRUCTION VIBRATION

Vibratory hammers for driving non–displacement piles usually have low to moderate force amplitudes and operating frequencies above 20 Hz. *Displacement piles* are driven by vibratory hammers with frequencies of around 10 – 40 Hz and commonly along with much higher force amplitudes [2]. The soil resistance to pile penetration and the seismic effect of vibratory driven piles depend substantially on soil conditions, pile type and vibratory hammer model. A coincidence of the operating frequency with the soil layer frequency may generate large ground vibrations of the soil surrounding the pile. The use of *vibratory hammers with variable frequency and force amplitude may minimize damage due to accidental ground vibration amplification*.

2. GROUND VIBRATION

The main characteristic waves that are generated when a vibrating load is placed on the surface of a soil (half space) are the compression wave (*P–wave*), the shear wave (*S–wave*), and the surface wave (*Rayleigh–wave*). Each of these waves has a characteristic velocity calculated from the following equations:

$CW \rightarrow C_P = (\lambda+2\mu/\rho)^{1/2}$, $SW \rightarrow C_S = (\mu/\rho)^{1/2}$ *and* $RW \rightarrow C_R = (0.87+1.12v / 1+v)\, C_S$,

where λ and μ are *Lamé coefficients* of elastic medium, v – *Poisson ratio* and ρ is soil density; C_P, C_S, and C_R are compression, shear and Rayleigh *waves velocities* respectively. The correspondence principle [3] can be applied to model *material damping* in the *viscoelastic medium* by the use of a complex *Lamé* coefficients $(\lambda + 2\mu)(1 + i\delta)$, where $\delta \approx \delta_E \approx \delta_G$ represents the hysteretic material damping ratio for the compression and shear waves respectively. Natural ground conditions permits the ground to be modelled as a damped, viscoelastic half space. The viscoelastic model of soil simulation using the complex modulus conception $E^* = E\,(1+i\delta E)$ and $G^* = G\,(1+i\delta G)$ respectively, offers a very good approach to the actual soil behavior (E, G and $\delta E \approx \delta G$ are real and imaginary components of complex modulus). The basic equations used to describe the viscoelastic half space analysis of wave propagation through the ground with modulus in complex form cannot be fully described here, see e.g. [1], [4].

Sources of construction vibrations generate body and surface waves in soil medium. Body waves propagate through the soil deposits and rock, see also Fig. 1. Compression (*CW*) and shear waves (*SW*) are the main types of body waves that should be taken into consideration at relatively small distances from the construction sources. Surface waves,

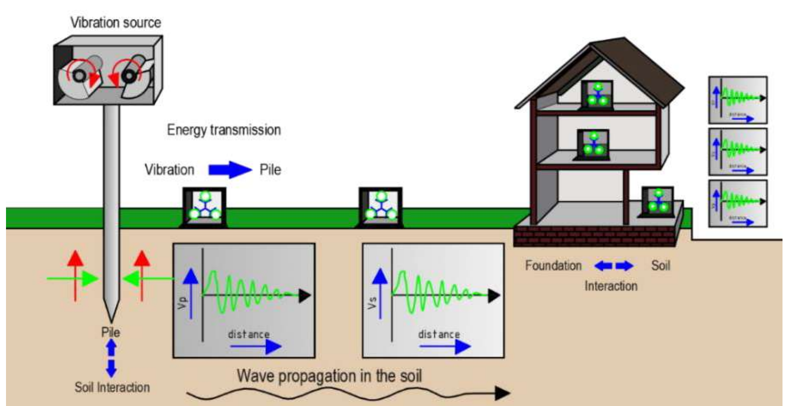

Fig. 1 Pile vibration energy propagation via waves through ground to building structure

of which Rayleigh waves (*RW*) are the primary type, propagate along the upper ground surface. *Rayleigh waves* have the largest practical interest for structural engineers because building foundations are generally placed near the ground surface. In addition, surface waves contain more than *2/3 of the total wave's energy* and their *peak particle velocity* [5] are dominant on *velocity vibration amplitude records*. The proximity of the frequency of *horizontal soil vibrations* to one of the building's natural frequencies may generate the conditions of r*esonance* in that building. Moreover, *vertical ground vibrations* can cause *dangerous* structural settlements. To prevent the unacceptable effect of construction vibrations, it is important to accurately *predict expected ground and structure vibrations* and also it is useful to *perform the monitoring* of the structure response due to construction vibrations. *The construction vibration monitoring enables the vibratory pile drivers operating mode regulation to avoid undesirable vibrations level of the structures and also undesirable effects on facilities performance and peoples.*

