Нуждин, Л.В. Прогноз колебаний большеразмерных свайных фундаментов с учетом резонансных эффектов / Л.В. Нуждин, В.С. Михайлов // Construction and Geotechnics. – 2024. – Т. 15, № 3. – С. 68–78. DOI: 10.15593/2224-9826/2024.3.06

Nuzhdin L.V., Mikhailov V.S. Prediction of vibrations of oversized pile foundations considering resonance effects. *Construction and Geotechnics.* 2024. Vol. 15. No. 3. Pp. 68-78. DOI: 10.15593/2224-9826/2024.3.06

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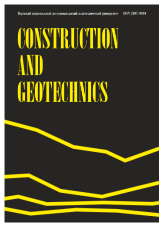
CONSTRUCTION AND GEOTECHNICS
Т. 15, № 3, 2024
http://vestnik.pstu.ru/arhit/about/inf/



DOI: 10.15593/2224-9826/2024.3.06
УДК 624.154.1

PREDICTION OF VIBRATIONS OF OVERSIZED PILE FOUNDATIONS CONSIDERING RESONANCE EFFECTS

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ARTICLE INFO

Received: 25 May 2024
Approved: 10 July 2024
Accepted for publication:
27 September 2024

Keywords:
spatial dynamic model of soil foundation, integral dynamic stiffness of pile cells.

ABSTRACT

The vibrations of the oversized pile foundation together with the soil base are considered on the basis of numerical investigation, including the approved quasi-static methods in the contact formulation of the problem, as well as complex combined spatial and contact models with a kinematic model of seismic impact. It has been demonstrated the disadvantages of the quasi-static linear-spectral method of calculation which includes unreasonable underestimation of shear forces in piles. The examples of the development of resonance effects with account for spatial seismic waves in a dispersed soil foundation increasing the internal forces up to three times and leading to the risk of foundation failure have been shown. The theoretical provisions and efficiency of replacing individual piles with enlarged dynamic pile cells are confirmed.

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ПРОГНОЗ КОЛЕБАНИЙ БОЛЬШЕРАЗМЕРНЫХ СВАЙНЫХ ФУНДАМЕНТОВ С УЧЕТОМ РЕЗОНАНСНЫХ ЭФФЕКТОВ

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О СТАТЬЕ

Получена: 25 мая 2024
Одобрена: 10 июля 2024
Принята к публикации:
27 сентября 2024

Ключевые слова:

пространственная динамическая модель грунтового основания, интегральная динамическая жесткость свайных ячеек.

АННОТАЦИЯ

Рассмотрены колебания большеразмерного свайного фундамента совместно с грунтовым основанием на основании численного исследования, включающего апробированные квазистатические методы в контактной постановке задачи, а также сложные комбинированные пространственные и контактные модели с кинематической моделью сейсмического воздействия. Продемонстрированы недостатки квазистатического линейно-спектрального метода расчета, в том числе необоснованное занижение перерезывающих усилий в сваях. Показаны примеры развития резонансных эффектов при учете пространственных сейсмических волн в дисперсном грунтовом основании, увеличивающие внутренние усилия до трех раз и приводящие к риску разрушения фундамента. Подтверждены теоретические положения и эффективность замены отдельных свай укрупненными динамическими свайными ячейками.

Introduction

Buildings and structures do not exist only under conditions of long-term static loads. One of the urgent tasks of foundation design is to take into account industrial and technogenic dynamics, explosive effects and seismics. Pile foundations in conditions of weak soils and their low horizontal stiffness are vulnerable to seismic effects, which can both decrease and significantly increase in the process of joint vibrations of the structure and the pile foundation.

At the moment, there are practically no reliably tested methods of calculation of oversized pile field for dynamic and seismic effects in the Russian Federation. The greatest attention of contemporary academics is paid to the calculation of piles under long-term impact conditions [1–3]. The existing calculation methods consider the vibrations of pile foundations of simple shape usually under machines with dynamic loads and of small size. Approaches to account for resonance are based on the theory of vibrations of systems with a small number of dynamic masses, but this does not meet the peculiarities of the development of surface waves in a continuous soil medium.

