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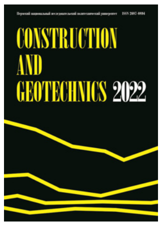

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CHANGE IN STRENGTH PARAMETERS OF DUSTY-CLAYEY SOILS DEPENDING ON THE TIME OF DYNAMIC LOAD IMPACT AND SOIL TYPE

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ABSTRACT

The method of high frequency vibratory driving and extraction of sheet piles is frequently utilized in the conditions of structurally unstable soils in St. Petersburg. However, with this method of installation (extraction) of sheet piles in the surrounding soil mass it arises oscillations that are transmitted to nearby buildings and housing, capable of causing dangerous phenomena in their undergroud and aboveground structures, mainly related to differential settlement of foundations.

The prediction of additional settlement of buidings in the surrounding area from vibrodriving/extraction of sheet piles is a complex, multi-factor task, and the level of the structural displacement of building, which is the main controlled parameter for the influence of dynamic loading on the foundation soil, according to the current regulatory documents Territorial Building Codes50-302-2004, Departmental Building Codes490-87, Russian State Standard 52892-2007 is merely an indirect criterion for assessment. To obtain a more accurate assessment of the development of additional settlements in buildings during high-frequency vibratory pile driving and sheet pile extraction, it is necessary to take into account not only the duration and frequency of the impact, but also the properties and type of soil itself.

The purpose of this reseach was to study changes in the strength parameters of silty-clay soils depending on the time of dynamic loads impact, the type and consistency of the soil itself, as well as changes in parameters depending on the “rest” time of the soil base after exposure to vibration.

The article presents the results and shows the tendency to reduce the parameters of soil strength after the application of dynamic load and the dependence of their change on the time of impact, on the type and consistency of the soil. It has been determined the dependence of changes in the strength parameters of the soil conditionally upon the "rest" time of the soil mass as a result of thixotropic re-storation, which will determine the economic attractiveness for the accident-free technology of this method.

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ИЗМЕНЕНИЕ ПАРАМЕТРОВ ПРОЧНОСТИ ПЫЛЕВАТО-ГЛИНИСТЫХ ГРУНТОВ В ЗАВИСИМОСТИ ОТ ВРЕМЕНИ ВОЗДЕЙСТВИЯ ДИНАМИЧЕСКОЙ НАГРУЗКИ И ТИПА ГРУНТА

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испытания на одноплоскостной срез, разжижение грунтов, тиксотропия, разупрочнение грунтов, тиксотропное восстановление, колебания грунта, основания и фундаменты, вибропогружение шпунтовых свай, виброизвлечение шпунтовых свай, шпунтовая свая.

АННОТАЦИЯ

Метод высокочастотного вибропогружения и виброизвлечения шпунтовых свай применяется достаточно часто в условиях слабых структурно неустойчивых грунтов Санкт-Петербурга. Однако при данном способе погружения (извлечения) шпунта в окружающем его грунтовом массиве возникают колебания, передающиеся расположенным рядом зданиям и сооружениям и способные вызывать опасные явления в их конструкциях как подземной, так и надземной частей, связанные в основном с неравномерными осадками фундаментов.

Прогноз дополнительной осадки зданий окружающей застройки от вибропогружения/извлечения шпунтовых свай является сложной, многофакторной задачей, а уровень колебания конструкции здания, являющейся основным контролируемым параметром влияния динамического воздействия на грунт основания, согласно действующим нормативным документам ТСН 50-302–2004, ВСН 490-87, ГОСТ Р 52892–2007 является лишь косвенным критерием оценки. Для более верного суждения о развитии дополнительных осадок зданий при высокочастотном вибропогружении и виброизвлечении шпунтовых свай следует дополнительно учитывать не только время и частоту воздействия, но и свойства и тип самого грунта.

Целью данного исследования являлось изучение изменения параметров прочности пылевато-глинистых грунтов в зависимости от времени воздействия динамической нагрузки, типа и консистенции самого грунта, а также изменение параметров в зависимости от времени «отдыха» грунтового основания после воздействия вибрации.

Приведены результаты и показана тенденция к снижению параметров прочности грунтов после приложения динамической нагрузки и зависимость их изменения от времени воздействия, от типа и консистенции грунта. Установлена зависимость изменения прочностных параметров грунта в зависимости от времени «отдыха» грунтового массива в результате тиксотропного восстановления, что будет определять экономическую привлекательность для безаварийной технологии данного метода.

Introduction

The method of high-frequency vibration driving and extraction of sheet piles at modern construction sites of St. Petersburg is used quite often due to its high productivity, the possibility of using a simple set of technical means and the reuse of the piles themselves, which determines its economic benefits [1–6]. However, its use, especially in weak water-saturated rocks of St. Petersburg, entails the destructuring of the foundation soil and, as a result, the violation of stability of the pit fence itself and additional settlement of the surrounding buildings [7–12].

