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Preparation of the non-cohesive soil sample and calibration of the pneumatical launcher in the dynamic soil test SHPB

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Abstract

The paper analyzes the problem of initial compaction of a non-cohesive soil sample on the example of dry silty sand samples. Two different compaction methodologies were used: I) dynamic compaction - using split Hopkinson pressure bar and II) vibration compaction - using a vibrating shaker. A better result of the compaction process was obtained for dynamic compaction with an initial pressure value of 0.5 bar (small difference in the result - both methods obtained comparable results). The paper also includes a numerical analysis of the calibration of the pneumatic launcher in the Matlab environment on the basis of the system of difference equations. The calibration process was carried out in the initial pressure range from 0.5 to 3.0 bar for three different variants of the bar-projectile length: 100 mm, 200 mm and 250 mm and compared with the experimental analysis - the results were consistent.

Keywords: sample preparation, non-cohesive soil, launcher calibration, soil dynamic testing, split Hopkinson pressure bar

1 Introduction

Research using the Split Hopkinson Pressure Bar (SHPB) test stand allows to learn about the dynamic characteristics of various materials used in construction, including steel, concrete, soil (cohesive and non-cohesive). In this paper, selected aspects of dynamic tests on non-cohesive soil samples are analyzed. Determining the dynamic characteristics of the soil is important in the area of protection of objects of high importance or critical infrastructure [1, 2]. This type of objects usually has a soil layer designed as an additional protective layer or a protective embankment - in a crisis situation the soil may be subjected to a dynamic load as a result of, for example, a shock wave caused by an explosive charge [6]. The publication [9] shows the use of tests based on the SHPB test stand to determine the dynamic characteristics of the soil - non-cohesive soil used as an additional protective layer of the temporary shelter. The effect of the combined phenomenon of a sharp increase in shock wave pressure and smooth relief is defined as a blast wave. Fig. 1 shows the Mach wave propagation scheme (it is a blast wave with a smoothed and uniform course). The Mach wave, according to the definition, is the resultant of an incident and reflected waves with almost even distribution [3].

The temporary shelters (ad hoc type) in their construction have an open casing. In order to increase the level of protection, additional sand covering was used. The role and significance of soil covering were indicated and included in the analysis of prefabricated structure proposals for the protection of critical infrastructure objects in the publication [7].

Proper preparation of the sample and SHPB test equipment is essential prior to testing. The reviews of the SHPB stand layouts together with the marked components and the soil samples used are presented in publications [4, 5, 8].

The aim of this paper is to show the methodology of two different variants of the preliminary preparation of a non-cohesive soil sample for dynamic tests and to perform the numerical and experimental calibration process of the

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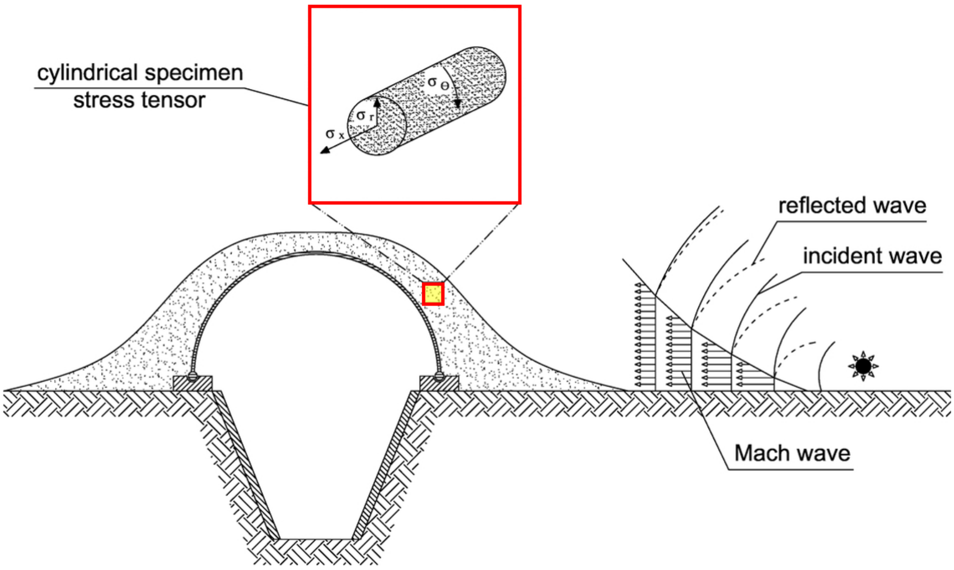

Figure 1. An example of a temporary shelter (ad hoc type) with the Mach wave marked and sand covering specimen with red marked (reprinted from [9]).

pneumatic launcher as an important component of the SHPB test stand.

