УДК 620.178.153

Dynamic testing of tribune structure of Poznan city stadium

Apanas L., mgr. inz., **Madaj A.,** dr hab. inz., **Siekierski W.,** dr. inz.

Poznan University of Technology, Poland

Анотація. Описані динамічні випробування частини трибун міського стадіону в м. Познань в процесі підготовки до ЄВРО-2012. Наводяться аналітичні результати випробувань і виводи на основі розрахунків, включаючи вплив вібрацій на глядачів і конструкції трибун. Для досягнення наочних результатів в умовах навантаження, характерних для трибун стадіону в період проведення футбольних матчів, були проведені спеціальні випробування. Виконано аналіз рухомого навантаження в результаті скупчення людей на випробовуваній трибуні при її майже повному заповненні. Також були проведені додаткові випробування на навантаження за наявності групи з 30 чоловік, що стоять на консолі.

Описані різного роду вертикальні переміщення, а також вертикально-горизонтальні прискорення в різних місцях споруди. Зазначено, що характер зареєстрованих коливань свідчить, що поведінка конструкції є задовільною щодо вимог будівельної динаміки. Зафіксовані параметри коливань консолі на другому рівні трибун показали, що вібрації мають незначний вплив на людський організм. Докладний аналітичний розгляд рівня комфортності глядачів на трибунах може виразитися в аналізі тривимірної рамної моделі відносно балок, ортогональних до рамних конструкцій і ярусів стадіону. Двомірна рамна модель, зазвичай використовувана для статичних розрахунків, може виявитися обмеженою в процесі відтворення фактичних динамічних характеристик споруди.

Оскільки виводи базуються на розгляді незавершених конструкцій трибун міського стадіону, то їх навряд чи можна застосувати в майбутньому для споруд, що перекриваються дахом. Динамічні характеристики споруди після закінчення будівництва можуть змінитися і повинні бути ретельно перевірені перш ніж вводити закінчені конструкції трибун в експлуатацію.

Аннотация. Описаны динамические испытания части трибун городского стадиона в г. Познань в процессе подготовки к ЕВРО-2012. Приводятся аналитические результаты испытаний и выводы на основе расчетов, включая влияние вибраций на зрителей и конструкции трибун. Для достижения наглядных результатов в условиях нагрузки, характерных для трибун стадиона в период проведения футбольных матчей, были проведены специальные испытания. Выполнен анализ подвижной нагрузки в результате скопления людей на испытываемой трибуне при ее почти полном заполнении. Также были проведены дополнительные испытания на нагрузку при наличии группы из 30 человек, стоящих на консоли.

Описаны разного рода вертикальные перемещения, а также вертикально-горизонтальные ускорения в различных местах сооружения. Отмечено, что характер зарегистрированных колебаний свидетельствует, что поведение конструкции является удовлетворительным согласно требованиям строительной динамики. Зафиксированные параметры колебаний консоли на втором уровне трибун показали, что вибрации имеют незначительное влияние на человеческий организм. Подробное аналитическое рассмотрение уровня комфортности зрителей на трибунах может выразиться в анализе трехмерной рамной модели в отношении балок, ортогональных к рамным конструкциям и ярусам стадиона. Двухмерная рамная модель, обычно используемая для статических расчетов, может оказаться

ограниченной в процессе воспроизведения фактических динамических характеристик сооружения.

Так как выводы базируются на рассмотрении незаконченных конструкций трибун городского стадиона, то их вряд ли можно применить в будущем для сооружений, перекрываемых крышей. Динамические характеристики сооружения после окончания строительства могут измениться и должны быть тщательно проверены прежде чем вводить законченные конструкции трибун в эксплуатацию.

Abstract. Dynamic testing of part of the tribune of Poznan city stadium, during its preparation for Euro 2012 is described. The analysis of test and computational results as well as discussion on vibration influence on spectators and tribune structure is given.

To achieve loading conditions typical for the stadium tribune, testing were carried out during football matches. Live load was introduced by crowd of spectators, gathered on tested structure, filling it almost to its full capacity. During an auxiliary testing loading consisted of group of 30 people located on tested cantilever.

Vertical displacements as well as vertical and horizontal accelerations were recorded in various locations of the structure.