3. STRUCTURE VIBRATIONS DUE TO CONSTRUCTION ACTIVITIES

Harmful vibration effects of construction activities occur frequently. Vibrations may produce direct damage to structures when excitation frequencies of ground vibrations do not match natural frequencies of structures. Such damage usually occurs in nearby structures at distances about one pile length from driven piles. Intensity of structure vibrations depends on soil–structure interaction which determines structure response to the ground excitation. Building vibrations having low and high frequencies are usually generated by Rayleigh and compression waves, respectively. There are two frequency ranges of structure responses: 2–30 Hz and 30–450 Hz. Perhaps structure vibration damage obtained without the effect of resonant structure response can be considered for the most *peak particle velocities* (PPV) of ground vibrations higher than about 50 mm/s for frequencies of 2–30 Hz, [5].

<u>*Resonant structure response*.</u> The proximity of the frequency ground vibrations to one of the building's natural frequencies may generate the condition of resonance. The PPV of structure vibrations can increases from two to seven times as high as vibrations measured at the ground. Under the condition of resonance, the maximum dynamic amplification even may be much higher, e.g. [6],[13]. Dynamic settlements – ground and foundation settlements as a result of relatively small ground vibrations in loose soils may occur at various distances from the source. *Densification and liquefaction of soils* can occur under the vibration effects of construction activities. Additional causes of damage – soil excavation associated with pile driving and made in close proximity to existing building can produce structural damage, too. Dowding [7] observed that permanent *excavation deformations induced in adjacent structure* generally exceeded those from pile driving equipment and suggested *taking into account the accumulated effect of repeated dynamic loads, from production pile driving*. This approach is especially *important for historic and old buildings and also for building in those great number people are allocated* (theatres, airports, schools, hospitals, etc.).

4. PREDICTION AND MONITORING OF THE BUILDING VIBRATION

4.1. Assessment of building vibration due to construction activities

Assessment of building vibration due to construction activities caused by pile driving is a problem that can be solved through the application of research. This research consists mainly of defining the relationship between *intensity fluctuations in the soil, the pile driving energy quantity and the distance from the vibration source*. Through intensity fluctuations can appear in different physical quantities, such as the oscillation velocity, acceleration, frequency, ground motion intensity, displacement and energy. There are accessible several standards in the field of measurement of vibration in the construction industry in the European Union (e.g.[11], [12]) and USA. In Slovakia in the field of measuring and assessing of building vibrations due to ground motion the most commonly used standard is Slovak Standard STN EN 1998 – 1/NA/Z1 (2010) based on EC8.

The usual concern related to construction vibration is building damage. A considerable amount of research has been done to define acceptable levels of construction–induced vibration to limit damage to neighboring buildings. Pre– and post– construction inspections and real–time monitoring systems are used to avoid damage claims associated with the construction process. For sensitive equipment or historic and old building also in the case of build buildings with allocation of many people, however, the vibration levels of concern are two to three orders of magnitude lower than those associated with even minor cosmetic damage. In such cases, more sophisticated monitoring systems are needed to measure and assess the potential adverse effects of construction–related vibration. This article describes also the evolution of remote monitoring systems (utilizing internet achievements, local *wi–fi* area, etc.) being used for the special case related to vibration in sensitive facilities of airport near construction sites.

