DE GRUYTER OPEN

CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

ISSN 2080-5187 CEER 2017; 24 (1): 169-183

DOI: 10.1515/ceer-2017-0012

Original Research Article

THE INFLUENCE OF ACCELERATION ON THE EFFICIENCY OF SAND COMPACTION TESTS CONDUCTED ON A VIBRATING TABLE

Waldemar St. SZAJNA[1]

University of Zielona Gora, Zielona Góra, Poland

Abstract

The paper presents a standard vibrating table for fresh concrete testing adopted for determination of maximum dry density ($\rho_{d\max}$) of sand. Vibration is an efficient method for coarse soil compaction therefore vibrating tables are useful for $\rho_{d\max}$ determination. Acceleration that the soil is subject to is one of the basic parameters of efficient compaction. A vibrating table with inertial excitation was supplemented by a frequency converter and subjected to dynamic tests. The results of measurements of dynamic parameters are included. The paper presents problems connected with this method and describes the relationship between efficiency of compaction and accelerations which the soil is subjected to.

Keywords: sand compaction, vibrating table, mechanical vibration measurements, density - acceleration relationship

1. INTRODUCTION

The strength and stiffness of soil, as a porous medium, depend mainly on its state of compaction. One of the parameters describing soil compaction is dry density ρ_d, defined as a ratio of the mass of dry sand to its total volume. Relative assessment of soil compaction is possible only when both minimum and maximum values ρ_d are determined which correspond to maximum and

[1] Corresponding author: University of Zielona Góra, Faculty of Civil and Environmental Engineering, Z. Szafrana st 1, 65-516 Zielona Góra, Poland e-mail: w.szajna@ib.uz.zgora.pl, tel. +48683284799

minimum values of porosity achievable for a given material in standard tests. The values are denoted $\rho_{d\min}$ and $\rho_{d\max}$, respectively.

In Poland, value $\rho_{d\max}$ is determined in laboratory tests carried out with the use of the vibration fork method, described in Polish Standard [6]. Szajna and Lechocka showed in [7] inconsiderable repeatability of results of soil compaction tests carried out with the vibration fork method. They suggested that compaction may be tested with the use of a vibrating table. They adopted a vibrating table for concrete mix consistency testing and presented how to use it in $\rho_{d\max}$ evaluation.

The idea of applying a vibrating table for sandy soil compaction was vastly analysed in the 1970s in [2], [3] and [4]. The mentioned authors imply that the efficiency of a compaction process depends on the following factors: vibration time, the volume of a testing vessel, the value of load applied to the surface and the total mass of the sample. However, the most important factors are the frequency of vibration and the corresponding acceleration which the sample is subjected to. The authors of the third of the mentioned papers suggest that within frequency of 20÷60 Hz, the acceleration values range 1.5÷2.5 *G*, where *G* is the acceleration due to gravity.

The vibrating table method is a standard method for the determination of $\rho_{d\max}$ used in the USA and described in ASTM Standard [1]. According to the standard, soil is vibrated for 12 min. at frequency f = 50 Hz. The required amplitude of vertical vibrations q_z should amount 0.24 mm. Thus, the essential parameter, i.e. acceleration, may be determined for harmonic vibrations on the basis of displacements and frequency from equation

$$a = \frac{d^2q}{dt^2} = (2\pi\, f)^2\, q\,, \tag{1.1}$$

where a is the acceleration, q is the displacement, f – the vibration frequency, and t is the time. Substituting the table parameters defined in the ASTM Standard in equation (1.1), the obtained required acceleration is a = 23.69 m/s^2, i.e. 2.41 *G*.

In [7], a vibrating table was used to investigate sand compaction at various excitation frequencies. Fig. 1a shows the efficiency of compaction in terms of medium values of densities $\rho_{d\max}$ obtained after 12 minute of vibration. The figure implies that the sand vibration is efficient at frequencies $f \geq 39$ Hz. A relatively good density was also achieved for frequencies 23.4 Hz and 31.2 Hz, which appeared to be close to the resonant frequencies.

Methods used for determination of volumetric density $\rho_{d\max}$ should not only be efficient but also should return repeatable results. Fig. 1b presents alterations in density ρ_d during vibrations at three selected excitation frequencies.

At frequency 18 Hz, the compaction process is stable but not efficient. The final value of density increased inconsiderably in relation to the initial value, which had been 1.55 g/cm^3 for all tests. In order to analyse the repeatability of results, two extreme curves, denoted by (a) and (b), for each of the two remaining frequencies (50 and 39 Hz), presented in Fig. 1b, show the dispersion of results. For frequency 50 Hz (curves marked with continuous lines with empty markers, Fig. 1b), the process is chaotic. Compacted and loose states of sand occur alternatively and the dominating phase after a specified period of vibration is random. Such performance was found for frequency 31.2 Hz and all frequencies $f > 40$ Hz. For frequency 39 Hz (dotted curve with filled markers in Fig. 1b), the process was monotonic, the obtained results revealed decent efficiency and inconsiderable dispersion.