In general, character of recorded vibrations lead to conclusion that structure behaviour is acceptable in terms of requirements concerning structural dynamics. Recorded vibration parameters of the cantilever of the II-nd level of the tribune show that the vibrations may be sensed uncomfortably by humans. Accurate analytical verification of comfort of spectators on the tribune may require analysis of 3D frame model, that would regard beams orthogonal to frames and auditorium decks. 2D frame model, used commonly for static calculations may turn out to be to limited in terms of replication actual dynamic characteristics of the structure.

Since all the conclusions concern unfinished structure of city stadium tribune, they must not be extended to future complete structure covered with roof. Dynamic characteristics of the structure, after its completion, may change and should be verified prior to submitting complete tribune structure to the public exploitation.

Key words: stadium, dynamic analysis, test tribune.

Introduction. Poznan city stadium has been refurbished to comply with UEFA requirements concerning stadiums for Euro 2012. Among others, new tribunes have been built. After completion part of tribune system it was opened to spectators of football matches.

The spectators reported uncomfortable behaviour of tribune structure, that is:

— strong, uncomfortable vibration of cantilever of II-nd level of tribune;
— phenomenon of swinging of III-rd level of tribune.

Thus the dynamic testing of existing part of the tribune was ordered. Fig. 1. shows the existing part consisted of tribune that was tested. The structure of tribune back as well as roof was present yet, during testing.

The paper describes the testing scope and results. The analysis of test results as well as its influence on spectators and tribune structure is given.

Fig.1. General view of tested structure of tribune

Structure description. Main load-carrying elements of the tested tribune are RC frames spaced by 9,0 m and connected with system of RC beams orthogonal to frame planes. RC frame beams between storeys, auditorium girders and auditorium decks with seats for spectators are precasted. Auditorium decks along tribune slope are connected by steel mandrels glued into special sockets. Access to tribune are provided by precasted / in-situ staircases. Frames are based on continuous and spot footings.

Structural elements are made of C40/50 concrete and reinforced with bars of AIIIN steel.

Testing description. Vibration generating loading. To achieve loading conditions typical for the stadium tribune, testing were carried out during football matches. Live load was introduced by crowd of spectators, gathered on tested structure, filling it almost to its full capacity. Data recording was carried out during tribune filling, during matches (as well as when goals were scored), during breaks and just after match ends, when people were leaving. Moreover, for the purpose of testing, spectators gathered on the cantilever of the II-nd level of the tribune, jumped up and down rhythmically. Effects of such behaviour may be recognized as being close to those of maximum possible strength.

Beyond testing during matches, also auxiliary testing was carried out. Loading consisted of group of 30 people located on tested cantilever. They induces vibrations by rhythmical jumping or by performing single skip from seats to auditorium floor. The latter was meant to allow for self vibration frequency assessment.

Scope and method of data acquisition. Displacements and accelerations of locations across the structure were recorded. Hottinger-Baldwin Measurement system was used, Inductive gauges recording displacements and inertial gauges recording accelerations were plugged to electric-to-numeric converter that allow for computer data registration and post processing using BEAM software of HBM.

In the case of the cantilever of the II-nd level of the tribune, the location of gauges were as follows:

- tip of cantilevered frame member – locations marked as F1 (vertical displacement) and P1 (vertical acceleration),
- tip of auditorium deck near tip of cantilevered frame member – locations marked as F2 (vertical displacement) and P2 (vertical acceleration),
- tip of auditorium deck in the midspan (between subsequent frames) – locations marked as F3 (vertical displacement) and P3 (vertical acceleration).

