Dynamic analysis of strength and human-comfort level of the football stadium structures at coordinated movements of audience

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Abstract. In the design of stadiums and other sports facilities it is necessary to take into account the dynamic performance caused by coordinated movement of groups of people. National standard technical documents do not contain guidance on the setting of dynamic loads caused by people, as well as admissible dynamic parameters of grandstands' structures in the stadiums caused by such actions that should be taken in consideration in the course of design. Therefore, it is necessary to develop appropriate recommendations. Based on the developed recommendations, analysis of stadium structures for dynamic loads caused by the audience movement was performed in the time domain by direct integration of motion equation using certified software package Lira 10.4. It was obtained that the dynamic human-comfort level in the grandstands and in the under-grandstand facilities was ensured. Recommendations were made based on the analysis of international and Russian standard technical documents, generalization of available experience in design, construction, and operation of such objects, including similar unique large span structures. Obtained accelerations of under-grandstand facilities were analyzed in accordance with the construction standards SN 2.2.4/2.1.8.566-96. It was revealed that the limit values for some structure points have been exceeded.

1 Introduction

In the design of stadiums and other sports facilities it is necessary to take into account the dynamic performance caused by coordinated movement of groups of people.

Dynamic loads due to coordinated movements of large numbers of people in the viewing area of the stadium grandstands cause vibrations of grandstands' structures, which in turn can reduce the human-comfort level, as well as have a significant influence on the bearing capacity of the structures.

The acceleration of the structures' oscillations is usually taken as the main value characterizing perception of vibrations by people. National standard technical documents do not contain guidance on the setting of dynamic loads caused by people, as well as admissible dynamic parameters of grandstands' structures in the stadiums caused by such

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actions that should be taken in consideration in the course of design.

According to the results of monitoring of the operated facilities status, as well as the targeted experiments, a crowd of people may cause significant dynamic loads on the grandstands within the frequency range from 1.5 to 3.3 Hz. This kind of impact is observed at a sudden change of position and coordinated movement of the audience [1-2].

The intensity of the dynamic loads depends on the nature of the actions [3]. Maximum loads are caused by rhythmic jumps. Dynamic loads will also largely depend on the probability with which they occur during a certain period, exciting a resonance in the structure.

It should be noted that the lower frequencies of grandstand structures' oscillations of a number of existing stadiums in free of people condition range from 2.2 to 17.0 Hz. As a consequence, a number of stadiums revealed significant accelerations and vibration amplitudes of cantilever beams of the grandstands, cracks in beams, objectionable resonant vibration, and a significant tangible vibration of the grandstands.

The authors of [4] concluded that the most fail-safe design should ensure the local oscillations frequency of the stadium grandstands at least twice the value of the predominant frequency of exposure.

The manual [1] states that grandstand structures meet the requirements of dynamic human-comfort level and strength at the smallest frequency of the local vertical oscillations is not less than 3.5 Hz, if the facility is used exclusively for sporting events, and 6 Hz, if the facility is used for holding live pop and rock concerts. The minimum frequency of the local oscillations of grandstands in the horizontal direction is limited to maximum of 3 Hz. The monograph [5] clarifies the minimum values of the global frequencies of the grandstand structures.

The first level of vibrations arising from the actions of the audience can be greatly irritating, and can disturb the comfort of people not involved in these actions, while the participants of the action do not complain. Higher vibration levels can cause more severe reactions of people and even panic. Allowable values for the first criteria are given in [6] ranging from 0.05g up to a maximum of 0.1g (where g is the gravity acceleration). However, there are reports of higher values, up to approximately 0.3g that did not cause any serious reactions in people. More recent works [7-8] provide more detailed information. However, these figures may need further adjustment.

