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Estimation of Additional Foundation Settlements Caused by Dynamic Loading in Urban Areas

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Abstract

Response of different soils to dynamic loading is of fundamental interest in many engineering, geophysical and environmental studies. Many methods have been proposed to estimate dynamic stability of soils. One more approach, based on laboratory cyclic testing, is discussed in this paper. In our tests, not only the specific features of examined soils, but also different conditions of static and dynamic loading have been taken into account. An analysis of the obtained experimental data explicitly supports the hypothesis of a logarithmic relationship between the axial deformation of soil in cyclic triaxial compression and the number of loading cycles. Evaluation of soil deformation under vibrodynamic loads can also be based on energy approach. The use of critical amount of energy dissipated by soil per its unit volume has been proved to be reliable even in a low dynamic stress range. Convergence of the proposed solution was proved using field measurements and observations. The proposed approach has been applied to evaluate additional settlements of structures founded on the basis of different soil profiles and under various static and dynamic loading conditions.

Key words: deformation of soils, dynamic stability, dynamic testing, vibration in urban area.

1. INFLUENCE OF TECHNICAL VIBRATIONS ON SOILS AND FOUNDATIONS IN URBAN AREA

Along with the increase of vibration intensity in urban areas caused by the development of railway and highway systems, as well as new subway stations and structures, the dynamic loads on the subsurface soils serving as building bases also increase noticeably. Stress waves propagating in soils caused by under- and above-ground transportation may affect the foundation stability. In case the newly built structures do not allow for protection from the dynamic effect, the old buildings may be damaged due to strains in their bases caused by the vibration load.

Any large-scale urban area is a united source of technical dynamic loads since stress waves from various single sources overlap. The vibration field has a dynamic effect on the geological environment, and notably on soils. Different sources within the city limits generate vibrations with frequencies from 2-5 to 60-70 Hz, sometimes up to 200 Hz, with the maximum particles displacement amplitudes being about (10-20)×10^{-6} m (Osipov and Medvedev 1997). Traffic is the main contributor to this permanent and always changing vibration field. Industrial equipment and heavy machinery are of minor importance since their impact is much more localized. The vibration effect from the industrial ventilation and air-conditioners is relatively negligible.

Dynamic loads from traffic are most dangerous because of their high activity and wide spreading, especially near the highways with heavy traffic. The main contribution to vibration field in the cities comes from rail transportation – tram and subway (Table 1). Near the railway, vibrations can sometimes rise to the level of seismologic scale magnitude 3-5 (at the distance within 25-40 m from the railway line).

Dynamic loads from different types of machinery usually propagate not so far from the source. Basically, they influence the properties of soils just under their own foundation. Usually, the dynamic loading from industrial machines (turbines, wind or water mills, etc.) have frequencies below 75 Hz for the displacement amplitude of 0.1-0.16 mm. But the important fact is that during the transformation of stress waves from the foundations into the ground and back their dynamic characteristics can sufficiently change.

Table 1

Sources of vibration and their influence in urban areas (Zhigalin and Lokshin 1991)

Source	Predominant frequency [Hz]	Parameters of soil particles vibration		Radius of zone of influence [m]
		velocity [×10^{-3} m/s]	acceleration [m/s^2]	
Railway	10-70	16-50	1-22	150-300
Tram	20-45	1.6-160	0.5-45.2	150-300
Subway	30-80	0.3-300	10-1800	6-120
Highway	10-20	0.005-0.07	0.003-0.011	40-100

Soils under foundations usually get additional strains under cyclic loads. These deformations result in the land subsidence, particularly under foundation built on loose sands. Also in the streets with heavy traffic these deformations can be much higher than in the streets with moderate traffic. Quantitative level of vibration can be estimated from its kinematic parameters, i.e., velocity and acceleration of soil particle vibration. The range of velocity of vibrating particles is rather wide for different sources and can cause various response of soils and building foundations.

2. METHODOLOGY FOR THE EVALUATION OF ADDITIONAL DEFORMATIONS OF SOILS

The main purpose of the research is to develop a methodology for the evaluation of additional soil deformations under the foundations under the conditions of long-term dynamic loads and to test it on the existing buildings. So, the main objective of the research was to characterize the vibration using field observations and to study its effect on the dynamic stability of soil base using laboratory dynamic testing data.

The sensitivity of soils to the dynamic loads was evaluated in triaxial cyclic undrained stress controlled tests. In such a test, specified dynamic stresses are applied to the sample and the resulting pore pressure and axial strain are measured as a function of loading cycle number. Tests have been carried out under dynamic stresses calculated from the measured kinematic parameters of vibration sources in the real soil massifs.

All sand samples were reconstituted by air pluviation technique and then saturated directly in the triaxial cell after filling all the pores with carbon dioxide to provide full subsequent saturation. Undisturbed clayey samples were cut off from the soil block. The samples were tested at their natural density and under *in situ* stresses, calculated from the overlying deposit density at the specified depth.