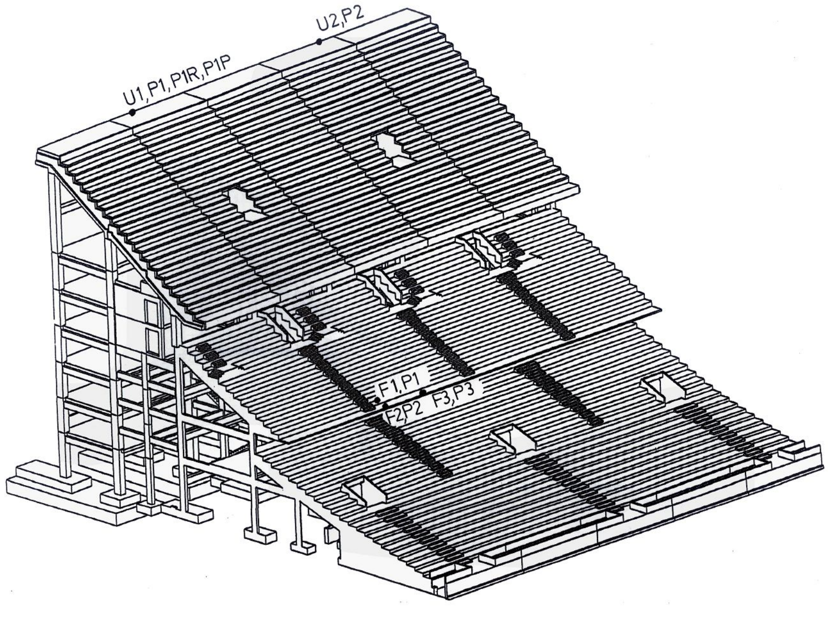

Fig. 2. General scheme of the tested tribune structure

In the case of peak of the III-rd level of the tribune, the locations were as follows:

- in the midspan 2-3 (between subsequent frames) – locations marked as U1 (horizontal displacement), P1 (horizontal acceleration, along U1), P1R (horizontal acceleration orthogonal to P1) and P1P (vertical acceleration),

— in the midspan 8-9 (between subsequent frames) – locations marked as U2 (horizontal displacement) and P2 (horizontal accelerations, along U2).

Test results. Results of tests that were carried out allow for the following conclusion:

— during crowd filling and emptying the tribune as well as during most of football matches, tribune vibrations are very small, hard to record by used equipment,
— recordable vibrations accompany agitation of spectators by certain events during football match,
— the largest values of amplitudes and accelerations occurred during organised jumping of group of 30 people.

Maximum values of recorded parameters of vibrations of the cantilever of the II-nd level of the tribune are given in table 1. Fig. 3 shows vibrations (gauge F3), induced by jump of 30-people group from seats to auditorium floor, while Fig. 4 gives respective acceleration (gauge P3).

Table 1

Chosen recorded data for the cantilever of the II-nd level of the tribune

Vibration source	Freq. [Hz]	Vertical displacement [mm]			Vertical acceleration [m/s^2]		
		F1	F2	F3	P1	P2	P3
Agitation on the tribune	2,5	0,24	0,36	0,42	0,16	1,05	0,92
"Organised" jumping	2,4	0,64	1,85	2,97	0,85	2,61	3,17
Single impulse	-	0,24	1,03	1,62	1,39	7,63	4,98
Jumping of 30-people group	2,1	0,33	1,30	2,04	1,19	7,48	3,23

After single impulse, self vibration frequency of the structure (at cantilever tip) was recorded to be about 10 Hz. the vibrations tapered off very quickly due to strong damping.

Maximum values of recorded parameters of vibrations of the III-rd level of the tribune are given in table 2.