For the reasons, mentioned above, the authors considered dynamic vibrations of the system "oversized pile foundation-soil foundation" with more than 25 piles in a group. Numerical theoretical studies were performed in order to develop a comprehensive method for calculating oversized pile foundations to predict the dynamic behavior of the system.

Methods of experiment and theoretical approach

A numerical study of vibrations of oversized pile foundations was carried out by the finite element method in the SCAD 21.1 computational complex using four approaches to modeling the pile foundation in the form of twenty different design schemes, five variants of the structure's number of storeys and two seismic impact models. In total, 720 particular variants of the ratio of the dynamic masses of the structure and the foundation, models of the foundation and impact were considered. The task of the first stage of the study was to assess the applicability of contact models. At the second stage of the study, the equivalence of seismic impact models with the linear-spectral method and the method of integrating the equations of motion was analyzed. At the third stage, the analysis of methods regarding the inertial characteristics of the foundation and the effects of resonance was carried out.

In the first stage of the research, two types of contact models are considered. The first type of contact models uses the scheme of non-uniform distribution of proportional deformation coefficients of the foundation according to the approach of N.Z. Gotman, which is developed for oversized pile foundations with distribution of variable bedding coefficient according to the Fuss-Winkler model type, depending on the distance of edge areas from the center of the pile field [4]. This proportional strain model is coded "MPD" in the results tables.

The authors have modified the N.Z. Gotman approach in order to apply it to the solution of dynamic problems. Instead of bedding coefficients according to the "load-settlement" dependences obtained on the basis of the results of in-situ tests of piles or their numerical modeling, experimental-empirical dependences for determining the equivalent and distributed dynamic stiffness of the base according to O.A. Savinov were used in the level of embedment of the conditional length of the foundation piles for a flexible membrane [5] with modified parameters in accordance with the provisions of SR 26.13330. The rules for separating the bedding coefficient distribution areas were also modified in order to model not only edge piles compression-bent in one direction, but also corner piles bent in two planes (Fig. 1).

Due to the necessity of obtaining at least three areas with distributed bedding coefficients for the underlying foundation at the level of the conditional foundation sole or embedment of equivalent pile length, the authors proposed to use the expressions according to [6]. These expressions fully correspond to the method of O.A. Savinov.

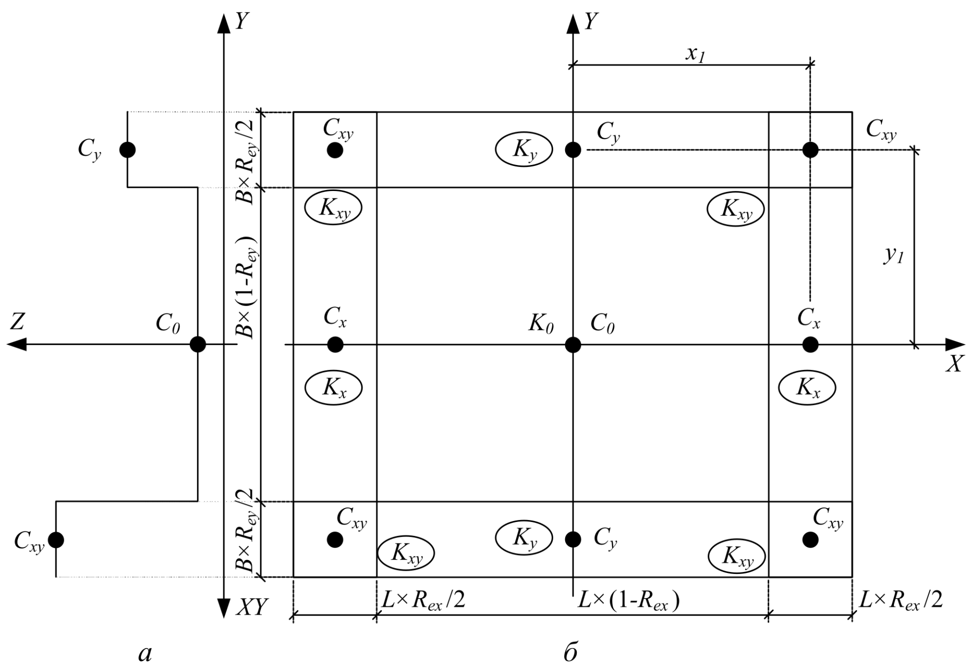


Fig. 1. Bedding coefficients in the modified method: *a* – lateral view; *b* – plan view