The upper part of the geological section of St. Petersburg is composed of weak water-saturated soils capable of turning into a quicksand state under external influences of various nature, including vibration, as well as restoring their strength in a state of rest. Dusty-clayey deposits of lacustrine and glacial genesis are covered with such properties [13]. The problems of reaction and behavior of soil under external dynamic load have been studied by many authors, the main of them are D.D. Barkan, S.L. Kramer, E.A. Voznesensky, A.Z. Ter-Martirosyan, A.Y. Mirny, V.V. Sidorov, V.V. Kapustin, V.A. Ershov [1, 6, 14–20] and others. The reaction of soils to the occurrence of dynamic stresses as a result of vibratory driving or extraction of sheet piles depends primarily on the type of soil, its structural connections and physical and mechanical properties [21, 22]. For example, sandy soils become compacted after exposure to dynamic load

[14, 23–25], the reaction of water-saturated dusty-clayey soils is expressed in partial or complete loss of stability as a result of the development of such processes as dilatancy and liquefaction – quicksand and thixotropy [26]. Under dynamic action deformation and strength characteristics are significantly reduced.

Previous studies on changes in the properties of soils are not enough to identify a clear dependence of their changes. Thus, the problem of assessing the applicability of the technology of high-frequency driving of sheet piles in the difficult geological conditions of the city is relevant.

Experimental part

The authors carried out experimental studies of changes in the strength characteristics of dusty-clay soils in laboratory conditions after vibration loads exposure. The first series of experiments is devoted to the study of changes in strength parameters depending on the time of vibration exposure, the second – on the time of "soil rest" and the third – on the consistency and type of soil.

The first series of laboratory experiments was carried out in order to determine the regularities of changes in the strength parameters of clay soils depending on the time of exposure to a dynamic load commensurate with the immersion time of one sheet pile.

The key parameters of the external dynamic stress are frequency, amplitude, and vibration acceleration. The frequency of high-frequency vibration immersion is in the range of up to 50 Hz, the value of vibration acceleration is normalized by Territorial Building Codes50-302-2004, Departmental Building Codes 490-87, Russian State Standard 52892-2007. The time of the dynamic load impact on the soil is not a normalized value and depends on the number and length of the pile to be driven at the construction site. The time of vibration immersion can reach 15–20 minutes in the geological conditions of Saint Petersburg.

The experiments were carried out in a single-plane shear device on samples of loam of soft plastic consistency with a moisture content of about 35 % according to the "non-consolidated-undrained" (NU) testing scheme on a single-plane shear device at "normal" loading levels of 50 and 100 kPa. Testing according to NU scheme is called "fast shear". Under testing of poorly permeable water-saturated loamy rocks according to this scheme it is possible to obtain an angle of internal friction φ and adhesion in the unstabilized state.

In the course of the experiment, the following time intervals of vibration impact on clay soils were considered: 5, 10 and 15 minutes, which generally corresponds to the time of immersion of a sheet pile in the geological conditions of Saint Petersburg.

Thus, a total of 4 tests were carried out, in each of which two twin samples were tested, the first - without vibration action, the second after 5 minutes, 10 minutes and 15 minutes of dynamic action on a vibrating stage at a frequency of about 50 Hz, which simulates the impact of vibration immersion or vibration extraction of sheet piles on the soil of the pile space.

The obtained graphs of shear resistance of soft-plastic loam before and after vibration action according to the "NU" scheme are shown in Fig. 1.

Parameters of strength properties of loamy soil obtained before and after 5, 10 and 15 minutes of vibration exposure are given in Table 1.

The results of the experiment show the reducing trend of internal friction angle at the increased time of dynamic load exposure, thus the value φ showed the reduction from 18 to 16, 13 and 9 degrees; i.e. the decrease ranged from 11 to 50 %. Whilr the amount of adhesion, which depends on the consistency of the soil, did not show any serious changes.