Vertical dynamic load distributed over the spectator areas of the grandstand $p_v(t)$ and caused by active actions of the audience should be taken as a sequence of half-sine pulses [9-10]:

$$p_v(t) = \begin{cases} \gamma_f k_s p_0 \cdot \sin\left\{\dfrac{\pi}{\alpha}\left(\dfrac{t}{T_p} - n\right)\right\}, & t \le (\alpha + n)T_p \\ 0, & t > (\alpha + n)T_p \end{cases} \tag{1}$$

where p_0 – is the normative weight of active mass of people distributed over the area, determined by the actual capacity of the examined zone of the grandstand at an average weight of one person equal to 0.67 kN; allowable value of p_o was taken equal to 1.8 kN/m^2 when calculating grandstands with fixed seats in the spectator area, and 2.25 kN/m^2 when calculating other grandstands, as well as passes; γ_f – is the load safety factor, assumed to be equal to 1.2 in the calculation of structures according to the ultimate limit state (ULS), and 1.0 in the calculation of structures according to the serviceability limit state (SLS), as well as when estimating dynamic human-comfort level in the grandstands; k_s – is the synchronization factor of an active actions of the audience, assumed to be 0.67; T_p – is the period of the pulses taken equal to 0.4 s; n = 0, 1, 2,..., N – is the ordinal number of the pulse; number of pulses $N+1$ shall be equal to at least five; α – is the contact ratio, assumed to be 0.5.

2 The calculation method of impact caused by coordinated movement of audience

In the design of the object titled "Construction of stadium to 45,000 seats in Saransk in the vicinity of Volgograd Street", recommendations were developed for the calculation of the stadium grandstands in terms of the dynamic loads from the movement of the audience, and the appropriate calculations were carried out.

Recommendations were made based on the analysis of international and Russian normative and technical documents, generalization of experience in design, construction, and operation of sports facilities, including similar unique large span structures [11-13].

1. Load-bearing structures of reinforced concrete blocks with grandstands and under-grandstand space should be designed according to two groups of ultimate behavior under static loads defined by applicable standard technical documents and Special Technical Regulations (STR).

2. Load-bearing structures of reinforced concrete blocks with grandstands and under-grandstand space should be designed according to two groups of ultimate behavior under a joint action of the relevant static loads and dynamic loads caused by the coordinated movement of audience, as defined by applicable standard technical documents, STR and recommendations.

The noted requirements can be considered to be fulfilled, if the value $\frac{p_0}{\gamma_f}\frac{y_{dyn}}{y_{stat}}$ (here y_{dyn} – is the greatest value of the grandstand structural deflection taken from the solution of the dynamic problem under load (1), y_{stat} – is the structural deflection of the grandstand under static load p_0, (other values are explained above)) does not exceed the full normative value of the uniformly distributed static load from the weight of people, taken into account in the calculation of the grandstand according to item 1, and determined by the STR or item 7 of Table 8.3 of the Design and Construction Specifications SP 20.13330.2011.

3. Load-bearing structures of reinforced concrete blocks of the grandstands must also meet the requirements of human-comfort level under the joint action of static loads and dynamic impacts identified by the recommendations.

Dynamic human-comfort level can be considered secured, if the maximum acceleration of the structures of the grandstand and ceilings of facilities under the grandstands, resulting from dynamic analysis, is not more than $0.5\sqrt{f}$ m/s^2 in the vertical direction and $0.25\sqrt{f}$ m/s^2 in the horizontal direction (here, f – is the corresponding lowest frequency of the local oscillations of the structure of grandstands and the ceilings of under-grandstand space, Hz).

4. A check according to two groups of ultimate behaviors in accordance with item 2 is allowed not to be performed:

- for reinforced concrete blocks of grandstands at a lower local oscillations frequency of at least 6 Hz with the prevalence of oscillations in the vertical direction and of 3 Hz with the prevalence of oscillations in the horizontal direction;
- for grandstand structures at a lower local oscillations frequency of not less than 12.5 Hz.

When calculating the modes and frequencies of the local oscillations, it is necessary to consider only permanent design loads (self-weight of structures, the load from floors and walls). The criticality-based safety factor is recommended to be taken equal to one. At piled foundation, it is allowed taking a rigid fixing in the top level of foundations. The elastic modulus of reinforced concrete structures should be taken as the initial value according to SP 63.13330.2012.