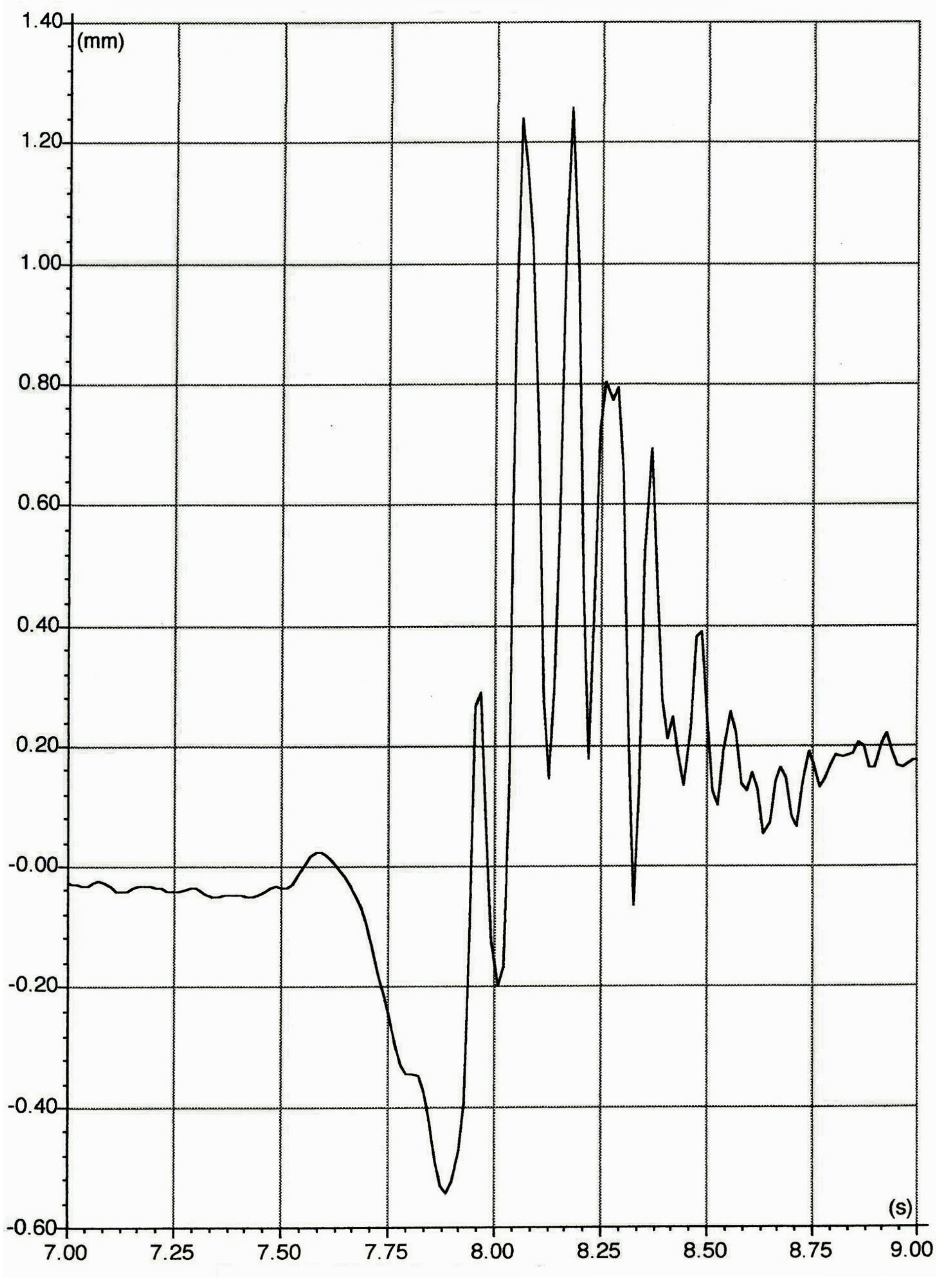

Fig. 3. Vibrations induced by jump of 30-people group from seats to auditorium floor (gauge F3)

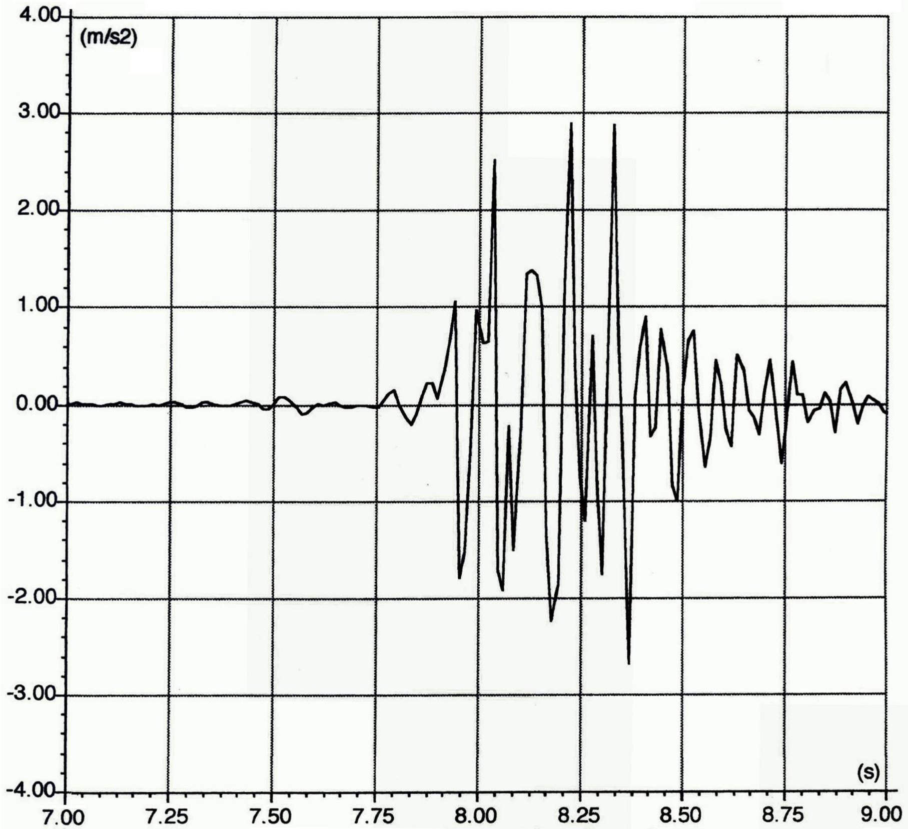

Fig. 4. Accelerations induced by jump of 30-people group from seats to auditorium floor (gauge P3)