For saturated sands, Skempton's parameter B (Skempton 1961) has been estimated before each test. This parameter controls saturation of the sample and also absence of air in the sample while measuring pore pressure $B = \Delta u/\Delta\sigma_3$, where $\Delta\sigma_3$ is the change of hydrostatic pressure in the cell, and Δu is the corresponding change of pore pressure. While at the complete saturation the parameter B equals 1.00 for loose sands, for dense sands it can be somewhat lower than 1.0 even when all the pores are saturated.

Prior to dynamic testing, preliminary consolidation of all samples was carried out step by step until reaching $\sigma_1' = \sigma_v'$ and $\sigma_3' = K_0\sigma_v'$, where σ_v' is the calculated normal effective stress at the depth of studied soil layer, and K_0 is the coefficient of lateral soil pressure at rest. For sands, $K_0 = 0.5$ was used as the one corresponding to young uncemented sands (Stokoe *et al.* 1985). The

K_0 value for clay soils was calculated using Jaky's equation (Mitchell 1993) for normally consolidated or lightly overconsolidated clays: $K_0 = 1 - \sin\varphi'$, where φ' is the effective angle of internal friction.

Stresses for the preliminary consolidation were calculated from density of soils as the overburden stress (stress from upperlying soils) at the depth of soil sampling using the equations:

$$\sigma_{\text{vertical}} = \rho g h, \tag{1}$$

$$\sigma_{\text{horizontal}} = 0.5\,\sigma_{\text{vertical}}, \tag{2}$$

where σ_{vertical} is the vertical stress, ρ is the soil density, g is the gravitational acceleration, h is the depth of soil sampling, and $\sigma_{\text{horizontal}}$ is the horizontal stress.

Additional stresses from the building were also taken into account after calculations of their vertical and horizontal parts at the same depth. Volume change during consolidation was controlled by the amount of pore water expelled into the burette connected to the pore pressure measurement system. The void ratio was recalculated automatically.

Dynamic loading was applied after the end of primary consolidation. Irregular vibration loading was in all cases simulated by an equivalent (in terms of power) harmonic dynamic loading with the frequency of 0.1 Hz. Principal stresses, pore pressure and axial strain were recorded 20-50 times every cycle. Amplitude of dynamic stresses was calculated using different methods according to known parameters characterizing the dynamic loading.

A possible foundation settlement was then calculated for every layer from the relative strain of the corresponding samples, basing on the idea that deviatoric strains development is reasonably well modeled in triaxial compression.

3. CASE HISTORIES OF APPLICATIONS OF THE PROPOSED APPROACH

3.1 Dwelling house in the center of Moscow

The first example used to test the proposed approach is a building in the centre of Moscow. This masonry house is located very close to the subway line and is influenced by its vibrations. The deformations have been accumulating for many years; cracks on the walls keep appearing and growing. In the process of evaluation of the building's condition and the reasons behind its lasting deformation, the vibrodynamic effect on the soils under the foundation was considered as well. It appeared that one of the main sources having a significant effect on foundation stability is the vibration from the subway transportation line located within 4 m from the building.

The upper layers of the deposits in the area of the building under consideration are composed of mostly alluvial clean loose medium grained sand. The density of sand increases with depth. The sand is poorly graded, with a moisture content of 10-12%. These sands are underlaid by Carboniferous limestones. The water-bearing horizon is located 9.0-10.5 m deep.

Dynamic stress calculation

The dynamic stresses in the soil under the foundation were calculated basing on field geophysical data. The spectral composition of the vibration field in Moscow, registered on the surface soil, lies in the range from 15 to 80 Hz. The range of low frequencies corresponds to the dynamic effect from wheel-based transport and various machinery. The range of 60-80 Hz characterizes vibration influence from the underground. Despite this, the influence from subway is two times stronger than the influence from wheel transport. The findings are illustrated in Fig. 1. Diagram on the left demonstrates the impulse recording (in ms) for different stations. Diagram on the right shows the spectral composition of vibration.

The evaluation of stress in the soil is based on the soil density, velocity of Rayleigh waves, and the velocity of soil particles oscillation

$$\sigma = \rho V_R C, \tag{3}$$

where ρ is the density of soil (in kg/m^3), V_R is the velocity of Rayleigh wave (in m/s), C is the vibrovelocity of soil particles (in m/s).