Рис. 1. Коэффициенты постели в модифицированном методе: *a* – вид сбоку; *b* – вид в плане

If we take the width of the edge area in fractions of the half-width of the foundation R_e equal not to a fractional fraction, but to neutral element (unit), then the expressions of the distributed stiffness of the base at the bending and torsional shape of vibrations according to Harden C.W. and Hutchinson T.C. will be converted to a known coefficient with a value of 2, corresponding to the method of SR 26.13330:

$$C_{eZ}^{i} = k_{z}^{i} \times dA;$$

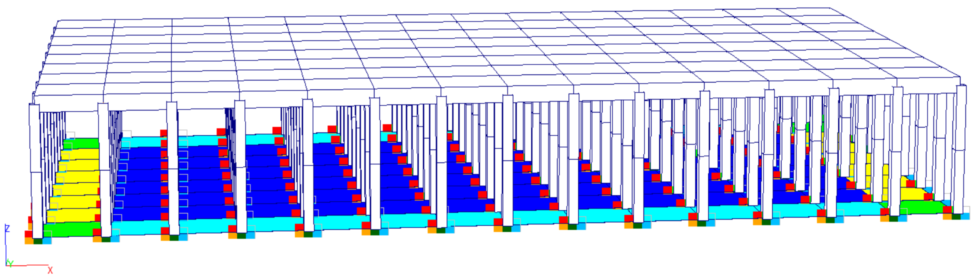
$$R_{eX} = 1; \qquad R_{kX} = \frac{C_{\varphi X}/C_Z - (1-R_{eX})^3}{1-(1-R_{eX})^3} = \frac{2-(1-1)^3}{1-(1-1)^3} = 2;$$

$$R_{eY} = 1; \qquad R_{kY} = \frac{C_{\varphi Y}/C_Z - (1-R_{eY})^3}{1-(1-R_{eY})^3} = \frac{2-(1-1)^3}{1-(1-1)^3} = 2; \tag{1}$$

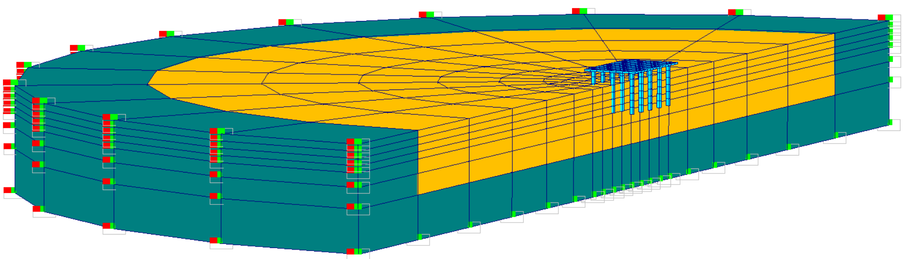
$$C_{\varphi X} = R_{kX} \times C_Z = 2C_Z; \qquad C_{\varphi Y} = R_{kY} \times C_Z = 2C_Z;$$

$$C_{\varphi XY} = (C_{\varphi X} + C_{\varphi Y})/2 = 2C_Z.$$

The second type of contact models considered to describe the dynamic stiffness of the foundation underlying an oversized pile foundation at the level of the bottom of individual piles or pile cells is the I.A. Mednikov and K.G. Shashkin half-space model [7, 8], which has the code "MPP". In the past publication of the authors [9, 10], this type of model is described in more detail, including approaches to the creation of spatial models. The general view of the considered contact and spatial models of a large-size pile field is shown in Fig. 2.