5. In case of failure to meet the requirements of human-comfort level (see item 3) according to dynamic analysis results, the design solution of reinforced concrete blocks of the grandstands (grandstands structures) should be changed.

6. Dynamic analysis of structures at impact (1) can be performed by any known methods of dynamic problem solving in the time or frequency domains with the use of certified computing codes. The used solution method must take into account transient processes under dynamic loading of structures.

7. When solving dynamic problem using the method of the dynamic response decomposition (DRD) according to the modes of natural oscillations, it is necessary to consider enough number of modes so that the lost part of the total dynamic response due to rejected (unaccounted) vibration modes would not be more than 5%. It is allowed determining the part of total dynamic response due to rejected (unaccounted) vibration modes using approximate method presented in [14].

8. The elastic modulus of the reinforced concrete structures should be taken according to SP 63.13330.2012.

9. Design-level damping of reinforced concrete structures should be taken equal to 5% of critical damping that corresponds to the coefficient of inelastic resistance γ=0.1 and a logarithmic damping index δ=0.31.

10. Dynamic impact (1) should be considered simultaneously with a uniformly distributed static load caused by the weight of people, according to STR or item 7 of Table 8.3 SP 20.13330.2011, as well as with wind and temperature effects, snow and ice loads, seismic and other special impacts.

11. In case of failure to meet the requirements of item 2, it is necessary to adjust the full value of the uniformly distributed static load caused by the weight of people when calculating the grandstand according to item 1.

Further we proceed directly to the calculation of the stadium.

Analysis of structures for dynamic loads caused by the movement of the audience is performed in the time domain by direct integration of the motion equation using certified software package Lira 10.4.

A graphic illustration of the dynamic load distributed over the spectator areas of the grandstand $p_v(t)$ (1) is shown in Figure 1.

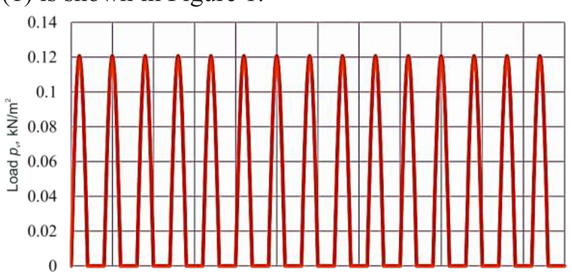

Fig. 1. Dynamic load distributed over the spectator areas $p_v(t)$, caused by the active movement of the audience.

The estimated damping of the reinforced concrete structures of grandstands was taken to be equal to 5% of critical damping that corresponds to the coefficient of inelastic resistance γ=0.1 and a logarithmic decrement δ=0.314.

When carrying out the calculation of the stadium, we analyzed all sectors; however the article describes the calculation of just one sector D, the structural design of which is shown in Figure 2.

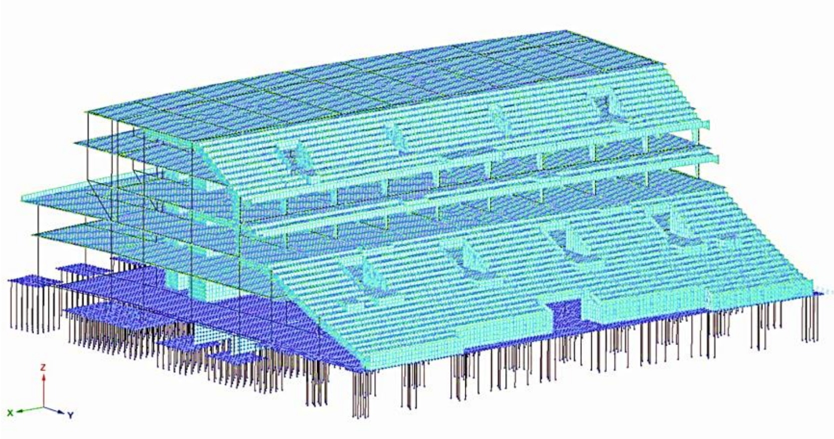

Fig. 2. Finite element model of sector D.