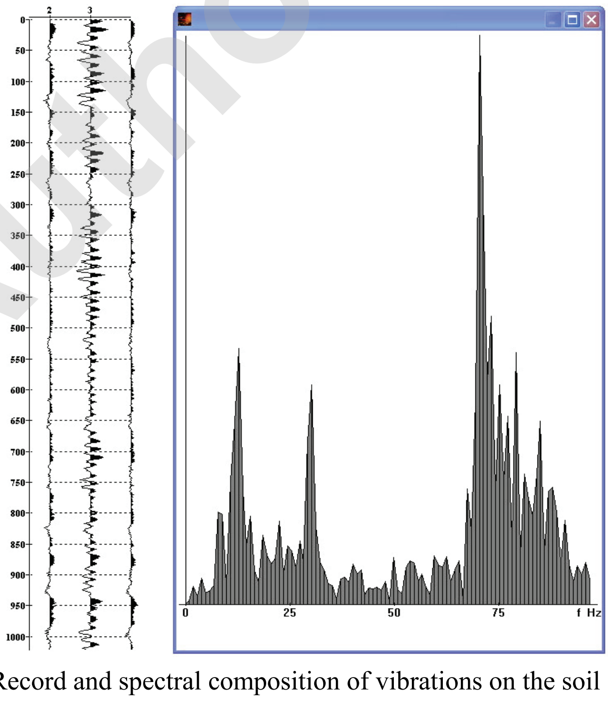

Fig. 1. Record and spectral composition of vibrations on the soil surface.

Taking the soil density equal to 1700 kg/m^3, the velocity of Rayleigh wave equal to 200 m/s, and the velocity of soil particles oscillation equal to 0.015-0.020 m/s, the calculated value of dynamic stress amplitude in the soil is about 5 kPa.

Though the intensity of dynamic load is not high, we should take into consideration that such dynamic loads affect the soil every day nearly from 5:30 till 1:00 a.m. (opening and closing time of the subway), so during the day it makes nearly 19.5 hours of the continuous influence. Taking into account the fact that such low dynamic stresses affect the soil for many years, the resulting accumulated strains can be very significant, although they develop very slowly.

Dynamic stability characteristics of the building basement soil

While modeling the vibration load, several significant assumptions were made. As mentioned above, the dynamic influence duration of the subway is nearly 19.5 hours a day. Considering that 200 cycles of the dynamic load in experiment equals the 0.5 hour time period, it is possible to calculate that during the day the soils in the basement of construction are exposed to a dynamic effect similar to 7 800 cycles. So during the year the number of load cycles run up to 2 847 000.

From the results of laboratory research we define the highest soil deformation that it endures during the every load cycle. The deformation development is represented in Fig. 2; test conditions are shown in Table 2. The

Table 2

Testing conditions. In all tests, the frequency was 0.5 Hz, the number of cycles was 200, and loading amplitude was 5.0 kPa

Depth h [m]	Consolidation parameters [kPa]		Moisture [%] and saturation	Axial deformation ε [%]
	σ_1	σ_3		
3.0	84	42	8	0.215
	84	42	saturated	0.817
4.0	90	45	9	0.652
	90	45	saturated	0.950
5.0	100	50	8	0.515
	100	50	saturated	1.746
6.0	118	59	10	0.238
	118	59	saturated	1.728
7.0	134	67	12	0.286
	134	67	saturated	0.879
9.0	170	85	12	0.137
	170	85	saturated	0.980

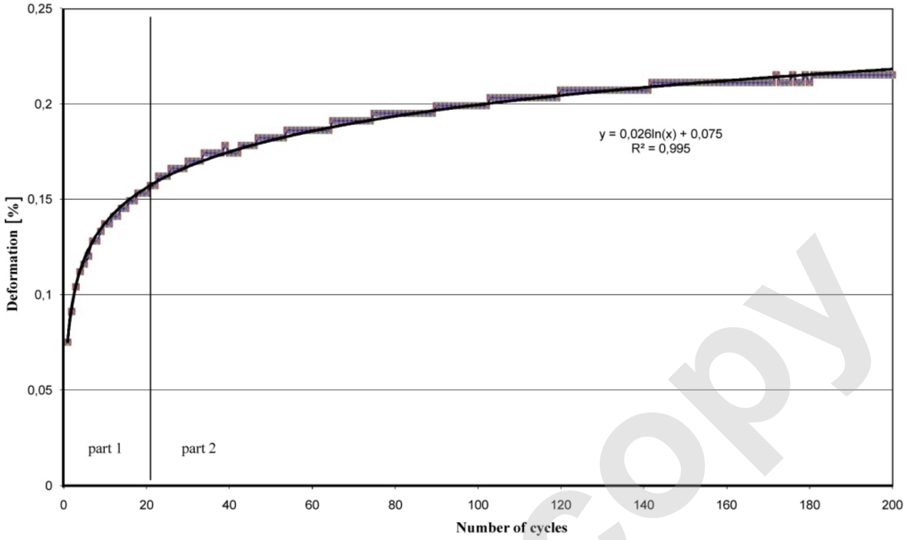

Fig. 2. Deformation of soils under the foundation during the dynamic loading *versus* number of cycles (σ_a = 5 kPa, f = 0.1 Hz). Medium grained sand (void ratio e = 0.63, relative density I_d = 0.54, natural moisture content W = 8%).