2 Methodology of preliminary soil sample compaction

In the process of preparing a non-cohesive soil sample for dynamic testing with the use of a split Hopkinson bar, it is important to ensure the initial state of soil compaction. This is an especially important step in the preparation process for dry samples with a low moisture content. Such a sample is in a two-phase or three-phase state - it has a gas phase (most often in the form of air). Failure to carry out the compaction process will result in incorrect results of the experiment - part of the bar-projectile impact energy will be used to thicken the air voids. The authors of the publication analyzed various methods of compaction of the same soil sample on the example of 6.5 g of silty sand (detailed characteristics of the type of soil used and other tests of this soil are shown in the publication [8]):

I. Dynamic compaction (using SHPB)

The compaction of the sample is carried out on the same SHPB test stand, which is then used to conduct the experiment. The tests are carried out for various variants of the bar-projectile velocity as a result of the initial pressure work from the pneumatic launcher (e.g. 2 bar, 3 bar, 5 bar). On the SHPB test stand used by the authors of the publication for the current design of the pneumatic launcher, for technical reasons (including friction in the barrel), it is possible to initiate a bar-projectile movement with a minimum pressure value of 0,50 bar (Fig. 2).

For this pressure value, an analysis of the initial compaction of the soil sample as a result of a bar-projectile impact was carried out, presented in Table 1.

The advantage of this compaction methodology is the use of the same equipment, which is later used to conduct the experiment - there is no need to use additional measuring equipment. On the other hand, the disadvantage is the process of dynamic impact on the samples - the initial pressure from the pneumatic launcher to the strike with the bar-projectile is several times lower than during the experiment, but there is still a dynamic impact causing a small phenomenon of damage to the soil skeleton of the sample.

II. Vibration compaction (using a vibration shaker)

The sample is compacted on a vibrating shaker. The soil is compacted by vibrating the shaker for 60 seconds. During the tests, the time of 60 seconds was selected as sufficient - the vibration process for a longer time of 120 seconds and 180 seconds did not cause a significant increase in the soil compaction value. A weight of about 1000 g is placed on the sample in order to improve the vibrating effect. During the operation of the shaker, the air voids are filled with the moving soil grains - the process of compaction takes place.

Figure 2. The value of the pressure given by the pneumatic launcher for the shot - initial compaction of the soil sample

Table 1. Analysis of the initial compaction of a soil sample as a result of a bar-projectile impact.

	Experiment trial number 1	Experiment trial number 2	Experiment trial number 3	Average value
Sample mass m_0 $[g]$	6.50	6.50	6.50	6.50
Sample length before the shot L_0 $[mm]$	11.68	11.91	11.60	11.73
Bulk density of the soil before the shot ρ_0 $\left[\frac{g}{cm^3}\right]$	1.75	1.72	1.77	1.75
Shot pressure $p[bar]$	0.50	0.50	0.50	0.50
Bar-projectile speed v_0 $\left[\frac{m}{s}\right]$	6.54	6.46	6.78	6.59
Sample length after the shot L_1 $[mm]$	10.36	10.43	10.46	10.42
Difference in sample length ΔL $[mm]$	1.32	1.48	1.14	1.31
Bulk density of the soil after the shot ρ_1 $\left[\frac{g}{cm^3}\right]$	1.98	1.97	1.96	1.97
Difference in sample bulk density $\Delta\rho$	0.22	0.24	0.19	0.22

The methodology of compaction of a dry non-cohesive soil sample consists of following stages:

- unscrew all securing screws / bolts in the rigid casing (Fig. 3a)
- place one side of the cap over the narrower part of the black stopper, to the end of the stopper (Fig. 3b);
- insert the spacer I inside so that it adheres to the surface of the black stopper - check that the spacer reaches the end of the free space and sticks to the black stopper by e.g. tapping the spacer I with a hammer handle (Fig. 3c);