a



b

Fig. 2. Examples of pile field models under consideration:
a – contact model by N.Z. Gotman for individual piles; *b* – spatial model with dynamic cells
Рис. 2. Примеры рассматриваемых моделей свайного поля: *а* – контактная модель
по Н.З. Готман для отдельных свай; *b* – пространственная модель с динамическими ячейками

In the second stage of the research, eight types of spatial models of linearly deformable foundation with the code "LDO" were considered. The first and second type of model is adopted with the full capacity of the modeled array, which is the size of three maximum dimensions of the circumscribed circumference *B*, equal to 33 meters for the studied example. The first type with the code "DS" is considered with a detailed model with individual discrete piles, the second type with the code "SJA" is considered with the use of enlarged pile cells which are described in [10]. The third and subsequent types of models are combined. The part of the spatial array in fractions of dimension *B* is preserved in them and a contact model of the half-space with the code "PP" up to the full depth of 3B is included.

At the third stage, a comparison of analytical and numerical methods for determining the additional inertial masses of the soil suspension involved in the oscillations was carried out. As a numerical method, it was used an approach for pile foundations of port facilities [11], which has the ending "IGP" in the code. Account for the inertial effect of the influence of the pile weight is carried out by adding from each pile to the mass of the superstructure the "attached" mass equal to:

$$\Delta M_{\text{св}.i} = 0,23 m_i l_i, \tag{2}$$

where m_i – mass per unit length of pile *i*; l_i – free length according to SR 24.13330.

The above mentioned approach is compared with the direct kinematic numerical calculation method with the estimation of the total mass of the inertial soil massif in the part of the modeled spatial thickness of the massif with the code "IGM".

It should be noted that the horizontal stiffness of the contact models was taken as the stiffness of the free length section of the pile, which is responsible for a conditional embedment in a completely rigid base at a distance of l_i from the bottom of the foundation piling. For spatial models, it is assumed the design pile length, but the spatial model of the soil foundation is made below grade at the depth of h_d , above which the soil resistance on the lateral surface of the pile is not taken into account [12].

Results and discussion

The results of the study are presented partially for the weakest and structurally unstable soils of category IV in terms of seismic properties according to SR 14.13330, for which the natural frequencies of the structure and the foundation may be comparable and the risk of resonance effects is high. The results with the data of calculations by the linear-spectral method based on quasi-static determination of inertial forces and the data of calculations by the kinematic method of integration of the equations of motion of the foundation are presented in Table 1. The summary analysis of resonance effects with respect to the inertial properties of the foundation is presented for III and IV categories of soils and is summarized in Table 2.

One of the results of the first stage of studies of vibration of contact models of oversized pile foundations is that in the absence of resonance effects, both methods of modeling seismic impact for weightless spatial models have comparable numerical values of internal forces, with the exception of transverse ones.

The linear-spectral method cannot always reflect the actual shearing behavior of piles. Due to the fact that the main first two forms of vibration for a pile foundation are bending forms, the inertial forces are correctly determined above the mark of the pile pinching at the lowest point corresponding to the free length. As a result, the bending moments in all the contact models considered are identical to each other and correspond to more complex spatial models. The longitudinal forces in the half-space model are also equivalent to the spatial models of the base in the discrete formulation of the problem and at the use of enlarged pile cells, confirming their applicability. The proportional deformation model gives some distortions for the longitudinal forces of the edge piles compared to the half-space model.

At the same time, the shear forces in the calculation of contact models by the method of integration of the equations of motion also correspond to the results of the calculation with the use of spatial models by both direct dynamic and linear-spectral methods. In calculating contact models by the linear-spectral method transverse deformations at the level of the foundation of the structure in the bending form are small, and in the higher forms vebrations involve an insignificant fraction of dynamic masses. As a result, the shear forces are close to zero values, what does not correspond to the nature of seismic action when the vibration process is transmitted to the structure in an ascending direction from the soil foundation. This fact was previously noted by the authors and third-party researchers by the example of seismic blast effects [13, 14]. At the second stage of the study with a weightless soil mass for all eight types of models their identity was confirmed, including the same dynamic stiffness and values of natural frequencies of vibrations of the structure. Also it was obtained identical internal forces, what confirms the correctness of theoretical provisions [9, 10] and the possibility of using pile cells.