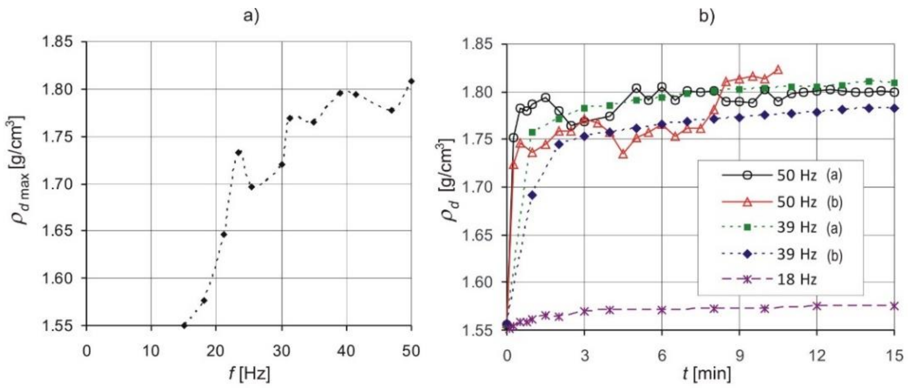

Fig. 1. Results of sand tests carried out on a vibrating table [7]: a) medium values of densities $\rho_{d\max}$ obtained after 12 min vibration, b) changes in density ρ_d during vibration (additional results are provided compared to outcomes presented in [7])

Summarizing the test results presented in Fig. 1, a general regularity was observed for frequencies within 15÷50 Hz, i.e. the effectiveness of sand vibration increases with an increase in the vibration frequency. However, there are some exceptions to this rule. One of them concerns the vibrations at resonant frequencies, for which higher densities were achieved than for the neighbouring frequencies. Another exception involves the instability of the process of compaction, which is characterized by alternating phases of soil densification and loosening, occurring at frequencies above 40 Hz and at a frequency close to the resonant one, i.e. 31.2 Hz. These observations suggest that vibration frequency is not an exclusive important parameter while sand compacting with the use of a vibrating table with inertial excitation. In this context, a question arises, what factors determine the effectiveness and repeatability of this method for soil compaction testing.

2. THE BEHAVIOUR OF A 1-D MODEL

Vibrating tables used in concrete mix consistency tests, and such table was used in this research, should have nominal amplitude of vertical displacements q_z = 0.5 mm, with vibration frequency 50 Hz, which results in acceleration values 49.35 m/s^2 (5.03 *G*). In [7], it was shown that the vibration process performed in the aforementioned conditions resulted in alternate sand compaction and loosening, probably due to excessive acceleration. To reduce the frequency of vibration, a frequency converter was applied and thereby the reduction of acceleration was achieved. The layout of the applied system is shown in Fig. 2. The total mass of vibrating elements of the table is denoted as *M*, while the mass *m* rotates with the eccentricity *e*. The figure indicates that the vibrating table used in the test has inertial excitation, which means that when changing the excitation frequency, the vibration amplitude is not constant and must be measured. Knowing the frequency and amplitude of vibration, the acceleration may be calculated from equation (1.1).

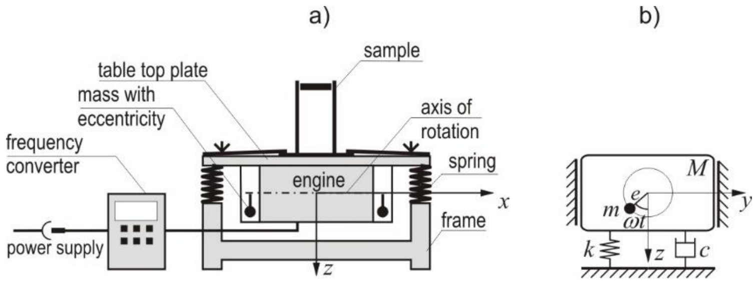

Fig. 2. Vibrating table: a) test layout (table with a frequency converter), b) a single degree of freedom dynamic model

To illustrate the idea of the influence of damping, excitation frequency and eigenfrequency on the behaviour of a system, a simple, one degree of dynamic freedom model is presented. A system, illustrated in Fig. 2b, consisting of mass *m* rotating with eccentricity *e* and angular excitation speed ω, generates the following centrifugal force

$$F_0 = m \cdot e \cdot \omega^2 . \tag{2.1}$$

The amplitude of the stationary vertical vibrations q_z may be determined from equation (see e.g. [5])

$$\mathrm{am}\, q_z = \frac{m \cdot e}{M} \frac{\eta^2}{\sqrt{\left(1-\eta^2\right)^2 + \gamma^2 \eta^2}} = \frac{m \cdot e}{M} \nu \cdot \eta^2 , \tag{2.2}$$

where: $\eta = \omega / \omega_n$ is a frequency ratio, ω_n is the angular frequency of a normal mode of free vibrations, γ is a dimensionless damping coefficient whereas ν is a dynamic coefficient.