received dependences reveal the samples' deformation evolution under the influence of the dynamic load in humid and water-saturated conditions. Samples are characterized by similar particle structure and nearly equal amount of the clay content (2-5%). All sand samples are characterized by high stability to the dynamic loading in humid condition. On the 200th cycle, sample deformations run up only to 0.14-0.65%. Besides that, the major part of the deformation (80%) takes place in the first stage of this process. In water saturation, the soil stability to the dynamic loads decreases, the soil deformations at the end of 200th cycle rise to the level of 0.9-1% and for the samples at 5 and 6 m depths the deformations during the experiment come to 1.8 and 1.7%. The most stable to the dynamic loads is the sample at 9 m (in humid state the deformation equals 0.14%, in water-saturated 1%). It is bound up with the fact that the sample taken from the 9 m depth is characterized by the highest static load value of weight from upper lying soil.

Because in the study area there is a possibility of water level to rise, it is necessary to make a prognosis for the behavior of sandy grounds during the rising of water level. Also, it is necessary to take into consideration the fact that when the dynamic load is applied, the water saturation enhances the ability of soils to rebuild their structure, because the pore pressure is getting higher and the effective stress is getting lower. That is why in case of water saturation it is necessary to consider initial deformation as well as long-term one.

To describe the soil deformation, diagrams were constructed. These diagrams show how axial deformation of the sample depends on the number of cyclic loading (Fig. 2). The correlation is best described by a logarithmic function. Using this correlation it is possible to estimate the deformation of soil for any period of structure exploitation. In the laboratory test, the number of cyclic loading was 200, which corresponds to 30 min of soil vibration in nature.

The first part of the diagram shows the deformation growing at a very high pace. This part was not taken into account in the process of evaluation. It was assumed that this part of the deformation had occurred in the past. All the moist samples showed high resistance to the dynamic loads. The deformation of samples at the 200 cycles of loading was only 0.5%. Most of the deformation (80%) occurred in the first part of the laboratory test.

When the saturation increases, the stability of soils under the dynamic loads starts to decrease. Deformation of saturated sands at the 200 cycles of loading was 1.7-1.8%. The most resistant to dynamic loads are the samples from the layer which is 9 m deep (1%). This happens because of higher static pressure from the upper layers.

The estimation of settlement in construction's basement soils

Calculations for different occasions of water level elevation were made for the period from 1 to 10 years taking into account thickness of all the sand soil strata (from 2.3 to 1.8 m depth). Refined figures are presented in Table 3 and Fig. 3. The data obtained testifies to the fact that in conditions of constant water level (9.8 m) deformations will rise to 0.004 m during the year and 0.013 m during 10 years. Such deformations will not affect the stability of basement. If the water level rises to depths of 8.6, 7.0, and 4.5 m, the value of soil settlement will be much higher. In Fig. 3 one can see how fast soils react to the influence of vibration in the water-saturated conditions. If the water level rises to a depth of 8.6 m, the forecasted deformation for the year from the moment of rise may reach 0.03 m, and for the period of 10 years – 0.427 m. Such deformations can be the reason of building's deformation. When the water level rises to a depth of 4.5 m, very significant settlement can be observed, which during the period of 10 years can reach 0.19 m. Such deformations are inadmissible; they result in intensive deformation of the building, taking it out of service.

The following conclusions can be made:

– While calculating predicted soil deformations under the dynamic loads it is necessary to take the change of water level into account. This is because the stability of saturated soil is much lower than the one of moist soils.

– The increase of static stress enhances the stability of all the evaluated soils to the dynamic loads, which is consistent with the modern concept about the behavior of sandy soil (Voznesensky 1997).

– New deformations of the building in the centre of Moscow city may be regarded as stabilized and not affecting the stability of building. The only threat of an additional increase of foundation deformation can occur with a rise in water level.

Table 3

Estimation of possible soil deformation under the building foundation in case of water level uplift (in mm)

Years	Water level up to			
	9.8 m	8.6 m	7.0 m	4.5 m
1	0	0	0	0
2	4.0	31.2	67.7	164.2
3	6.4	34.1	71.7	170.7
4	8.1	36.2	74.5	175.3
5	9.4	37.8	76.7	178.8
6	10.5	39.1	78.5	181.7
7	11.4	40.2	80.0	184.2
8	12.2	41.1	81.3	186.3
9	12.8	41.9	82.5	188.2
10	13.5	42.7	83.5	189.9