The second important conclusion based on the results of the second stage of numerical studies of pile field vibrations is the confirmation of the possibility of replacing the lower part of the spatial mass of the soil foundation with a contact mathematical model of half-space. Such substitution can be performed in the absence of resonance effects in the foundation up to the bottom of individual piles or enlarged dynamic pile cells, what significantly reduces the resource intensity of the calculation model.

The analysis of the methods of acounting the inertial properties of the soil foundation by introducing the mass of the soil suspension into the spatial models of the linearly deformed foundation performed at the third stage of research did not allow obtaining positive results. This is caused by the fact that the given approach was developed for the simplest rod-like computational models. For spatial models, the empirical dependencies for estimating the attached masses are insufficient.

The four types of spatial models of the linearly deformable foundation considered at the third stage of the study with respect to the inertial properties of the soil mass made it possible to identify the effects of resonance in five cases out of twenty analyzed scenarios of the ratio of the number of storeys of buildings and the dynamic stiffness of the foundation according to its seismic properties, what follows from Table 2. The results of the analysis showed the same values of resonance increments of force factors in spatial models of a linearly deformable foundation to a depth of 3B with identical results for individual piles and for enlarged pile cells, what confirms the possibility of their application for large-sized pile foundations. Therefore, further analysis of the movement of the entire soil mass and the characteristic points of the large-sized pile field was performed for dynamic pile cells.

Based on the analysis of the data in Table 2, we can see that for power 3B, the peaks of maximum increments of force factors are manifested in the case of coincidence of the periods of natural vibrations of the structure of the corresponding floor TS and periods of the soil mass TIII and TIV with soils of types III and IV by seismic properties. This indicates the presence of an inverse effect of the vibration of the structure on the vibrations of the foundation at a given frequency or period of vibration of the structure.