Relation (2.2) implies that the amplitude of vibration is proportional to the unbalanced moment of rotating mass $m \cdot e$, dynamic coefficient ν, and the square of the frequency ratio η. At the same time, it is inversely proportional to the total mass of the system *M*. It means that parameters of a specific vibrating table with inertial excitation force depend on the applied excitation frequency, and the weight of the tested sample.

Fig. 3a shows the relationship between the frequency ratio η and dimensionless amplitude of vibration $\nu\,\eta^2$, at four selected values of dimensionless damping coefficient γ = 0.1; 0.2; 0.4 and 0.8. At low excitation frequencies, the displacement amplitudes take low values. Approaching the resonant frequency, displacements rapidly increase and their extreme values for η = 1 strongly depend on the damping coefficient. When the ratio η >> 1, the vibration amplitudes stabilize and equal 1.

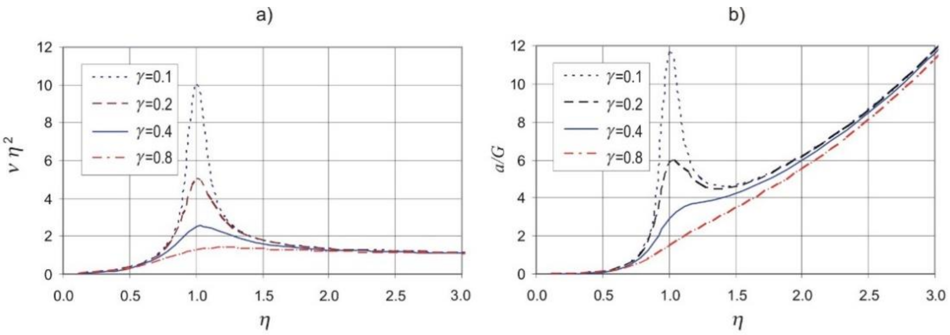

Fig. 3. Effect of damping coefficient γ on: a) a dimensionless amplitude of vibration $\nu\,\eta^2$, b) a dimensionless acceleration *a/G*, including the change in the frequency ratio η

Knowing the amplitude of displacements for each excitation frequency, it is possible to determine the acceleration amplitudes using equation (1.1) – Fig. 3b. The figure shows that at constant amplitudes of vibration, the accelerations increase with the square of excitation frequency. The figure demonstrates a significant impact of frequency ratio η and damping coefficient γ on accelerations experienced by the system. Assuming the curve obtained for considerable damping (γ = 0.8) as a referential one, it may be stated that in cases with lesser damping, resonance introduces a local disturbance into the curve shape, manifesting an increase in the acceleration dependant on the value of damping.

Fig. 3 presents the idea of the expected movements and accelerations of the oscillating system with one degree of freedom at four selected, constant values of damping, while increasing the frequency of excitation. The real system, i.e. the table top, is a rigid plate mounted on 4 springs and has 6 degrees of freedom. The resonant frequencies associated with the particular degrees of freedom complicate the above picture of vibrations and require laboratory examination of the individual components of displacements and accelerations.

3. CHARACTERISTICS OF THE SUBJECT OF RESEARCH AND THE MEASUREMENT EQUIPMENT

To study the sand compaction, a vibrating table used for standard determination of the consistency of concrete mix was adapted. The nominal amplitude of the table vibration is 0.5 mm, at an oscillation frequency of 50 Hz. The dimensions of the table top are as follows: length L = 39 cm, width B = 26 cm. The engine power is 0.1 kW.

The steel cylinder is 130 mm high, its diameter is 75 mm and the wall thickness is 2.15 mm. An additional base, in a form of a steel sheet, was welded to the underside of the cylinder, which allows attaching the cylinder to the vibrating table. The total mass of the cylinder with a soil sample is 4866 grams, which includes: the mass of the cylinder base (2726.4 g), the weight of the piston (534.7 g), the weight of cylinder fastening elements (1004.9 g) and the weight of the sand sample amounting 600 grams. The geotechnical characteristics of the tested sand are presented in [7].