In the course of calculations we have determined the local mode shape and the oscillation frequencies of the reinforced concrete unit of grandstand and floor structures.

The local mode shape and the oscillation frequencies of the reinforced concrete unit of grandstand structures are shown in Table 1.

Table 1. The frequencies of local oscillations of the reinforced concrete unit of grandstands

Mode shape number	Frequencies		Period, s	Mod. weight, %	Sum of the mod. weights, %
	Circular frequency, rad/s	Frequency, Hz			
1[1)]	19.715	3.138	0.319	13.21	13.21
2	22.553	3.590	0.279	22.82	36.03
3	24.155	3.844	0.260	10.10	46.12
4	32.755	5.213	0.192	0.04	46.17
5	32.805	5.221	0.192	0.05	46.22
6	47.608	7.577	0.132	0.29	46.51
7	50.498	8.037	0.124	11.43	57.94
8[2)]	52.972	8.431	0.119	0.25	58.19
9	56.622	9.011	0.111	0.24	58.43
10	56.922	9.060	0.110	2.56	60.99

[1)] The lowest frequency of local oscillations of the reinforced concrete unit of the grandstands in the horizontal direction;
[2)] The lowest frequency of local oscillations of the reinforced concrete unit of the grandstands in the vertical direction;

The local mode shapes and oscillation frequencies of grandstand structures of the lower tier are shown in Table 2. The results for the other grandstands and floor structures are not presented in the article.

Next, calculations were performed for the impact of (1) using direct dynamic method. We have identified points of maximum horizontal and vertical accelerations for each tier of the grandstands and each floor structure.

Table 2. Local oscillations frequencies of the lower tier of the grandstands structure

Mode shape number	Frequencies		Period, s	Mod. weight, %	Sum of the mod. weights, %
	Circular frequency, rad/s	Frequency, Hz			
1	100.99	16.073	0.062	0.00	0.00
2	101.00	16.075	0.062	7.58	7.58
3	101.84	16.208	0.062	0.75	8.33
4	101.89	16.217	0.062	0.00	8.33
5	102.24	16.273	0.061	1.55	9.88
6	117.22	18.657	0.054	0.53	10.41
7	117.25	18.660	0.054	3.92	14.33
8	119.46	19.012	0.053	0.19	14.53
9	119.46	19.012	0.053	2.92	17.45
10	123.97	19.731	0.051	0.09	17.54

3 Basic calculation results

Below are the basic calculation results of the sector D of the stadium in Saransk.

1. The condition for the necessity to check the stadium grandstands with respect to the ultimate limit (ULS) and serviceability limit (SLS) states (Table 3).

2. Assessment of the dynamic comfort level of people staying in grandstands and under-grandstand facilities (Table 4).

According to the results obtained, the dynamic human-comfort level of staying in grandstands and under-grandstand space is ensured. The study confirms that in the design of stadiums and other sports facilities it is necessary to ensure that the frequency of natural oscillations of grandstands and under-grandstand facilities structures premises is not less than the limiting value [1, 4, 5]. This value is directly related to the predominant frequency of exposure at coordinated movements of audience [3].

This conclusion is true for stadium used as sports facility, because for this type of structures there are no standards for a human-comfort level. Acting in Russia sanitary norms SN 2.2.4/2.1.8.566-96 applicable to industrial facilities, residential and public buildings, where there may be long-term vibration, but not at the stadium and other structures where vibration may be short-lived and requirements for their limitation should be less stringent [2]. Therefore, the methodology uses materials mainly from foreign sources [6, 8].

But on the other hand, some space under the grandstands can be considered as the premises similar to those in public buildings or administrative-and-managerial facilities. In this case, in accordance with the SN 2.2.4/2.1.8.566-96 there are strict requirements for limiting vibration (Table 5).