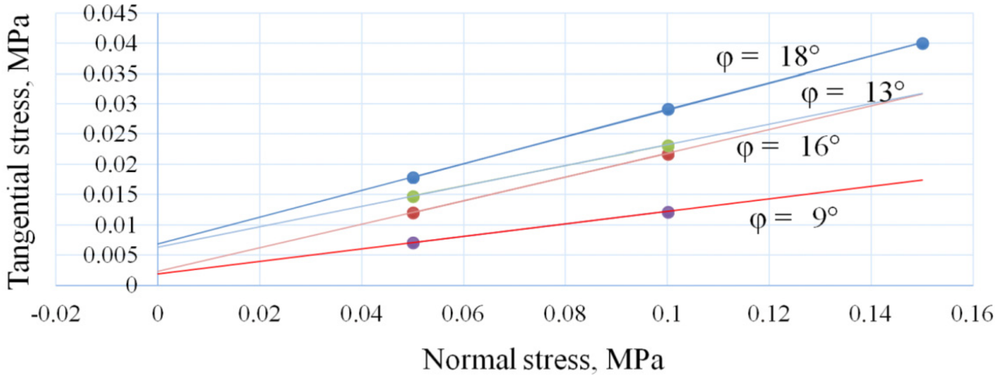

Fig. 1. Results on in-single plane shear of loam of a soft-plastic consistency. Blue color – the soil was tested without the impact of dynamic load; orange color – the soil was tested after 5 minutes of exposure to dynamic load; gray color – the soil was tested after 10 minutes of exposure to dynamic load; red color – the soil was tested after 15 minutes of exposure to dynamic load

Рис. 1. Результаты на одноплоскостной срез суглинка мягкопластичной консистенции. Синий цвет – грунт испытан без воздействия динамической нагрузки; оранжевый цвет – грунт испытан после 5 мин воздействия динамической нагрузки; серый цвет – грунт испытан после 10 мин воздействия динамической нагрузки; красный цвет – грунт испытан после 15 мин воздействия динамической нагрузки

Table 1

Parameters of strength properties of loamy soil obtained before and after 5, 10 and 15 minutes of vibration exposure

Таблица 1

Параметры прочностных свойств суглинистого грунта, полученные до и после 5, 10 и 15 минут воздействия вибрации

Name	Angle of internal friction φ, degrees	Reduction of internal friction angle, %	Adhesion, kPa
Vibration-free	18	0	2–7
Vibration exposure time – 5 minutes	16	11	2–7
Vibration exposure time – 10 minutes	13	27	2–7
Vibration exposure time – 15 minutes	9	50	2–7

The second series of experiments was also carried out according to the "NU" scheme in a single-plane shear device in order to determine the change in the strength parameters of the soil as a result of thixotropic reduction. In the course of the experiment 3 samples of undisturbed loam composition of soft-plastic consistency were tested in 2, 4 and 10 days of "rest" after 10 minutes of their dynamic exposure by vibrating table. The amplitude-frequency effect of the vibrating table on soil samples did not exceed 50 Hz, which is comparable to the effect of vibration immersion or vibration extraction of sheet piles on the soil of the pile space.

According to different authors, the duration of thixotropic restoration and strengthening of structural bonds varies significantly for clay soils of different chemical and mineral composition, dispersion and humidity. So, if the soil is a purely thixotropic system, it will fully restore its strength to the initial level, regardless of the dynamic load parameters. In contrast to a quasi-thixotropic system, the final strength of such systems after dynamic action either slightly does not reach or slightly exceeds the initial value [26, 27].

For young loams and clays, the recovery process ends in the first day, for more compacted clays – in the first ten days. Also, in addition to the composition and condition of the soil, the restoration process is influenced by the impact parameters, which cause partial or complete destruction of structural bonds.

The restoration of property parameters is of decisive importance in the problem of vibration extraction of sheet piles [28]. Vibration extraction with the purpose of sheet pile reuse can significantly reduce the cost of work, which in its turn determines the economic attractiveness of this method.

Thus, as a result of thixotropic restoration of the foundation soil the parameters of strength properties obtain their initial values and this fact signifies the safety of further work on pile extraction. In other words, the immersiom and extraction of piles without any temporary intervals will lead to a catastrophic decrease in the angle of internal friction and adhesion, the transition of the soil to the state of heavy liquid. The obtained graphs of shear resistance of soft-plastic loam after 2, 4 and 10 days of "rest" according to the "UN" scheme are presented in Fig. 2.

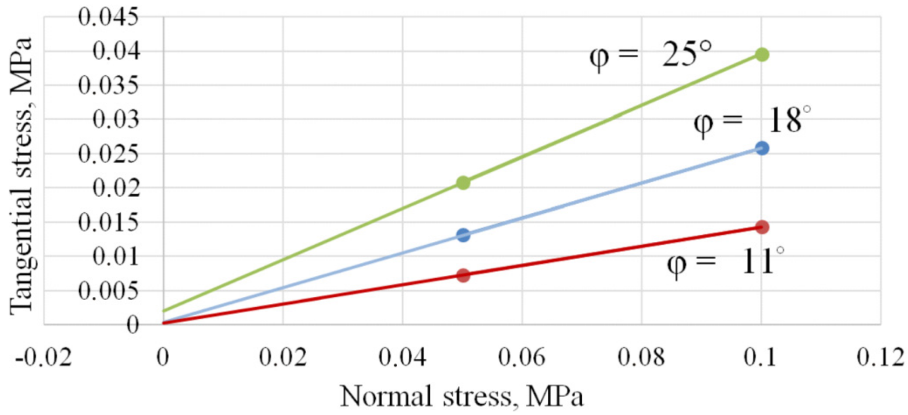

Fig. 2. Results of in-plane shear test of soft plastic loam. Orange color - after 2 days of "rest", blue color – after 4 days of "rest", gray color – after 10 days of "rest"
Рис. 2. Результаты испытания суглинка мягкопластичного на одноплоскостной срез. Оранжевым цветом – после 2 сут «отдыха», синим цветом – после 4 сут «отдыха», серым цветом – после 10 сут «отдыха»