To adjust the frequency of the forced oscillation, a frequency inverter was used, allowing the operation of the system in the range 0 ÷ 50 Hz, with increment of 0.02 Hz. The converter was plugged into the table's power line - see Fig. 2b. The study was conducted in the range of vibration frequency 15 to 50 Hz with increment of 1 Hz. However, at frequencies close to resonant ones, the increment was by 0.5 Hz.

Dynamic tests were performed with the use of a vibration gauge produced by Brüel & Kjær, equipped with an accelerometer with a load sensitivity of 10 pC/ms^{-2}, allowing one-direction measurements of displacements, velocities and accelerations. The gauge allows testing structures which oscillate at vibration frequencies from 0.3 Hz to 15 kHz. At frequencies from 0.3 Hz to 1 kHz, it is possible to measure the acceleration in the range of 0.001 ÷ 10 G. At frequencies from 10 Hz to 1 kHz, the resolution of displacement measurements is 0.001 mm. An oscilloscope, connected to a computer and allowing the observation of vibration waves in a graphical form, was attached to the vibration gauge.

Mass *m* rotating eccentrically in the *yz* plane (see Fig. 2b) generates vibrations of the table top with components in both directions (*y* and *z*). However, the method of attaching the table top allows the generation of linear and rotational displacements in all directions and planes. Linear displacements for each direction along the axes of the *xyz* system, shown in Fig. 2, are denoted as q_x, q_y, q_z. The rotations of the rigid table top in particular planes are denoted as θ_{xy}, θ_{xz} and θ_{yz}.
A rigid cylinder, containing the tested sand, was fastened to the vibrating table. Being subjected to vibration of the cylinder, individual sand grains experienced independent displacements and rotations which were impossible to be observed. Therefore, amplitudes of linear displacements of the geometric centre of the sand sample are treated as representative values of the measurements. The position of the sample centre depends on the state of sand compaction obtained at a given vibration frequency, after a nominal time of 12 minutes. Studies performed in [7], imply that the level of the geometric centre of the sample, measured along the vertical axis of the cylinder from the surface of the table, ranges from 51.8 mm, at a frequency of 50 Hz, to 59.3 mm, at a frequency of 15 Hz. For the measurements of the amplitudes of displacements, a constant, average height of the sample centre of h_c = 55 mm was assumed, Fig.4a.
Amplitudes of horizontal displacements of the sample centre were determined based on measurements made on the vertical wall of the cylinder. For example, Fig. 4a shows the position (h1) of the accelerometer which allows measurements of displacements caused by rotations in the *yz* plane and horizontal displacements of the plate in the *y* direction. The locations of all points at which amplitudes of horizontal displacements were measured are shown in Fig. 4b as rectangles with the letter h and a number.
Vertical displacements of the sample centre are equal to vertical displacements of the centre of the plate. Vertical displacements of any arbitrary point of the plate are conditioned by translation and rotation components of vibration. Due to the fact that the measured magnitudes are amplitudes of displacements, and not the displacements themselves, the measurements in the corners of the table top were not sufficient to determine the values of rotations, and thus to determine the vertical displacements of the centre of the plate. For example, Fig. 4c shows that even though the amplitudes of vertical displacements of points 1 and 3 are known, it is still impossible to state clearly whether the plate and the cylinder experience uniform vertical displacements (solid lines) or symmetric rotations (dashed lines).

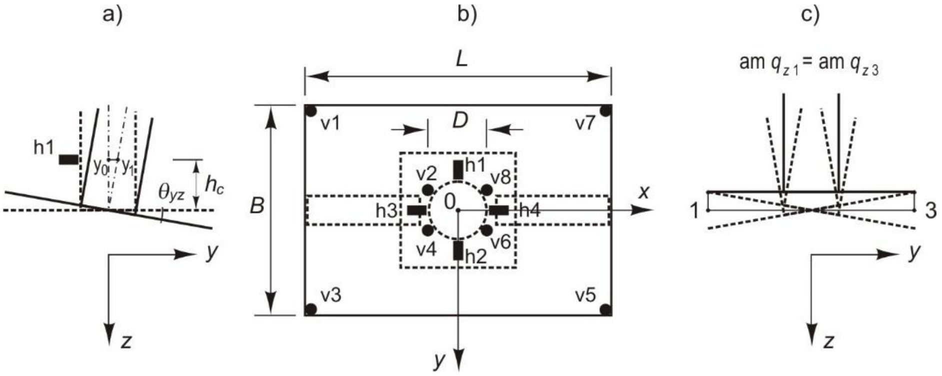

Fig. 4. Measurement of the amplitudes of the system displacements:
a) the position of the accelerometer to measure horizontal component q_y,
b) the location of the measurement points for vertical (v) and horizontal (h) components,
c) possible positions of the table top and the cylinder at symmetric rotations

The introduction of additional measurement points, in the vicinity of the cylinder, allowed the determination of the searched values. The arrangement of all measurement points, where amplitudes of vertical displacements were measured, is shown in Fig. 4b in the form of circles with the letter v and a number. In the case of tests of the table without a sample, the measurements were taken directly in the centre of the plate, instead of measurements performed in points: v2, v4, v6 and v8.