Table 3. The condition for the necessity to check the stadium grandstands with respect to the ultimate limit (ULS) and serviceability limit (SLS) states

Structure	Local oscillations frequency	
	Minimum value $f_{\min}$, Hz	Minimum limit value $f_{\lim}$., Hz
Grandstand unit (horizontal oscillations)	3.1	3.0
Grandstand unit (vertical oscillations)	8.4	6.0
Grandstand of the lower tier	16.1	12.5
Grandstand of the middle tier	15.8	12.5
Grandstand of the upper tier	21.3	12.5

Table 4. Assessment of the dynamic comfort level of people staying in grandstands and under-grandstand facilities

Structure	**Accelerations in the Y axis direction**		**Accelerations in the Z axis direction**	
	Maximum value $a_{y(x),\max}$ **, m/s²**	**Limit maximum value** $0.25\sqrt{f}$ **, m/s²**	**Maximum value** $a_{z,\max}$ **, m/s²**	**Limit maximum value** $0.5\sqrt{f}$ **, m/s²**
Grandstand of the lower tier	0.28	1.00	0.70	2.00
Floor structure at the elevation +8.900	0.04	0.44	0.35	1.41
Grandstand of the middle tier	0.10	0.99	0.43	1.99
Floor structure at the elevation +13.100	0.04	0.44	0.28	1.64
Grandstand of the upper tier	0.27	1.15	0.45	2.31
Floor structure at the elevation +21.500	0.06	0.44	0.29	1.51

Table 5. Requirements for limiting vibration (SN 2.2.4/2.1.8.566-96)

The mean geometric frequencies of the bands, Hz	**Admissible values along the X_o, Y_o, Z_o axes**			
	Vibration accelerations		**Vibration velocities**	
	$m/s^2 \cdot 10^{-3}$	**dB**	**$m/s^2 \cdot 10^{-3}$**	**dB**
2	10.0	80	0.79	84
4	11.0	81	0.45	79
8	14.0	83	0.28	75
16	28.0	89	0.28	75
31.5	56.0	95	0.28	75
63	110.0	101	0.28	75

Let compare the obtained results with the requirements of construction standards SN 2.2.4/2.1.8.566-96 for point of floor structure at the elevation +8.900. The results are shown in Table 6.

Table 6. Comparison of obtained results with requirements for limiting vibration

The mean geometric frequencies of the bands, Hz	**Vibration accelerations**	
	Values obtained along *Z* axis	**Admissible values along the X_o, Y_o, Z_o axes**
	$m/s^2 \cdot 10^{-3}$	**$m/s^2 \cdot 10^{-3}$**
2	10.0	10.0
4	30.0	11.0
8	240.0	14.0
16	62.0	28.0
31.5	64.0	56.0
63	13.0	110.0

It is seen from the Table that the maximum accelerations of points in under-grandstand space exceed in terms of bands the limit values indicated in SN 2.2.4/2.1.8.566-96. In accordance with GOST 27751-2014 these results indicate non-compliance with requirements, corresponding to the serviceability limit state (SLS).

In this work, we did not analyze under-grandstand structures space in terms of zoning by category. Therefore, without additional research we cannot state that the construction standard requirements have been violated.

4 Conclusions

1. According to the requirements of item 4 and the above presented calculation results, it is established that the test of the grandstands of the stadium in Saransk in terms of preventing the occurrence of the ultimate limit (ULS) and serviceability limit (SLS) states at the joint action of dynamic impacts (Fig. 1) and other loads and impacts is allowed not to be performed.
2. The calculations of grandstands of the stadium in Saransk with regard to loads from the movement of audience have proved availability of the dynamic human-comfort level in grandstands and under-grandstand space.
3. Fulfillment of requirements for dynamic human-comfort level in grandstands and under-grandstand space of the sports facilities according to the above methodology does not guarantee the fulfillment of requirements SN 2.2.4/2.1.8.566-96 for certain categories of under-grandstand facilities.
4. Under-grandstand space of the sports facilities should also be checked for vibration in accordance with SN 2.2.4/2.1.8.566-96.

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