4.2. The analytic – experimental prediction models

The analytic–experimental approach suggests the test and the theory data combination to calculate the prediction level of ground vibration. In this process as an input data can be used accelerations (velocities) spectrum $\overline{S}_{\ddot{w}\ddot{w}}(\omega)$ measured at the nearest ground point to the different kind of piles and hammers and *generate experimental spectra data bank for authorized driving equipment and the same procedure to use for individual case study*. On the surface (at a distance) of a linear viscoelastic half space, *the acceleration response spectrum* $S_{\ddot{w}\ddot{w}}(\omega)$ can be expressed [8] in terms to *the input spectrum of ground vibration accelerations* $\overline{S}_{\ddot{w}\ddot{w}}(\omega)$, by

$$S_{\ddot{w}\ddot{w}}(\omega) = |H(\omega)|^2 \overline{S}_{\ddot{w}\ddot{w}}(\omega) \tag{1}$$

where $|H(\omega)|^2$ is the magnitude frequency response function for the half space medium and $\ddot{w}(t)$ is vibration accelerations amplitude of the surface measured at a distance l from the measured point near the pile driving site. The *frequency response function* – FRF (or *transfer function*) of the ground can be derived via experimental *impulse seismic method* (ISM) or *cross–hole test data*, from which *elastic and* *attenuation parameters* of the ground can be obtained, too. The measuring output response acceleration spectrum at the distance $S_{\ddot{w}\ddot{w}}(\omega)$ due to input accelerations spectrum $\overline{S}_{\ddot{w}\ddot{w}}(\omega)$ the FRF – $H(\omega)$ is possible derived by (1), too.

5. EXPERIMENTAL MEASUREMENTS ON SITE

5.1. The building site description

The new part of the *M. R. Štefánik Bratislava Airport* building development involved the relocation of the old technological collector under area of the operated airport buildings into the part of reinforced concrete collector along the new terminal and the terminal under reconstruction. Reinforced concrete tube collector cross section has internal dimensions of 2.5 m wide and 3.3 m high. The thickness of the walls, ceiling and base plate are consistently 300 mm tube is structurally designed as a reinforced concrete structure using a U–shaped, covered with prefabricated ceiling. Foundation of the collector and its technical chambers and it is about one meter below the ground water level an therefore it was necessary to make earth works using steel sheet pile (profiles Larsen 3n, length 10 m), which enabled to encircle the collector site very shortly after water pumps installation and the performing water pressure insulation. Sheet piles driving were performed by vibration ramming machines (MS 16HFV and 206H40). Trench shoring was insured by Larsen 3n steel sections for an average pit bottom depth of 5.3 m (Fig. 2).

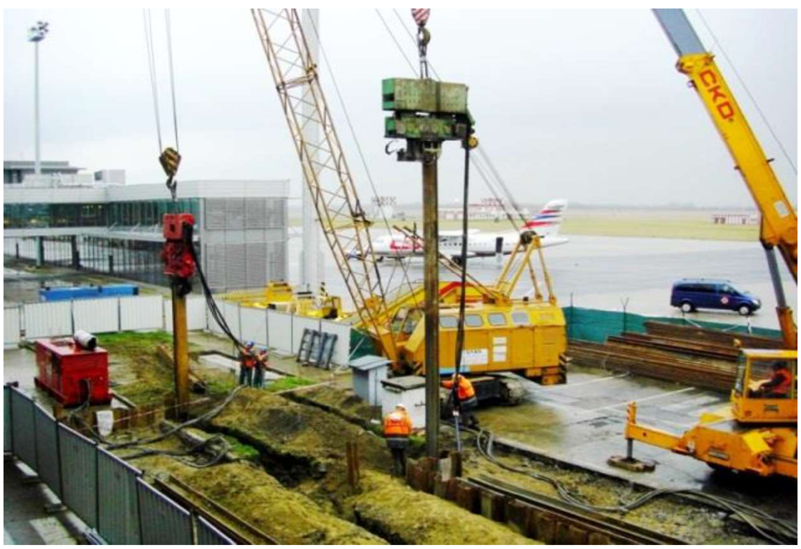

Fig. 2 Vibratory pile driving in collector site. The Airport Bratislava, Location L2

5.2. The Experimental tests at nearby construction site and airport building

The ground vibrations and airport building response due to pile driving were measured by accelerometers BK – 8306 (Brüel–Kjaer). The output signals from the pickups were pre–amplified and recorded on portable PC equipped with A/D converters software packages *NI* (*National Instrument*). The experimental analysis has been carried out by off–line method, [1]. The ground and structure vibrations frequencies were obtained using *spectral analysis* of the recorded ground response dynamic components, which are considered as *ergodic and stationary*. Spectral analysis (spectra, PSD–$G_{ik}(j)$) was performed via *National Instrument* software package NI LabVIEW. The *wave velocities* have been investigated by means of *the correlation and spectral analysis* [8] in order to obtain cross *correlation functions* $R_{xy}(t)$ and *coherence function* $\gamma_{xy}^2(f)$.