4. RESEARCH RESULTS AND ANALYSIS

The studies included vertical and horizontal vibrations as well as rotations of a vibrating table with a fastened sand sample and the table itself (without a sample), at various frequencies of excitations. At first, the tests were performed for a vibrating table with a sand sample. Fig. 5a and 5b show a waveform of vibration in time, vertical and horizontal respectively, at the frequency of 39 Hz. The curve is regular and has a sinusoidal waveform. Fig. 5c and 5d present the course of vertical and horizontal vibrations at the excitation frequency of 50 Hz. In this case, the sinusoidal course of vibrations is interfered by additional vibrations, which are especially distinct for horizontal oscillations (Fig. 5d). These disturbances are most probably caused by oscillations of a piston covering the sample. In several tests performed at this frequency, there were a few incidences that the piston fell out off the cylinder, despite immersing it two centimetres below the edge of the cylinder.

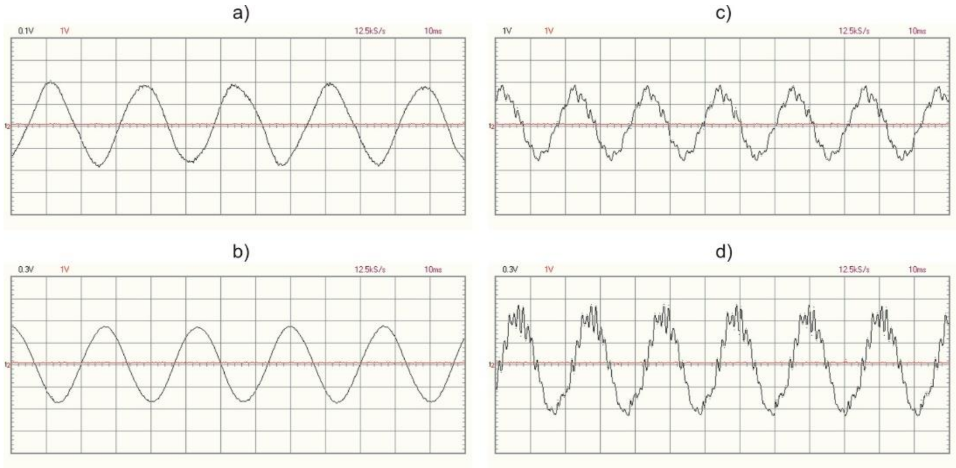

Fig. 5. Waveform of vibrations in time registered on the oscilloscope: a) vertical vibrations along axis z, at frequency f = 39 Hz, b) horizontal vibrations along axis y, at f = 39 Hz, c) vertical vibrations along axis z, at f = 50 Hz, d) horizontal vibrations along axis y, at f = 50 Hz

Fig. 6 shows the amplitude of the vertical displacements q_z of the centre of the table without a sample (dotted line) and with a sample (solid line), obtained at successive excitation frequencies. There are clear differences in the waveforms of both lines at frequencies above 40 Hz. The nominal amplitude of oscillations of the centre of an unloaded table at frequency of 50 Hz should be 0.5 mm. However, the measured value is higher and equals q_z = 0.55 mm. The vertical displacement of the centre of the table loaded with the sample is only 0.18 mm. The waveform, obtained for the table with the sample, shows that for the studied range of frequencies, the resonance occurs three times: at about 22 Hz, 31.5 Hz and 42.5 Hz. The vertical displacement q_z, at a frequency of 31.5 Hz did not reach high values, but the resonance phenomenon, accompanied by the movement of the vibrating table slipping on the lab floor, was clearly observed. In the case of the unloaded table, the resonance with large vibration amplitude (amounting to more than 1.3 mm) was observed at the frequency of 44 Hz.

All the subsequent test results refer to the table with a soil sample fixed to it. Fig. 7 shows the relationship between oscillation frequencies and the horizontal displacements of the sample in directions y and x. The figure shows that the horizontal displacements q_y are of the same order as the vertical displacement, as shown in the previous figure, and their fluctuation is lower. The maximum amplitude of displacement q_y occurs at the resonant frequency of 31.5 Hz and is less than 0.6 mm. However, horizontal displacements are much lower.