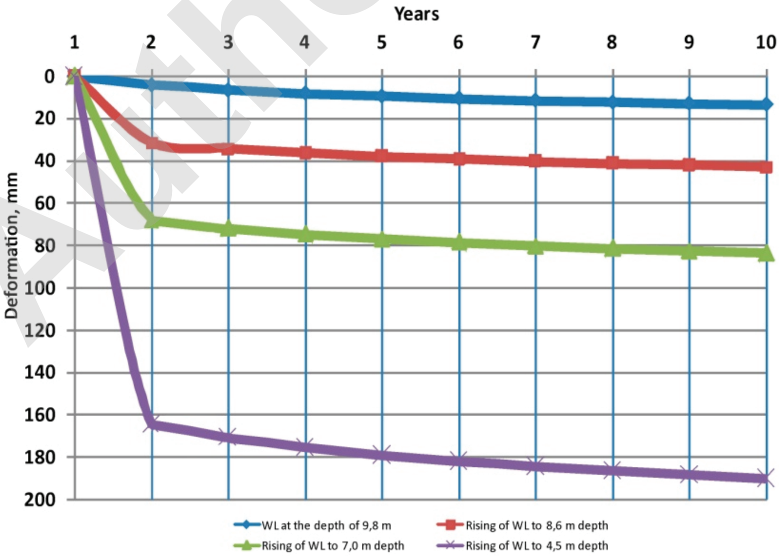

Fig. 3. Deformation progress in case of different water level uplift. Colour version of this figure is available in electronic edition only.

3.2 Estimation of building deformation in Togliatti

One more example to show how it is possible to estimate foundation deformation under static and dynamic loading comes from Togliatti city. Complex geological investigations were carried out to find out the reason of building list (0.5 m) as a result of nonuniform settlement. The geological site of the area is characterized by high variation of soil parameters and their irregular distribution. Also the deformation of soils can respond to dynamic loading, occurring during evacuation of flood water through the spillway dam situated close to the observed building.

To find out true reasons of deformation, the influence of static loading as well as dynamic loading was calculated.

Geological structure of the investigated area

During the completed exploration program, two geologic units, in descending sequence, were encountered: the Quaternary covering sediments and Quaternary alluvial sediments.

The Quaternary covering sediments encountered in all boreholes consist of clay sand and loams. They have low moisture and show subsidence by additional static loading. At the exploration, this layer varies in thickness from 2.5 to 4.5 m. These sediments overlie a sequence of Quaternary alluvial sediments. The alluvial deposits consist of loams and clay sands and usually contain lenses or thin layers of sands. Alluvial sediments occur at a depth of 2.5-4.5 m and vary in thickness from 7 to 13.5 m. The underlying alluvial deposits consist of fine sands with thin layers of loams and clay sands. The thickness of this unit exceeds 20 m.

According to the results of drilling and laboratory testing, nonuniform structure of subsurface soils under the emergency building is observed. Several clay layers are characterized by higher moisture content and lower deformation modulus. There is a difference between geological structure under north-west and south-east corner of the foundation. Under the north-west corner, several layers of soft low-plastic loam were found. For example, sediments encountered under one of the corners of the building include low-plastic loam with a higher moisture content. This layer is 0.80 m thick. The same situation was observed with the layer encountered only under the north-west corner which contains fine sand of 0.30 m thickness. Underlying sediments also contain soft low-plastic loam.

Estimation of soil deformations under different parts of the building show that while the pressure from building was uniform and equaled to 260 kPa, difference in settlement between opposite corners should have reached 0.10 m. The building should have taken an inclination (list) of 0.164 m from the vertical given. Different value of inclination under different corners can cause stepwise increase of loading on the north site of the building and a final increase of list up to 0.47 m on a height of 46 m.

As we can see, the building took a list first of all as a result of ununiform deformation parameters of underlying soils. Estimated list is in a close agreement with the measured list of 0.50 m. Calculation of deformation was made for the eventual period of building maintenance and considering that the list happened at once time. This suggests that there are other factors precipitating ununiform settlement.

It was also mentioned that the periods of settlement activation follow evacuation of flood water through the spillway dam. The reaction to the water evacuation comes a bit later than the dynamic loading occurs. It means that the water evacuation can cause additional deformation of buildings due to vibrocreep of subsurface clay deposits.

In this research we were trying to estimate not only the dynamic stability of soils in their natural conditions, but also in conditions of higher moisture content. It was modeled in the cell of TRIAX operators while moisturizing the sample by drainage. Due to these tests, the behavior of soils in some special conditions could be estimated.

Estimation of stresses

Dynamic stresses were estimated using numerical seismic recordings during the evacuation of flood water through the spillway dam. According to the geophysical data, amplitude of vibrovelocities near the body of interest was 25-250 μm/s, while the maximum vibrovelocities can reach 0.0012 m/s. Dynamic stresses were estimated in the same way as for the example of building in Moscow city (eq. 3). Vertical dynamic stresses lie in the range from 168 to 1006 Pa. The minimum amplitude of dynamic loading during the test was 200-1000 Pa. Dynamic stresses are extremely low in the city, but they exert their effect on buildings 1.5-2 months a year for 27 years.

The estimation of vibrodynamic influence on soils was based on the developed energy approach. This method is based on universal energy criterion of dynamic stability. The calculation was made in total stresses using measured experimental stresses and deformations (Voznesensky 1999). The degree of soil stability from the site of energetic process can be estimated due to total amount of energy dissipated by its unit volume during all cycles to the prescribed stage of deformation (or liquefaction). The higher the value, the more dynamically stable the soil is. The total amount of dissipated energy can be calculated as a part of all the energy which comes from the source of vibration. Thus, based on energy and radius of influence as well as damping of soils, after calculation of dissipated energy we can estimate their dynamic stability.