The parameters of the strength properties of loamy soil of soft plastic consistency obtained after 2, 4 and 10 days of "rest" of samples of 10-minute dynamic impact by a vibrating table depending on the time of "rest" of the samples are presented in Table 2.

Table 2

Parameters of strength properties of loamy soil
after 2, 4 and 10 days of "rest" after dynamic impact

Таблица 2

Параметры прочностных свойств суглинистого грунта после
2, 4 и 10 сут «отдыха» после динамического воздействия

	Angle of internal fiction φ, degrees	Adhesion, kPa
Time of "rest" – 2 days	11	2–5
Time of "rest" – 4 days	18	2–5
Time of "rest" – 10 days	25	2–5

The results showed that during the so-called "rest" the angle of internal friction restores the initial value after 4 days, and after 10 days of "rest" the value exceeds the initial one.

The third series of tests was carried out by the in-plane shear device, also according to the "NU" scheme, in order to determine the dependence of changes in the parameters of strength properties after dynamic action in different types of soils. Samples of loam of various consistencies and dusty sandy loam were tested. Three samples were tested. The first is a sandy loam of undisturbed composition of plastic consistency. The second is the undisturbed loam of soft plastic consistency. The third is a sample of the disturbed composition of fluid-plastic loam. The test samples had a density of 1.78–1.83 g/cm^3 and a humidity of 25 to 37 %.

The tests were performed on 2 samples of plastic sandy loam at a load of 50/150 kPa and 100/150 kPa, on 2 samples of soft plastic loam and 2 samples of fluid plastic loam at a load of 50/100 kPa [29]. One sample was tested without prior vibration and the other was subjected to vibration for 10 min at a frequency greater than 50 Hz. In total, 2 samples of dusty plastic sandy loam, 1 sample of fluid plastic loam, and 2 samples of soft-plastic loam were tested [29]. Tests of sandy loam and fluid loam were carried out earlier and described in [29]. The strength parameters obtained before and after exposure to vibration are presented in Table 3. The results of soft-plastic loam testing on the in-plane shear according to the "UN" scheme are presented in Fig. 3.

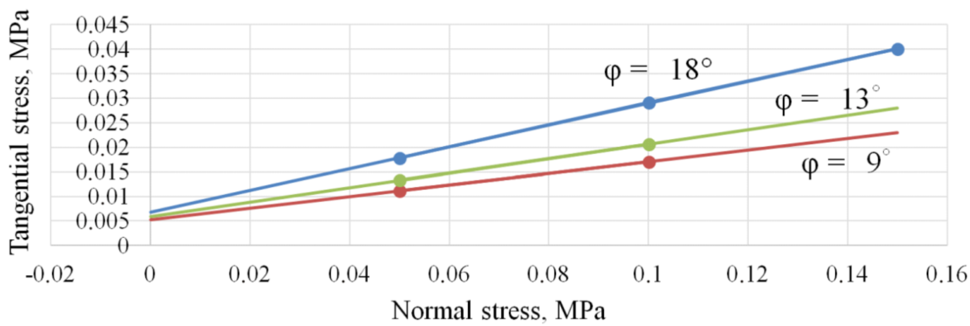

Fig. 3. The results of soft-plastic loam testing on the in-plane shear.
Blue color – the soil was tested without the impact of dynamic load; gray and orange color – the soil was tested after 10 minutes of exposure to dynamic load
Рис. 3. Результаты испытания суглинка мягкопластичного на одноплоскостной срез.
Синий цвет – грунт испытан без воздействия динамической нагрузки; серый и оранжевый цвет – грунт испытан после 10 мин воздействия динамической нагрузки

Table 3

Parameters of strength properties of dusty clayey soil before and after high-frequency impact

Таблица 3

Параметры прочностных свойств пылевато-глинистого грунта до и после высокочастотного воздействия

Type of soil	Number of sample, time of vibration impact 10 minutes	Angle of internal friction φ before vibration impact, degrees	Angle of internal friction φ after vibration impact, degrees	Reduction of internal friction angle, %	Adhesion, kPa
Plastic sandy loam	1	30	23	24	0
	2	42	29	31	0
Cumuloplastic loam consistency	1	5	2	60	0
Loam of soft coplastic consistency	1	18	13	27	5–7
	2	18	9	50	5–7

The parameters of strength properties of dusty-clayey soil obtained before and after exposure to vibration according to the "NU" scheme are presented in Table 3.