Table 2

Chosen recorded data for the III-rd level of the tribune

Vibration source	Freq. [Hz]	Vertical displacement [mm]		Vertical acceleration [m/s^2]			
		U1	U2	P1	P2	P1P	P1R
Agitation on the tribune	2,3	0,21	0,26	0,03	0,06	0,01	0,02
“Organised” jumping	2,4	1,30	1,40	0,26	0,20	0,02	0,06

Computational model for dynamic analysis. Numerical computations were carried out. Finite element method was used. Tested structure was modelled as plane frame. Computational model view is given in Fig. 5.

Model regards rigid and pinned connections between beams and columns (bolded ends of beams in Fig.1 marks pinned supports).

State of structure completion during testing as taken into account (lack of the most external columns and supported on them beams as well as lack of roof).

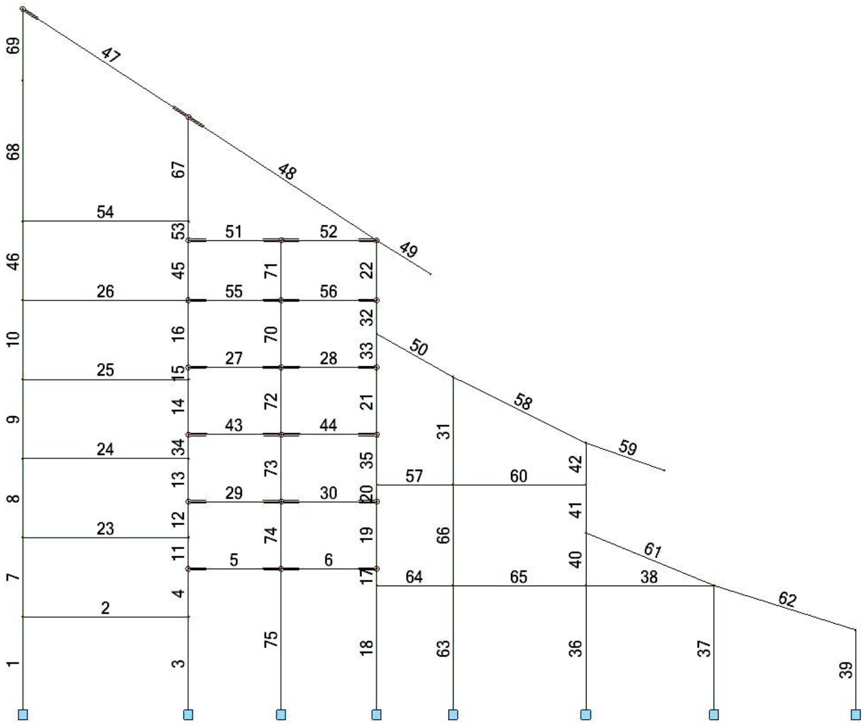

Fig. 5. General view of computational model of tested structure

The following material data was assumed:

— self weight of concrete $\gamma = 25$ kN/m^3,
— Young modulus of concrete E = 38 GPa.

In the next stage of analysis the cantilever (the element 59 of computational model in Fig. 2) of the II-nd level of the tribune was analysed separately, as fixed at one end.

Modal analysis was used to compute self vibration frequencies of the structure.

Tables 3 gives analyses results, namely: self vibration frequencies for the whole structure and for the separated cantilever. Results for two cases are given:

— case of total weight disregarding spectators weight,
— case of total weight regarding spectators weight.

Table 3

Self vibration frequencies

Vibration mode	Frequencies [Hz] in the computational case of:	
	disregarding spectators weight	regarding spectators weight
the whole tribune structure		
1	1,54	1,43
2	4,41	4,09
3	7,65	7,09
4	9,50	8,81
5	10,03	9,30
6	10,29	9,54
7	11,24	10,42
8	11,95	11,08
the separated cantilever of II-nd level of tribune		
1	9,41	7,49

Discussion of test results. Vibration influence on people. Tests show that the most dangerous vibrations for humans are those of frequencies close to self frequencies of vibrations of various part of human body [1, 2]. In case of standing people resonances occur for ranges: 5÷ 6 Hz and 11÷12 Hz, and in case of sitting people – for ranges 4÷6 Hz and 11÷12 Hz.