To this end, we need to calculate critical amount of energy dissipated by unit volume of soil at a certain stage of deformation. It is necessary to use programs of high rate registration (every 10-20 ms) during all the test to obtain a plain hysteresis loop. At the same time, this huge number of registered values makes it possible to divide the diagram of stresses onto a finite set of infinitesimal rectilinear segments. The total volume of energy dissipated by the unit volume of soil to every specified moment of dynamic loading can be estimated by the following formula:

$$\Delta W = \sum_{i=1}^{n-1} 0.5(\sigma_{i+1} + \sigma_i)(\varepsilon_{i+1} - \varepsilon_i)\,, \tag{4}$$

where σ is the increment of stress deviator regarding to the initial level, ε is the axial deformation, n is the number of recorded values.

While calculating stresses in kPa and deformation as decimal (m/m) the specific dissipated energy will be in kJ/m^3. Application of energy criteria makes it possible to calculate values in total stresses. This solves the problem of reliable pore pressure measurement.

The energy approach provides opportunity to estimate dynamic stability of soils under the dynamic loading of low intensity, using as a criterion the dissipated energy calculated during the test of much higher dynamic amplitude. Final conclusion about the influence of vibrocreep on the irregular settlement of investigated house can be made while comparing amounts of the energy dissipated in soil to the specified strain for the whole period of building exploration (years 1975-2002). To reach this goal, parallel dynamic tests were carried out with the essentially higher loading amplitude (20-90 kPa).

The level of stress was entered in numerical form (bites), but the effective stress amplitude depends also on soil sensitivity. It was considered by using different stress amplitudes as follows:

Stage 1: 200-1000 Pa (600 Pa average).

Stage 2: 800-1300 Pa (1000 Pa average).

Stage 3: 17.3-21.2 kPa (20 kPa average).

Stage 4: 36.5-46.3 kPa (42 kPa average).

Stage 5 (for several samples only): 84.3-92.5 kPa (85 kPa average).

Most of the samples were tested by the sinusoidal stress frequency of 0.5 Hz, which corresponds to spectral maximum of registered microseism. One sample was tested by 0.1 Hz to estimate the influence of lower frequency.

To estimate dynamic stability of subsurface soils, the results of 20 laboratory tests were analyzed. All the samples were tested after the preliminary consolidation by the stresses corresponding to the natural stresses. The static loading from the building was also taken into account. The amplitude of dynamic loading has been increased step by step every 100-200 cycles of loading. The number of cycles for the majority of samples came to 500-700 cycles. All the investigated soils showed quite enough stability to the dynamic loading. The example of hysteresis loop during dynamic loading is

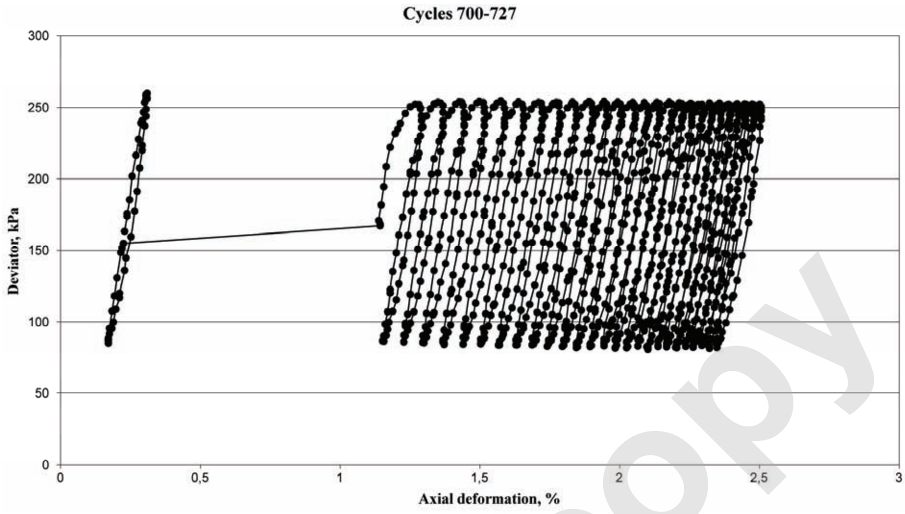

Fig. 4. Hysteresis loop during step by step dynamic loading.