Laboratory tests according to the "NU" scheme showed a tendency to reduce the angle of internal friction after exposure to vibration from 24 to 60 %, depending on the type and consistency of the rock, while the amount of adhesion, depending on the consistency, did not change.

The data obtained by the authors coincide with the results of studies carried out by other researchers. For example, tests on loess-like loam under vibration effects at MGSU showed a change in strength by 8–17 % [30].

Interesting data were obtained at 2 sites in St. Petersburg, when soils "before" and "after" vibration immersion were subjected to a static sounding test [29]. The results of static sounding showed a decrease in the resistance to probe immersion by 30–70 % at a depth of 1.5–6 m from the day surface during the vibro-immersion of sheet piles and a decrease of 15–85 % during the vibro-extraction of sheet piles. The results of field and laboratory studies showed good convergence.

Conclusion

1. Studies on the determination of strength parameters by the method of in-plane shear according to the "NU" scheme after dynamic action showed a decrease in the angle of internal friction in sandy loam by 30 %, in soft-plastic loam by 30–50 %, in fluid-plastic loam by 60 %. As it turned out, the amount of adhesion does not react to vibration.
2. Laboratory studies aimed at determining the strength parameters of soft plastic loam according to the time of exposure to vibration load from 5 to 15 minutes showed a decrease in the angle of internal friction from 11 to 50 %. The magnitude of the adhesion did not change significantly and was in the range of up to 7 kPa.
3. Studies on determination of the strength parameters of soft-plastic loam after 2, 4 and 10 days of "rest" showed an increase in the angle of internal friction to the initial value after 4 days, and after a 10-day "rest" the value exceeds the initial value, which indicates the repackaging of particles and the restoration of structural bonds. Thus, weak clay rocks after complete or partial destruction of thixotropic-coagulation structural bonds by dynamic load are able to increase strength to or even higher than the initial value. And this fact characterizes these soils as a quasi-thixotropic system.

The process of restoring the structural ties of weak water-saturated dusty-clayey soils of St. Petersburg plays an important role in the process of extracting sheet piles for the purpose of their reuse. For example, the repeated application of a dynamic load during high-frequency vibration extraction can lead to a catastrophic decrease in parameters and the transition of the soil to the state of a heavy liquid as well as the loss of stability of buildings falling into the zone of influence.

Финансирование. *Исследование не имело спонсорской поддержки.*
Конфликт интересов. *Авторы заявляют об отсутствии конфликта интересов.*
Вклад авторов. *Все авторы сделали равный вклад в подготовку публикации*

Reference

1. Barkan D.D. Vibrometod v stroitel'stve [Vibromethod in construction]. Moscow, Gosstroyizdat, 1959, pp. 1-11.

2. Vasilyuk L.V. Vibropogruzheniye shpunta vblizi sushchestvuyushchikh zdaniy v gruntovykh usloviyakh Sankt-Peterburga [Vibration immersion of sheet piling near existing

buildings in soil conditions of St. Petersburg]. *Inzhenerno-geotekhnicheskiye izyskaniya, proyektirovaniye i stroitel'stvo osnovaniy, fundamentov i podzemnykh sooruzheniy: sb. tr. Vseros. nauch.-tekhn. konf. po geotekhnike*, 2017, Saint Petersburg, pp.307-315.

3. Verstov V.V., Gaydo A.N., Ivanov YA.V. Tekhnologiy ustroystva ograzhdeniy kotlovanov v usloviyakh gorodskoy zastroyki i akvatoriy. Saint Petersburg, Lan, 2014, 366 p.

4. Deckner F., Viking K., Hintze S. Wave patterns in the ground: case studies related to vibratory sheet pile driving. *Geotechnical and Geological Engineering*, 2017, vol.35, iss. 6, pp. 2863-2878. DOI: 10.1016/j.soildyn.2017.01.039

5. Meijers P., Tol A.F. The Raamsdonksveer sheet pile test, measured surface settlements during vibratory sheet piling. *Proc. 14th Eur. Conf. Soil Mech. and Geotech. Eng. Madrid*, 2007, pp. 603-609.

6. Verstov V.V., Belov G.A. Sovershenstvovanie tekhnologicheskikh reshenii po pogruzheniiu i izvlecheniiu shpunta vibratsionnym metodom [Perfection of technological decisions on immersing and extraction of steel sheet piles by vibrating method]. *Vestnik grazhdanskikh inzhenerov*, 2007, no 4 (13), pp. 38–44.