Only at frequencies 22.5, 30 and 50 Hz, they reach the values of the order of 0.1 mm.

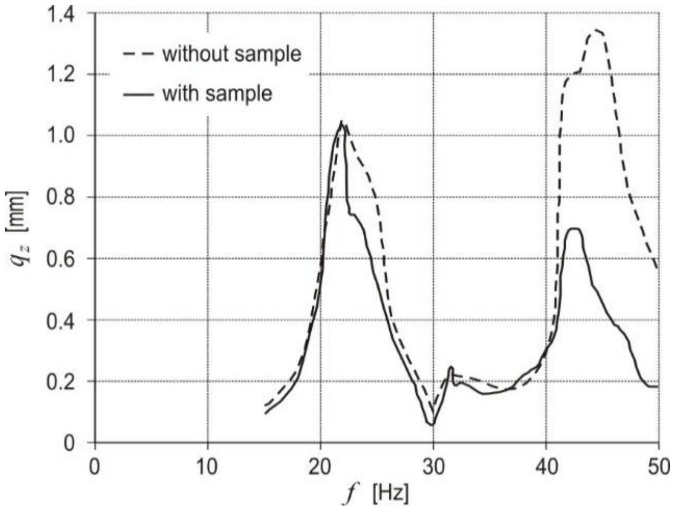

Fig. 6. The influence of the oscillation frequency on the amplitude of vertical displacements q_z of the centre of the table

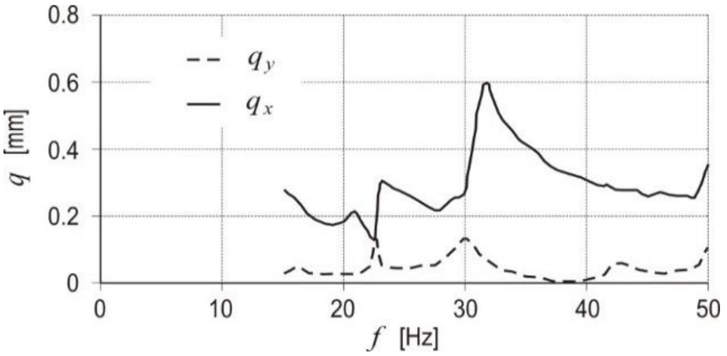

Fig. 7. The influence the oscillation frequency on the amplitudes of horizontal displacements q_x and q_y of the centre of the sample

On the basis of the measured vertical displacements, the rotations of the table top were determined. Significant rotations, of the order of 0.6º, are present in the *yz* plane at 50 Hz and at the resonant frequency of 31.5 Hz. At the resonance frequency of 22.5 Hz, the rotation is of the order of 0.1º. The envelopes of the peak values of vertical displacements of the plate in the *yz* plane at the resonant frequencies of 22.5 Hz and 31.5 Hz, are shown in Fig. 8. The figure indicates that oscillations at the frequency of 31.5 Hz are of a clearly rotational character.

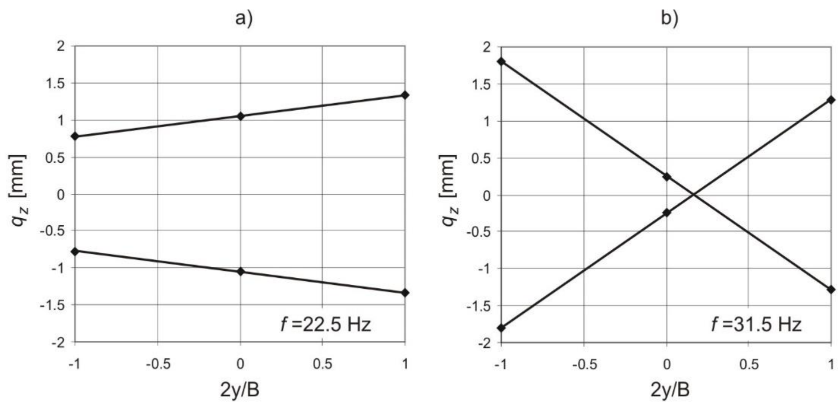

Fig. 8. Envelopes of peak values of vertical displacements of the table top in the *yz* plane at frequencies: a) 22.5 Hz, b) 31.5 Hz

Let us now proceed to the analysis of accelerations which accompany individual displacements of the system. Fig. 9a shows three curves, describing dimensionless accelerations of the centre of the soil sample (*G* - is the acceleration due to gravity). The first curve, with triangular markers, presents the values of vertical components a_z of accelerations of the sample. The second curve, a solid line without markers, shows the values of horizontal components a_y. The third curve, with square markers, shows the values of horizontal components a_x. A comparison of the curves implies that within the frequencies 28 ÷ 40 Hz and above 47 Hz, horizontal accelerations a_y are dominant. For other frequencies, components a_z take the highest values. Accelerations a_x are inconsiderable.