Table 1

Analysis of internal forces in the angle pile for the IV category of foundations

Таблица 1

Анализ внутренних усилий в угловой свае для основания IV категории грунтов

Method of force calculation / Code of model		Model number of storeys	MPD-DS	MPD-SYA	MPP-DS	MPP-SYA	LDO-DS-ZV	LDJ-SYA-ZV	LDO-СЯ -2V-PP	LDO-SYA-1.5V-PP	LDO-SYA-V-PP	LDO-SYA-0.6V-PP	LDO-SYA-0.ZV-PP	LDO-SYA-0.25V-PP	LDP-DS-VZV-IGP	LDO-SYA-ZV-IGP	LDO-SYA-V-PP-IGP	LDO-SYA-0.25V-PP-IGP	LDO-DS-ZV-IGM	LDO-SYA-ZV-IGM	LDO-SYA-V-PP-IGM	LDO-SYA-0.25V-PP -IGM
Linear spectral method	Nlsm, kN	5	12	5	5	6	3	7	7	7	7	7	7	7	3	8	8	7	–	–	–	–
		10	20	8	8	10	5	11	11	11	11	11	11	11	5	12	12	12	–	–	–	–
		15	27	10	11	14	7	15	15	15	15	15	15	15	7	16	16	16	–	–	–	–
		20	34	13	14	17	9	19	19	19	19	19	19	19	9	20	20	19	–	–	–	–
		25	40	15	16	20	10	23	23	23	22	22	22	22	10	23	23	23	–	–	–	–
	Mlsm, kN·m	5	28	28	29	29	30	29	29	29	29	29	29	29	34	34	33	33	–	–	–	–
		10	48	48	49	48	50	49	49	49	49	49	49	49	53	53	53	52	–	–	–	–
		15	65	65	66	65	67	66	66	66	66	67	67	67	71	70	70	70	–	–	–	–
		20	81	80	82	81	84	82	82	82	82	83	83	83	87	85	85	85	–	–	–	–
		25	95	95	97	96	99	97	97	97	97	98	98	98	102	100	100	100	–	–	–	–
	Qlsm, kN	5	–	–	–	–	13	12	12	12	12	12	12	12	14	14	14	14	–	–	–	–
		10	–	–	–	–	21	21	21	21	21	21	21	21	23	22	22	22	–	–	–	–
		15	–	–	–	–	29	28	28	28	28	28	28	28	30	30	30	30	–	–	–	–
		20	–	–	–	–	36	35	35	35	35	35	35	35	37	36	36	36	–	–	–	–
		25	–	–	–	–	42	41	41	41	41	42	42	42	44	43	43	43	–	–	–	–
Integration of equations of motion	Niur, kN	5	12	5	5	6	3	7	7	8	8	8	7	8	3	7	8	8	1	1	7	9
		10	20	7	8	10	5	11	12	12	12	12	11	12	5	11	12	12	1	4	23	13
		15	27	10	11	13	7	15	16	16	16	16	15	16	7	15	16	16	3	8	33	17
		20	33	12	14	16	9	19	19	20	19	19	19	19	9	19	20	20	7	16	38	20
		25	39	15	16	19	10	22	23	23	22	22	22	23	10	22	23	23	13	31	40	23
	Miur, kN·m	5	30	30	29	29	30	28	30	31	31	31	30	33	31	30	33	34	5	5	29	38
		10	47	46	49	47	50	46	48	50	50	50	49	52	51	47	51	53	16	15	94	56
		15	65	64	66	64	67	62	64	66	66	66	65	68	68	64	67	69	33	31	140	72
		20	79	77	82	79	84	79	81	82	82	82	81	83	86	80	83	84	71	68	161	87
		25	93	91	97	94	99	92	93	95	95	96	94	97	100	94	97	99	133	129	171	101
	Qiur, kN	5	15	15	15	14	13	12	13	13	14	13	13	14	14	13	14	15	2	2	12	17
		10	24	23	25	24	22	20	21	21	21	21	21	22	22	20	22	23	7	7	40	24
		15	33	32	33	32	29	27	27	28	28	28	28	29	29	27	29	30	14	13	60	31
		20	40	39	41	40	36	34	34	35	35	35	34	36	37	34	36	36	30	29	69	37
		25	47	46	49	47	43	39	40	41	41	41	40	42	43	40	41	42	57	55	73	43

Table 2

Analysis of Resonance Effects in Spatial Models of a Linear Deformable Base Relative to Models with a Weightless Foundation

Таблица 2

Анализ резонансных эффектов в пространственных моделях линейно-деформируемого основания относительно моделей с невесомым основанием

Code of model	Storeys	Category III soil foundation by seismic properties						Category IV soil foundation by seismic properties					
		T_S, s	T_{III}, s	K_R	ΔN, %	ΔM, %	ΔQ, %	T_S, s	T_{IV}, s	K_R	ΔN, %	ΔM, %	ΔQ, %
98 m Linear Deformable Foundation Model with Pile Cells													
LDO.SYAZV	**5**	0.65		+	–36	–38	–38	0.72		–	–84	–83	–83
	10	0.92		+	60	59	59	1.02		+	–66	–67	–67
	15	1.13	**1.23**	+	132	133	132	1.25		+	–48	–51	–50
	20	1.31		+	**145**	**144**	**144**	1.44		+	–12	–14	–14
	25	1.46		+	130	130	130	1.61	**2.40**	+	40	41	41
Model of a 30 m thick linear deformable foundation with pile cells and a contact model of the underlying half-space to a depth of 98 m													
LDO,SYA,PP,V	**5**	0.65		+	**50**	**51**	**50**	0.72		–	–4	–8	–8
	10	0.92		+	39	40	40	1.02		+	90	90	90
	15	1.13	**1.23**	+	30	29	29	1.25		+	**111**	**112**	**112**
	20	1.31		+	24	23	23	1.44		+	96	97	97
	25	1.46		+	19	19	18	1.61	**2.40**	+	79	80	80