7. Mangushev R. A., Lashkova E. B., Smolenkov V. YU., Zaytsev M. A. Opyt sooruzheniya podzemnykh parkingov v usloviyakh slabykh gruntov Sankt-Peterburga. [Experience of building underground parking lots in the conditions of weak soils of Saint - Petersburg]. *Vestnik grazhdanskikh inzhenerov*, 2015, no. 5(52), pp. 91-100.

8. Mangushev R.A., Gurskii A.V. Otsenka vliianiia vdavlivaniia shpunta na dopolnitel'nye osadki sosednikh zdanii [Impact assessment of indentation of steel piles on additional settlements of adjacent buildings]. *Geotekhnika*, 2016, no2, pp. 34–41. DOI: 10.25296/2221-5514-2020-12-1-32-44.

9. Mangushev R.A., Gurskii A. V., Polunin V.M. Otsenka dinamicheskogo vozdeistviia ot vibropogruzheniia shpuntovykh svai na zdaniia okruzhaiushchei zastroiki v usloviiakh slabykh vodonasyshchennykh gruntov [Astimation of dynamic effects from vibration dipping of sheet piles on environmental buildings in conditions of weak water-saturated soils]. *Construction and Geotechnics*, 2020, vol.11., iss. 3, pp. 102–116. DOI: https://doi.org/10.15593/2224-9826/2020.3.09.

10. Mangushev R.A., Gurskii A.V., Polunin V.M. Uchet vliianiia tekhnologicheskikh osadok zdanii okruzhaiushchei zastroiki pri ustroistve shpuntovykh ograzhdenii sosednikh kotlovanov [Taking into account the influence of technological precipitation of buildings of the surrounding development when installing sheet pilling fencesof neighboring diches]. *Zhilishchnoe stroitel'stvo*, 2020, no. 9, pp. 9–19. DOI: https://doi.org/10.31659/0044-4472-2020-9-9-19.

11. Mangushev R.A., Nikiforova N.S., Koniushkov V.V., Osokin A.I., Sapin D.A. Proektirovanie i ustroistvo podzemnykh sooruzhenii v otkrytykh kotlovanakh. Moscow, ASV, 2013, 256 p.

12. Polunin V.M. Prognoz dopolnitel'nykh deformatsii zdanii i sooruzhenii v protsesse vysokochastotnogo vibrirovaniia shpuntovykh svai [Forecasting additional deformations of buildings caused by the process of high-frequency sheet piles' vibration]. *Vestnik grazhdanskikh inzhenerov*, 2022, no. 2, pp. 74-83.

13. Dashko R. E., Aleksandrova O. YU., Kotyukov P. V., Shidlovskaya A. V. Osobennosti inzhenerno-geologicheskikh usloviy Sankt-Peterburga, istochnikov vibratsionnykh vozdeystviy. [Features of engineering and geological conditions of Saint Petersburg, sources of vibration effects]. *Razvitiye gorodov i geotekhnicheskoye stroitelstvo*, 2011, no. 13, pp. 24-71.

14. Bakhtin B. M. Uchet vliianiia vibratsii na soprotivlenie peschanogo grunta sdvigu [Accounting of vibration influence on shear resistance of sand soil]. *Gidrotekhnicheskoe stroitel'stvo*, 2012, no. 1, pp. 42–47.

15. Voznesenskii E. A. Dinamicheskaia neustoichivost' gruntov [Dynamic instability of soils]. Moscow, LENAND, 2019, 264 p.

16. Voznesenskii E. A. Dinamicheskaia neustoichivost' gruntov [Dynamic instability of soils]. Abstract of Ph. D. thesis. Moscow, 2000, 54 p.

17. Voznesenskii E. A. Zemletriaseniia i dinamika gruntov. *Sorosovskii obrazovatel'nyi zhurnal*, 1998. no2, pp. 101–108.

18. Kramer S.L. Geotechnical earthquake engineering, Prentice Hall, 1996, p. 529-539.

19. Chopra A.K. Dynamics of structures-theory and applications to earthquake engineering. 2nd ed. Prentice Hall, 1995.

20. Kapustin V.V., Ozmidov O.R., Ozmidov I.O. Metody issledovaniya dinamicheskikh poley napryazheniy i dinamicheskoy ustoychivosti gruntovykh massivov. [Research methods of dynamic stress fields and dynamic stability of soil massifs]. *Inzhenernyye izyskaniya*, 2014, no. 1, pp. 48-53.

21. Deckner F., Viking K., Guillemet C., Hintze S. Instrumentation system for ground vibration analysis during sheet pile driving. *Geotechnical Testing Journal*, 2015, vol.38, iss. 6, pp. 893-905. DOI: 10.1520/GTJ20140275.

22. Deckner, F., Viking, K., Hintze, S Aspects of ground vibrations due to pile and sheet pile driving. *Electronic Journal of Geotechnical Engineering*, 2015, vol. 20, iss. 19, pp. 11161-11176.