Evaluation of structural vibrations by humans inside looks differently. The highest human sensitivity to accelerations occur for ranges:

— in the case of vertical vibrations: 4÷8 Hz,
— in the case of horizontal vibrations: 1÷2 Hz.

Limitations of vibration accelerations are applied to vibration frequencies negatively sensed by human. In general allowable accelerations depend on method of structure exploitation by people, intervals between vibrations of «uncomfortable» acceleration and on the fact if the vibration are announced somehow or not [3, 4]. In the case of stadium tribune one may assume requirements as for office buildings – the factor inducing vibrations of certain acceleration is announced and the value of vertical acceleration should not exceed 0.6÷0.8 m/s^2, while the value of horizontal acceleration should not exceed about 0,5 m/s^2.

In terms of negative influence of vibrations on durability and load carrying capacity of structures [3], the main issues are:

— amount of cycles of loading variation during exploitation period,
— level of stresses present within structural members.

Thus, it is hard to set an unambiguous criterion for safety of structural exploitation and assurance of structural durability in the same time.

Vibration of cantilever of II-nd level of tribune. All recorded vibrations have frequencies between 2,1 Hz and 2,5 Hz, that is typical for jumping or marching people. Such vibrations are sensed by humans and, in cast of large amplitudes and accelerations, are uncomfortable. Accelerations recorded during matches on frame cantilever were 0,85 m/s^2, but At the cantilever tip they reached values almost four times as big (3,17 m/s^2). Whereas the former value is acceptable, the latter one may be uncomfortable for humans.

Vibration of III-rd level of tribune. Recorded vibration frequencies of 2,3÷2,4 Hz are sensed by humans. Vibration parameters (amplitude of max. 1,4 mm, horizontal acceleration of max 0,26 m/s^2) do not exceed generally tolerated values. Additional role may play the height factor (top of the tribune is 25 m over ground level) that, combined with sensed vibrations, may generate fear.

Conclusion. Testing driven conclusion.

1. Self vibration and induced vibration frequencies of the whole structure do not exceed the threshold of the highest sensitivity of humans to vertical vibrations.

2. Recorded vibration parameters of the cantilever of the II-nd level of the tribune show that the vibrations may be sensed uncomfortably by humans.

3. Vibration frequencies of the III-rd level of the tribune are typical for this type of structures. Frequencies of induced horizontal vibrations of the III-rd level of the tribune are on the threshold of elevated human sensitivity. This may be possible reason of negative feelings of spectators present there.

4. In general, character of recorded vibrations lead to conclusion that structure behaviour is acceptable in terms of requirements concerning structural dynamics.

Test versus analysis results comparison based conclusion

1. Computed self vibration frequencies and induced by spectators vibration frequencies differ from each other. Thus, there is no direct threat of resonance. However, due to simplification of computational model this conclusion should be approached with caution.

2. Accurate analytical verification of comfort of spectators on the tribune may require analysis of 3D frame model, that would regard beams orthogonal to frames and auditorium decks. 2D frame model, used commonly for static calculations may turn out to be to limited in terms of replication actual dynamic characteristics of the structure.

Final remarks

Since all drawn conclusions concern unfinished structure of city stadium tri bune, they must not be extended to future complete structure covered with roof. Dynamic characteristics of the structure, after its completion, may change and should be verified prior to submitting complete tribune structure to the public exploitation.

Literature

[1] Ciesielski R., Kawecki J. Maciąg E. Ocena wpływu wibracji na budynki i ludzi w budynkach, (Assessment of vibration influence on buildings and on people in buildings), ITB, Warszawa, 1983.

[2] Ciesielski R., Kawecki J. Maciąg E. Drgania drogowe i ich wpływ na budynki (Road traffic induced vibrations and their influence on buildings), WKiŁ, Warszawa, 1990.

[3] EN 1992 Eurocode 2 Concrete.

[4] PN-88/B-02171 Ocena wpływu drgań na ludzi w budynkach (Polish Standard – Evaluation of influence of vibrations on people in buildings.

Надійшла до редколегії 22.06.2010 р.