In view of the complexity of vibrations of the system, the resultant accelerations of the centre of the sample are shown in Fig. 9b. They were determined with formula $a = \sqrt{a_x^2 + a_y^2 + a_z^2}$. The resulting curve is rising, which is in line with the general tendency described in the analysis of the 1-D model, and its consecutive peaks are in the zones of resonance.

The curve refers to the centre of the sample, but can be considered as an averaged characteristic of acceleration of the whole sample, although the accelerations of the lower and upper parts of the sample may slightly deviate from the presented values, which is due to the rotation of the plate and the rigid cylinder. On the basis of the studies of density conducted in [7] and the study of the dynamic characteristics of a vibrating table, a relationship between a relative acceleration of the sample and the obtained volumetric density of sand after 12 minutes of vibration can be formulated. The appropriate relation is shown in Fig. 10. A triangular marker was used to indicate the results which were obtained for a stable compaction processes. Circular marker indicates the results obtained in unstable processes during which the compactness of sand alternately changed (from tightly to loosely compacted and vice versa). The layout of the triangles forms a strongly rising line (dotted line). This means that the greater acceleration of soil sample is, the higher value of density $\rho_{d\max}$ is obtained. This dependence is valid for the acceleration values up to 2.77 *G*. Starting from acceleration 3.75 *G*, the compaction process is unstable and the resulting density may depend on whether the end of the vibration falls on a phase dominated by compaction or loosening of the soil.

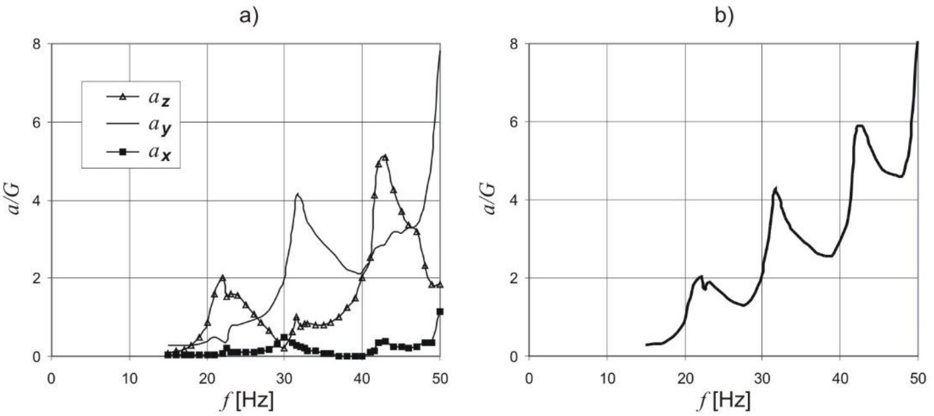

Fig. 9. Dimensionless accelerations of the soil sample at various oscillation frequencies: a) vertical components a_z and horizontal components a_y and a_x, b) resultant values

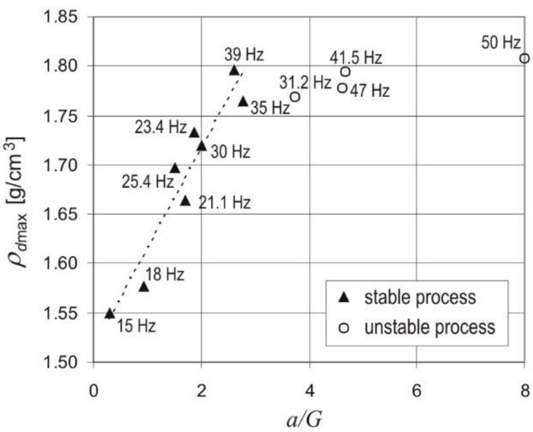

Fig. 10. The relationship between acceleration and bulk density of sand after 12 minutes of vibration (the number at points indicate the frequency of vibration)

5. CONCLUSIONS

On the basis of the carried out studies the following conclusions may be formulated:

- The dynamic parameters of the vibrating table with inertial excitation depend on the weight of the tested sample and the oscillation frequency of the system. This means that values of the amplitudes of displacements may be different from nominal values provided by manufacturers, and are conditioned by the change of the sample mass and the vibration frequency.
- Soil compaction on a table with inertial excitation can be an effective method to study density $\rho_{d\max}$ and can give repeatable results, provided that the table is appropriately adapted for testing. It is essential that the table is complemented with a frequency converter. By changing the excitation frequency, appropriate values of amplitudes of displacements and accelerations ensuring the effectiveness and repeatability of results can be obtained.
- For the table loaded with a sample, three resonant frequencies of about 22.5, 31.5 and 42.5 Hz were observed. Another resonant frequency occurs probably at more than 50 Hz. For the first resonant frequency, vertical displacement dominated. For the second - the rotations of the table plate around axis *x* were observed.
- Dominant components of the generalized displacements of the tested table with the cylinder are: vertical displacements and horizontal displacements in the direction of *y*-axis as well as rotations around *x*-axis. Horizontal displacements and rotations result in significant total horizontal displacements of the centre of the sample.
- Due to rotational vibrations of the table plate, it is very important to fix the sample at the same place of the table. The sample attached in different locations experiences different accelerations.
- The main factor that conditions the efficiency of sand compaction on a vibrating table are the accelerations which the sample is subjected to (see Fig. 10).
- Greater acceleration values enable obtaining higher density $\rho_{d\max}$ of sand. The dependence is valid only up to a certain boundary value of acceleration. In the case of this study, carried out for acceleration values below 2.77 *G*, the compaction process was stable and then the increase of the vibration time resulted in higher density. Subjecting a soil sample to vibrations with accelerations greater than the limit (in this case more than 3.75 *G*) caused alternating compaction and loosening of the soil, and thus the obtained result of $\rho_{d\max}$ was dependant on the phase which dominated at the time of completion of vibration.

REFERENCES

1. ASTM D 4253 – 00: *Standard test methods for maximum index density and unit weight of soils using a vibratory table*, West Conshohocken, American Society for Testing and Materials 2000.
2. Brand E.W.: *Some observations on the control of density by vibration*, in: Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils, Baltimore, ASTM STP523 1973, 121-132.
3. Cumberledge G., Cominsky R.J.: *Maximum density determination of subbase materials*, in: Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils, Baltimore, ASTM STP523 1973, 141-155.
4. Dobry R., Whitman R.V.: *Compaction of sand on a vertically vibrating table*, in: Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils, Baltimore, ASTM STP523 1973, 156-170.
5. Langer J.: *Dynamics of building structures*, Wrocław, Wydawnictwo Politechniki Wrocławskiej 1980 (in Polish).
6. PN-88/B-04481: *Engineering soil. Testing of soil samples*, Warszawa, Polski Komitet Normalizacyjny 1988 (in Polish).
7. Szajna W.St., Lechocka P.: *Evaluation of tapping fork and vibrating table methods used for testing dry density of sand*, Roads and Bridges, 15 (2016) 5-20.

WPŁYW PRZYSPIESZENIA NA EFEKTYWNOŚĆ ZAGĘSZCZANIA PIASKU NA STOLE WIBRACYJNYM

Streszczenie

Wibrowanie jest skuteczną metodą zagęszczania gruntów gruboziarnistych, stąd stoły wibracyjne wykorzystywanie są w niektórych krajach do wyznaczania maksymalnej gęstości objętościowej szkieletu gruntowego $\rho_{d\max}$ tych materiałów. Przyspieszenie, którym poddawany jest grunt jest jednym z podstawowych parametrów skutecznego zagęszczania. W pracy przedstawiono możliwość przystosowania standardowego stołu wibracyjnego, wykorzystywanego do badań konsystencji mieszanki betonowej, do wyznaczania gęstości $\rho_{d\max}$ piasku. Stół o wymuszeniu bezwładnościowym został uzupełniony o przetwornik częstotliwości i poddany badaniom dynamicznym. W artykule zamieszczono wyniki pomiarów parametrów dynamicznych stołu. Wibrujący blat stołu oprócz przemieszczeń pionowych doznaje także innych form drgań. Przemieszczenia poziome i obroty skutkują znacznymi sumarycznymi przemieszczeniami poziomymi próbki. W układzie obciążonym próbką stwierdzono trzy częstotliwości rezonansowe. W wyniku badań zaobserwowano w przybliżeniu liniową zależność pomiędzy przyspieszeniem, któremu poddawana jest próbka a gęstością $\rho_{d\max}$. Przy większych przyspieszeniach uzyskuje się większe gęstości, jednakże zależność taka obowiązuje tylko do pewnej granicznej wartości przyspieszenia, powyżej której proces staje się niestabilny.

Słowa kluczowe: zagęszczanie piasku, stół wibracyjny, pomiary drgań mechanicznych, zależność gęstość - przyspieszenie

Editor received the manuscript: 14.11.2016