23. Yershov V.A. Dinamicheskiye svoystva peschanykh gruntov i ikh uchet v otsenke ustoychivosti zemlyanykh sooruzheniy [Dynamic properties of sandy soils and their consideration in assessing the stability of earth structures]. Doctor's degree dissertation, Leningrad, 1970, 180 p.

24. Isakhanov E.A, Kvashnin M.Ia., Abiev B.A., Alpyspaeva Zh. Soprotivlenie sdvigu nesviaznykh gruntov pri staticheskikh i vibratsionnykh nagruzkakh. *KazKKA Khabarshysy*, 2013, no. 4 (83), pp. 4 – 9.

25. Denies N., Holeyman A. Shear strength degradation of vibrated dry sand, *Soil Dynamics and Earthquake Engineering,* 2017, vol. 95, pp. 106-117. DOI: 10.1007/s10706-017-0285-x.

26. Strokova L.A. Dinamika gruntov [Soil dynamics]. Tomsk: Tomskii politekhnicheskii universitet, 2018, 190 p.

27. Qian J., Li S., Zhang J., Jiang J., Wang Q. Effects of OCR on monotonic and cyclic behavior of reconstituted Shanghai silty clay. *Soil Dynamics and Earthquake Engineering,* 2019, no. (118), pp. 111–119. DOI:10.1016/j.soildyn2018.12.010.

28. Chunyuk D. Yu., Kozmodemianskiy V. G., Kopteva O. V. Inzhenernyye izyskaniya dlya proyektirovaniya fundamentov sooruzheniy vblizi istochnikov vibratsionnykh vozdeystviy [Engineering surveys for the design of foundations of structures near sources of vibration]. *Promyshlennoye i grazhdanskoye stroitelstvo,* 2017, no. 10, pp. 54-58.

29. Polunin V. M., Cheremkhina A.P. Izmenenie prochnostnykh parametrov dispersnykh gruntov posle vysokochastotnogo vibrirovaniia [Change in strength parameters of dispersed soils after high-frequency vibration]. *Construction and Geotechnics*, 2021, vol. 12, iss. 1, pp. 46–56. DOI: 10.15593/2224–9826/2021.1.04.

30. Ter-Martirosyan A. Z., Mirnyy A. YU., Sidorov V. V. Laboratornyye ispytaniya gruntov v Moskovskom gosudarstvennom stroitelnom universitete (MGSU-MISI) [Laboratory soil testing at the Moscow State University of Civil Engineering]. *Inzhenernyye izyskaniya*, 2013, no. 8, pp. 60-65.

Библиографический список

1. Баркан Д.Д. Виброметод в строительстве. – М.: Госстройиздат, 1959. – 316 с.

2. Василюк Л.В. Вибропогружение шпунта вблизи существующих зданий в грунтовых условиях Санкт-Петербурга // Инженерно-геотехнические изыскания, проектирование и строительство оснований, фундаментов и подземных сооружений: сб. тр. всерос. науч.-техн. конф. по геотехнике. – СПб., 2017. – С. 307–316.

3. Верстов В.В., Гайдо А.Н., Иванов Я. В. Технологий устройства ограждений котлованов в условиях городской застройки и акваторий. – СПб.: Лань, 2014. – 366 с.

4. Deckner F., Viking K., Hintze S. Wave patterns in the ground: case studies related to vibratory sheet pile driving // Geotechnical and Geological Engineering. – 2017. – Vol. 35, iss. 6. – P. 2863–2878. DOI: 10.1016/j.soildyn.2017.01.039

5. Meijers P., Tol A.F. The Raamsdonksveer sheet pile test, measured surface settlements during vibratory sheet piling // Proc. 14th Eur. Conf. Soil Mech. and Geotech. Eng. – Madrid, 2007. – P. 603–609.

6. Верстов В.В., Белов Г.А. Совершенствование технологических решений по погружению и извлечению шпунта вибрационным методом // Вестник гражданских инженеров. – 2007. – № 4 (13). – С. 38–44.

7. Опыт сооружения подземных паркингов в условиях слабых грунтов Санкт-Петербурга / Р.А. Мангушев, Е.Б. Лашкова, В.Ю. Смоленков, М.А. Зайцев // Вестник гражданских инженеров. – 2015. – № 5 (52). – С. 91–100.