Ground dynamic parameters. To calculate the prediction of vibration level and dynamic response for projected a new airport terminal T2 building in adjacent operating T1 terminal building it was needs to know the *building site soils dynamic parameters and FRF.* The in situ impact tests were performed [1], at the T2 terminal building site (35,0 m distance from T1), see also Fig. 3. The object of experimental measurements of transient signal was to find:

• the Raleigh's and share wave velocities by using standard equipment of ISM,

• the same dynamic characteristics as mentioned in stationary signals investigation (at nearby pile region) *via the spectral and correlation procedures*.

The tests result: C_R = 155.10 ms^{-1}; δ_G = 0.117; E_0 = 149.20 MPa; G_0 = 55.95 MPa.

The calculation includes data: λ_R = 9.2 m, ρ = 1950 kgm^{-3}, α = 0,0398 (m^{-1}), l = 16 m, (B2–B4, ISM measured points distance) F_{RE} =1.061457 and ν = 0.33.

The *attenuation coefficient* α (m^{-1}) was obtained by *Golicyn's formula* via *standard deviations of displacement amplitude* vibration values σ(0) and σ(y) at the distances l_0,ly from source of excitation using the *displacement PSD*–$G_{ii}(0)$ and $G_{kk}(y)$, see also [9].

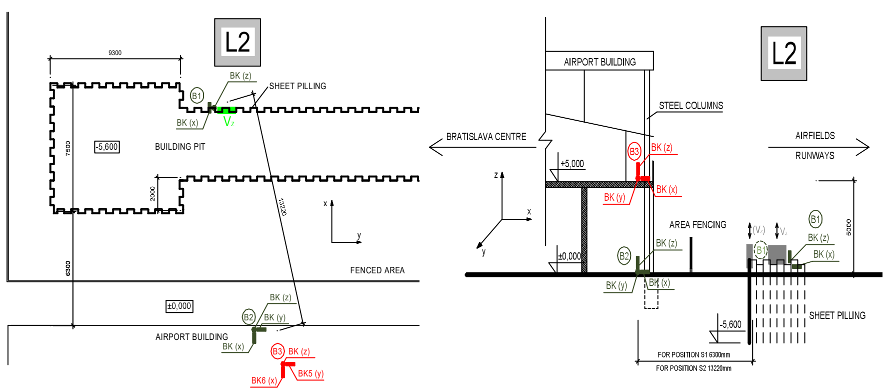

Fig. 3 Measured points positions at L2 location in top view and cross section

Buildings structure dynamic response (BSDR). The *main purpose of the pile driving tests at the site was to control the distance where ground vibrations could be expected to be lower than the limiting value recommended* e.g. by STN EN 1998–

1/NA/Z1 (2010*)* or ***vibratory pile drivers*** **(VPD)** *operating mode regulation*. To achieve this purpose it was also useful to apply e.g. the Swedish Standard (1999) where maximum allowable calculated vibration velocity (vertical component) is v_{max} = 7,8 mm/s. Before starting of tests and monitoring BSDR series it was set up the operation modes rating of all using pile drivers to avoid unfavorable level of vibration (standars level on foundation or ceiling) on airport terminal structure (calibration). However, some concern was expressed with regard to environmental considerations (occupants). It was reason to carry out 9 series measurements and 10 days continual monitoring of the dynamic response of the airport terminal buiding structure at selected representative points, (Fig. 3). Short description of used *monitoring system*: The sensors are connected to an analyzer that also provides power to the sensors. The analyzer was connected to a laptop computer served only as communication devices to pull data off the analyzer, see also [10]. The laptop was connected to the internet network, it allows remote control, remote data download and a conduit for alarm notifications. Information about the objects, type of measurement and the distances to the source of vibration caused by the VPD are given in [1].