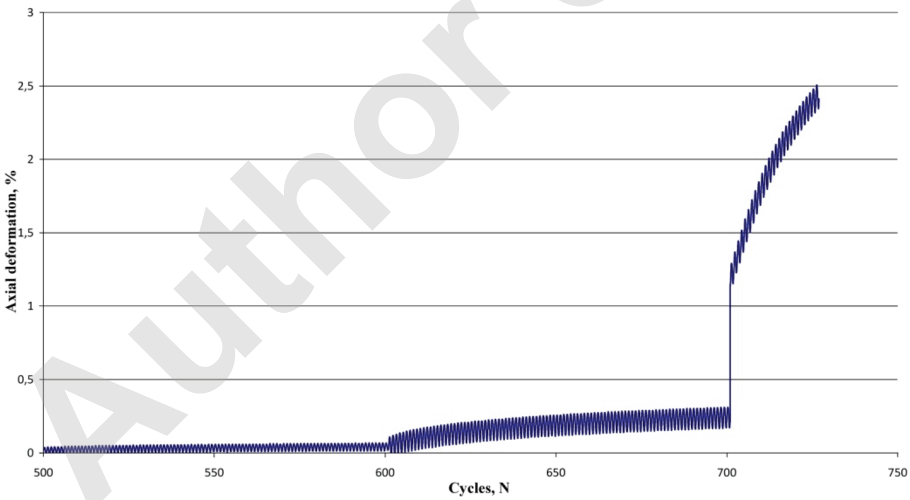

Fig. 5. Typical diagram of deformation growing under the dynamic loading.

shown in Fig. 4. In this stage, deformations increase very slowly. The soil behavior during the dynamic loading is shown in Fig. 5.

Expecting small variations of stresses and duration of tests, the energy approach was used for the estimation of soil deformations. This method uses energy dissipation intensity modulus, E_w, which can be characterized by specific dissipated energy for the relative deformation unit:

$$E_W = \frac{\Delta W_\varepsilon}{\varepsilon}, \tag{5}$$

where ΔW_ε is the unit dissipated energy (in kJ/m^3) calculated for every test, and ε is the relative axial strain of the sample, reached during the test.

For most occasions, E_W was calculated for the deformation of 0.3% (if it was reached during the test), otherwise it was estimated for the maximum deformation. This method allows comparing dynamic stability of soils even in different stages of their deformation. The higher the E_W, the more stable the soil is.

Calculations showed different E_W values for the clay soils from different layers (Fig. 6). For most samples it varies from 83.3 to 890 kJ/m^3. Several soils have E_W equal to 1053 kJ/m^3; for other samples it falls down to 2 kJ/m^3. Subsurface covering of loams and clay sands by natural moisture usually shows the highest energy intensity.

In conditions of moisturizing, the dynamic stability of soils notably decreases. For some of them, the power intensity modulus decreases 5 times while soil moisturizing grows from 8 to 14%.

Using the obtained data, the most dynamically unstable layer was picked out, which contains sensitive clay deposits of 4 m thickness on a depth of 9-13 m. Through this layer, E_W, changes from 83 to 470 kJ/m^3. It is relatively lower at the north-west corner of the building and comes to 257 kJ/m^3.

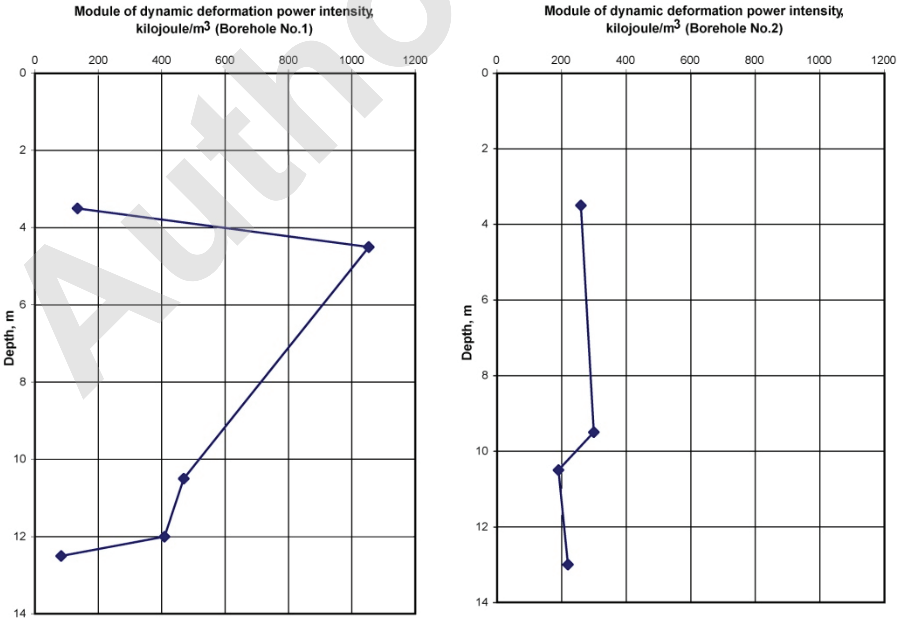

Fig. 6. Dynamic stability of soils under the foundation in conditions of natural moisture content.