8. Мангушев Р.А., Гурский А.В. Оценка влияния вдавливания шпунта на дополнительные осадки соседних зданий // Геотехника. – 2016. – № 2. – С. 34–41. DOI: 10.25296/2221-5514-2020-12-1-32-44

9. Мангушев Р.А., Гурский А.В., Полунин В.М. Оценка динамического воздействия от вибропогружения шпунтовых свай на здания окружающей застройки в условиях слабых водонасыщенных грунтов // Construction and Geotechnics. – 2020. – Т. 11, № 3. – С. 102–116. DOI: 10.15593/2224-9826/2020.3.09

10. Мангушев Р.А., Гурский А.В., Полунин В.М. Учет влияния технологических осадок зданий окружающей застройки при устройстве шпунтовых ограждений соседних котлованов // Жилищное строительство. – 2020. – № 9. – С. 9–19. DOI: 10.31659/0044-4472-2020-9-9-19

11. Проектирование и устройство подземных сооружений в открытых котлованах / Р.А. Мангушев, Н.С. Никифорова, В.В. Конюшков, А.И. Осокин, Д.А. Сапин. – М.: АСВ, 2013. – 256 с.

12. Полунин В.М. Прогноз дополнительных деформаций зданий и сооружений в процессе высокочастотного вибрирования шпунтовых свай // Вестник гражданских инженеров. – 2022. – № 2. – С. 74–83.

13. Особенности инженерно-геологических условий Санкт-Петербурга источников вибрационных воздействий / Р.Э. Дашко, О.Ю. Александрова, П.В. Котюков, А.В. Шидловская // Развитие городов и геотехническое строительство. – 2011. – № 13. – С. 24–71.

14. Бахтин Б.М. Учет влияния вибрации на сопротивление песчаного грунта сдвигу // Гидротехническое строительство. – 2012. – № 1. – С. 42–47.

15. Вознесенский Е.А. Динамическая неустойчивость грунтов. – М.: ЛЕНАНД, 2019. – 264 с.

16. Вознесенский Е.А. Динамическая неустойчивость грунтов: автореф. дис. … д-ра геол.-минералог. наук. – М., 2000. – 54 с.

17. Вознесенский Е.А. Землетрясения и динамика грунтов // Соросовский образовательный журнал. – 1998. – № 2. – С. 101–108.

18. Kramer S.L. Geotechnical earthquake engineering. – Prentice Hall, 1996. – P. 529–539.

19. Chopra A.K. Dynamics of structures-theory and applications to earthquake engineering. 2nd ed. – Prentice Hall, 1995.

20. Капустин В.В., Озмидов О.Р., Озмидов И.О. Методы исследования динамических полей напряжений и динамической устойчивости грунтовых массивов // Инженерные изыскания. – 2014. – № 1. – С. 48–53.

21. Instrumentation system for ground vibration analysis during sheet pile driving / F. Deckner, K. Viking, C. Guillemet, S. Hintze // Geotechnical Testing Journal. – 2015. – Vol. 38, iss. 6. – P. 893–905. DOI: 10.1520/GTJ20140275

22. Deckner F., Viking K., Hintze S. Aspects of ground vibrations due to pile and sheet pile driving // Electronic Journal of Geotechnical Engineering. – 2015. – Vol. 20, iss. 19. – P. 11161–11176.

23. Ершов В.А. Динамические свойства песчаных грунтов и их учет в оценке устойчивости земляных сооружений: дис. … д-ра. техн. наук. – Л., 1970. – 180 с.

24. Сопротивление сдвигу несвязных грунтов при статических и вибрационных нагрузках / Е.А. Исаханов, М.Я. Квашнин, Б.А. Абиев, Ж. Алпыспаева // КазККА Хабаршысы. – 2013. – № 4 (83). – С. 4–9.

25. Denies N., Holeyman A. Shear strength degradation of vibrated dry sand // Soil Dynamics and Earthquake Engineering. – 2017. – Vol. 95. – P. 106–117. DOI: 10.1007/s10706-017-0285-x

26. Строкова Л.А. Динамика грунтов. – Томск: Изд-во Томск. политехн. ун-та, 2018. – 190 с.

27. Effects of OCR on monotonic and cyclic behavior of reconstituted Shanghai silty clay / J. Qian, S. Li, J. Zhang, J. Jiang, Q. Wang // Soil Dynamics and Earthquake Engineering. – 2019. – No. (118). – P. 111–119. DOI: 10.1016/j.soildyn2018.12.010

28. Чунюк Д.Ю., Козьмодемьянский В.Г., Коптева О.В. Инженерные изыскания для проектирования фундаментов сооружений вблизи источников вибрационных воздействий // Промышленное и гражданское строительство. – 2017. – № 10. – С. 54–58.

29. Полунин В.М., Черемхина А.П. Изменение прочностных параметров дисперсных грунтов после высокочастотного вибрирования // Construction and Geotechnics. – 2021. – Т. 12, № 1. – С. 46–56. DOI: 10.15593/2224–9826/2021.1.04

30. Тер-Мартиросян А.З., Мирный А.Ю., Сидоров В. В. Лабораторные испытания грунтов в Московском государственном строительном университете (МГСУ-МИСИ) // Инженерные изыскания. – 2013. – № 8. – С. 60–65.