At that, in the case of reducing the depth of the spatial array to the value B and replacing the remaining part with the underlying half-space on the soil base of III and IV categories on seismic properties, a resonant increase of up to 2.5 times of force factors in the form of longitudinal forces, bending moments and transverse forces in the heads of the analyzed piles is observed. The resonant increase occurs at other frequencies associated with the formation of surface wave vibrations of the soil mass. An example of a detailed analysis of such vibrations is shown in Fig. 3 at the moment of movement of the soil mass and the pile foundation with enlarged cells at the point of maximum negative displacement of the foundation piling.

Thus, the calculation method proposed by the authors makes it possible to take into account the risk of mechanical safety of the pile foundation in the conditions of the most dangerous surface wave's development. The problem of the required thickness of the modeled soil mass should be solved at the stage of engineering-geophysical, seismological and seismotectonic surveys during specifying the initial seismicity of the site during seismic microzoning. In particular, it should be solved by recording microseismic vibrations of the upper part of the geologic section represented by dispersed soils with the use of the borehole method [15]. Spectral analysis of the microseismic sounding data and analysis of the ground base surface motion at different points of the construction site allow us to determine the resonance properties that are more responsive to surface seismic waves. This information is necessary to determine the depth of the spatial part of the modeled array by the method of successive approximations.

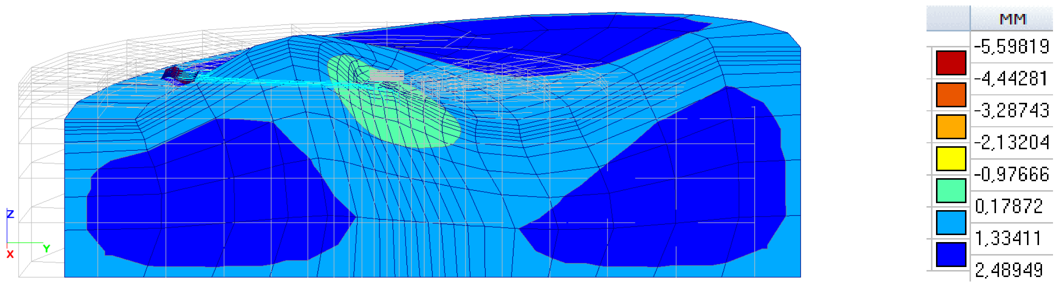


Fig. 3. Analysis of vibrations of a 15-storey building on the basis of category IV in a model with an inertial mass of 3B at the time of extreme displacements at the level of the foundation piling
Рис. 3. Анализ колебаний 15-этажного здания на основании IV категории в модели с инерционным массивом 3В в момент экстремальных перемещений в уровне ростверка

Conclusion

Among the presented results of the study, two main conclusions related to the safety of pile foundations should be emphasized.

Firstly, the linear-spectral method of accounting for seismic effects does not allow involving a sufficient number of dynamic masses, what excludes transverse forces in piles from the calculation results and leads to the risk of failure of the bearing structures of the pile foundation at the moment of maximum displacement in the seismogram. This risk can only be taken into account by kinematic analysis of internal forces in piles by the numerical method of direct integration of the equations of motion.

Secondly, the use of a kinematic model of seismic effects takes into consideration the possibility of surface wave development in a continuous soil medium. In case of resonance effects, the internal forces in the pile foundation can increase up to three times leading to destructive consequences. The proposed calculation method using the combined model allows taking into account surface waves based on the results of field studies of the microseismic field.

In addition, the theoretical provisions and the efficiency of replacing individual piles with enlarged dynamic pile cells have been confirmed.

Финансирование. *Финансовая поддержка не оказывалась.*
Конфликт интересов. *Авторы заявляют об отсутствии конфликта интересов.*
Вклад авторов. *Все авторы сделали равный вклад в подготовку публикации.*

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