Using the results of laboratory test, the most sensitive clay layer was picked up at a depth from 9 to 13 m. Some more tests with duration of 10,000 cycles were made to consider the period of time when the dynamic loading occurs. This time comes to 1.5-2 months a year for 27 years. This time equals to 139,968,000 cycles of dynamic loading. The deformation of soils can be defined using the equation:

$$\varepsilon(\%) = 0.0303 \ln N - 0.219 \tag{6}$$

with the correlation factor of 0.97 (Fig. 7).

Estimation of deformations

Calculation of additional deformations for the whole period of exploration gives us soil deformation of 0.014 m for the layer of soft clay (4 m). The difference in deformation between opposite corners rises up to 0.301 m, and the building takes a list of 0.493 m. This list closely agrees with the real measured deformations. This confirms our assumption about the definite role played by continuous dynamic loading. At the same timer, this factor is not significant if to compare it to the static deformation, and amounts to 2.5%.

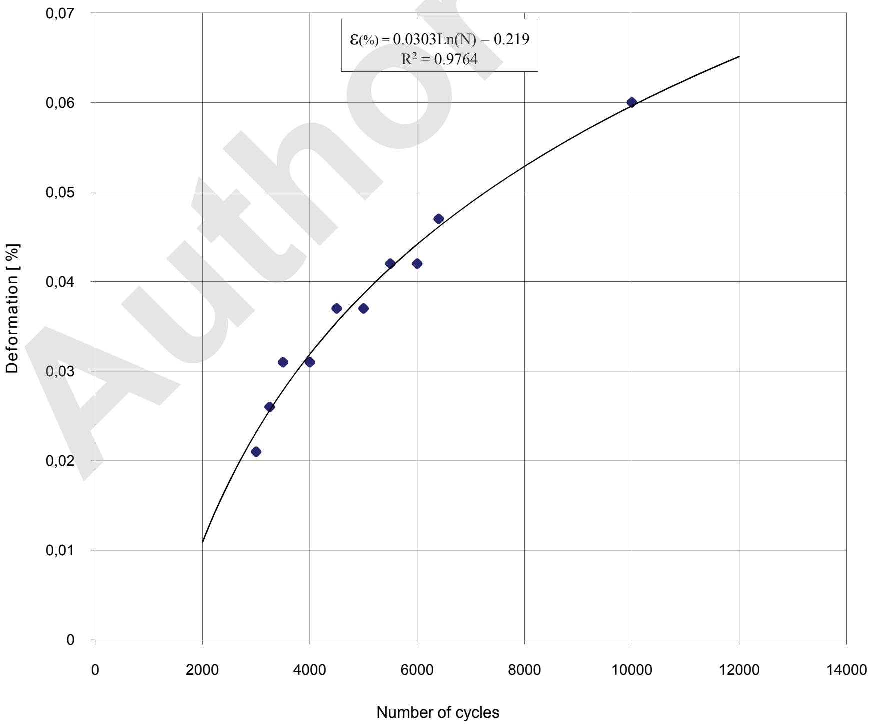

Fig. 7. Accumulation of soil foundation deformations under the dynamic loading.

Thus, the main reason of foundation deformation is dissimilar geological structure of subsurface soils. Some lenses happened to be softer under one of the corners of building. Deformation under static loading was followed by deformation under dynamic loading as a result of vibrocreep occurring every year after the evacuation of flood water through the spillway dam. Additional moisturizing of soils can also cause decrease of their mechanical parameters, but the calculated deformations closely agree with the measured settlement of building, even without taking this factor into account.

4. CONCLUSIONS

The methodology described here is used to estimate deformation in soils under the long-term vibrations. It gives an opportunity to predict deformations using:

- vibrometry data and specification of machinery with dynamic loads,
- dynamic laboratory tests,
- characteristics of buildings (additional static loadings from buildings).

This methodology has the following limitations:

- Dynamic characteristics of machinery also depend on the soil properties.
- During continuous vibration, it is in some cases impossible to estimate the phase of dynamic loadings, which may sometimes result in underestimation of the initial strains.
- Density of sands cannot be correctly defined *in situ*.

The development of deformations at a low rate can be described by a logarithmic function. The water level should be taken into account for deformation prediction, because in the case of full saturation of the soil its strains distinctly increase.

As obtained from the test, the medium grained sands with low (5%) fines content have a higher tolerance to dynamic loadings. This is explained by high total area of contacts and friction increase in the system. Sands with high fines content, 20-25%, are most instable. This is explained by the formation of coagulation contacts and friction reduction in system.

The static stress enhances the dynamic stability of all the studied soils. This is in agreement with the modern concept of soil behavior.

The energy approach provides opportunity to estimate dynamic stability of soils under the dynamic loading of low intensity, using as a criterion the dissipated energy calculated during the test of a much higher dynamic amplitude. A final conclusion about the influence of vibrocreep on the irregular settlement of the investigated building can be made upon estimating the amounts of energy dissipated in the soil.

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