As an example of the of the VPD induced vibrations velocities spectral analysis result (PSD) on the structure at point BK2 and also the ground and structure velocities time histories functions $v(t)$ at points **BK1** and **BK2** at are plotted on Fig. 4. Results of experimental tests and monitoring via extreme data values of all measurements are summarized in the accompanying Fig. 5.

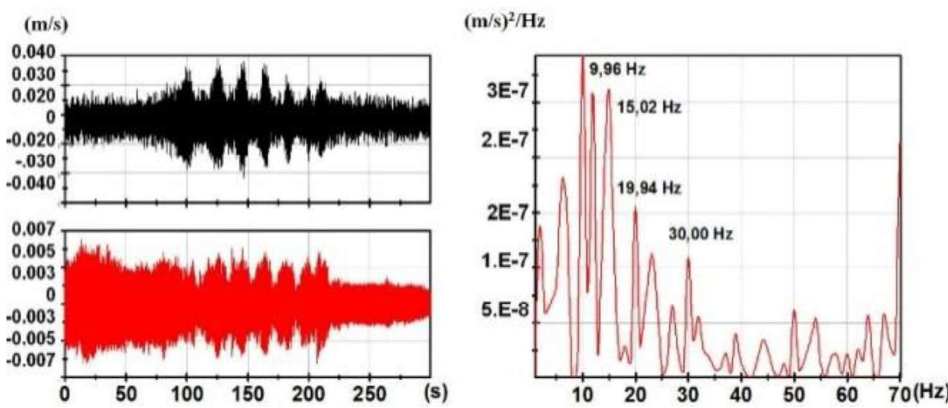

*Fig. 4 Examples of vibration velocities amplitude time histories **$\dot{w}$(t),** $\dot{w}(t)$ and PSD $G_{\dot{w}\dot{w}}(f)$ at Airport Bratislava, Location L2; pickups **BK1(z)** and BK2(z),Test Nr.6*

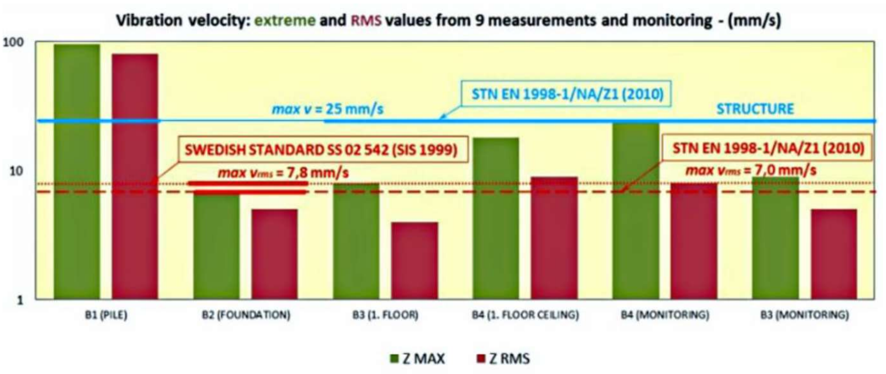

Fig. 5. Results of 9 experimental tests and 10 days monitoring in comparison to [11], [12]

CONCLUSION

- This paper presents an overview of some prediction model for the ground–borne vibrations and the buildings structure dynamic response due to pile driving process. The numeric–experimental approach based on application of spectral and correlation analysis to calculate (FEM) ground dynamic response at the distance and dynamic response of building structures situated nearby construction works area were introduced.
- The relevant calculation procedure and experimental measuring procedure were suggested and applied in the case study of pile driving process at the airport construction site, too.
- The *main purpose* of the pile driving tests was *to determine the distance* where the ground and building vibrations levels will be lower than the codes limiting values during optimal vibratory pile drivers operating was achieved.
- From comparisons of experimental tests and building monitoring extreme data values of all measurements it follows that all data of standards prescription values and criteria regarding airport building structure during guided vibratory driving of sheet piles working in the adjacent construction site were fulfilled.

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