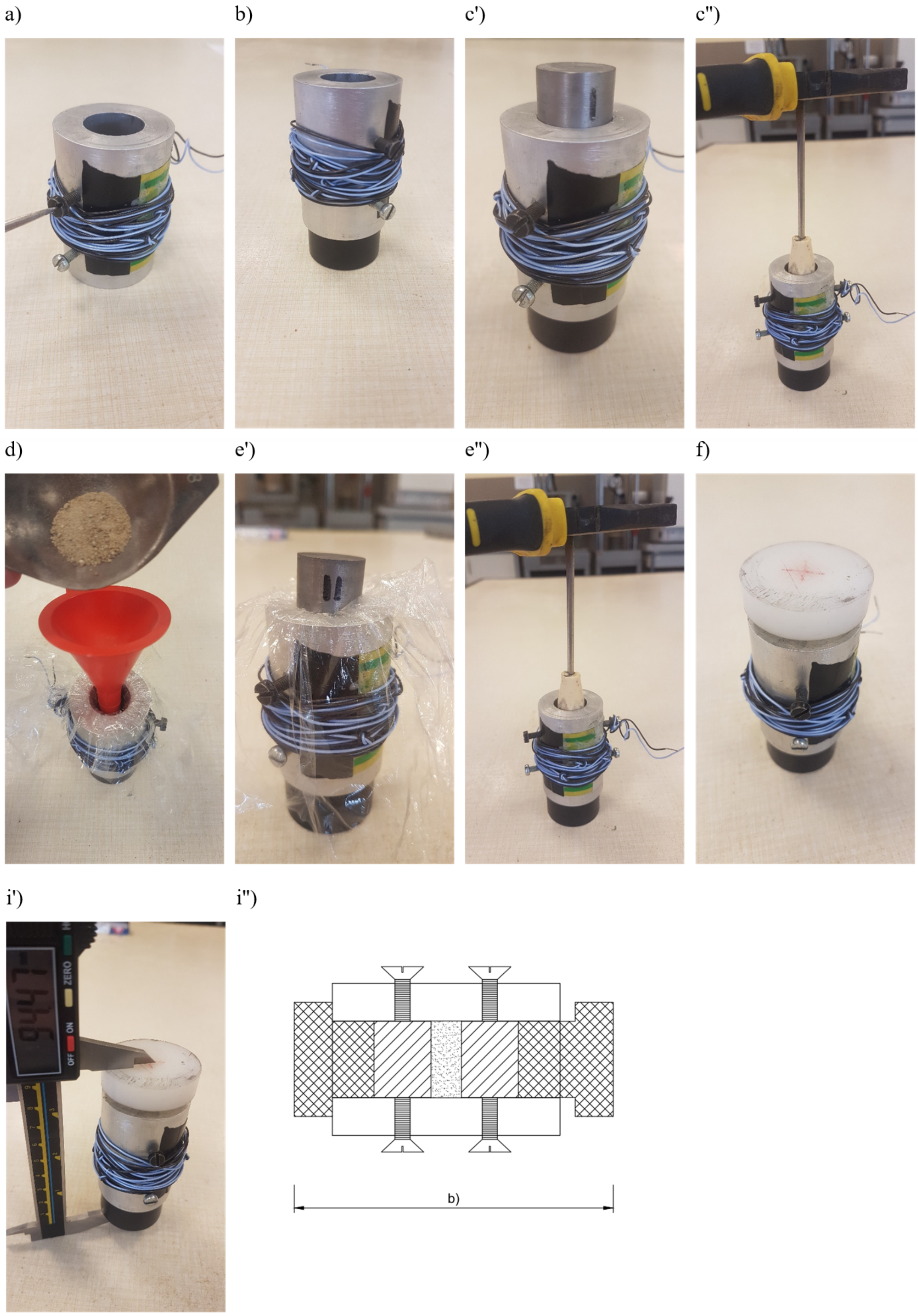

Figure 3. Following stages of the methodology of the vibratory compaction of the soil sample.

- tighten the screws / bolts that immobilize spacer I;
- place the soil sample into the foil-protected space of the casing and gently spread the sample to the sides of the rigid casing (Fig. 3d);

- insert spacer II inside so that it adheres to the sample surface - check that the spacer has reached the end of the free space and sticks to the sample by e.g. tapping the spacer II with a hammer handle (Fig. 3e);
- insert the white stopper with the narrow part into the rigid casing hole (Fig. 3f);
- measure the length a - the length between the outer edges of the black stopper and the white stopper - before the compaction process (Fig. 3g);
- put a metal weight on the white stopper - additional load approx. 1000 g (Fig. 3h);
- switch on the shaker for 60 seconds and at the same time protect the set against tipping over as a result of shocks;
- after switching off the shaker, remove the metal weight;
- tighten the screws / bolts that immobilize spacer II;
- measure the length b - the length between the outer edges of the black stopper and the white stopper - after the compaction process Fig. 3i);
- remove the white and black stopper - the sample in rigid casing is ready for testing with the Hopkinson bar (immediately before the test, unscrew the four screws / bolts to allow the movement of spacer I and II).

The analysis of the initial compaction of the soil sample as a result of the operation of the vibrating shaker, presented in Table 2, was carried out.

Table 2. Analysis of the initial compaction of a soil sample as a result of the operation of a vibrating shaker.

	Experiment trial number 1	Experiment trial number 2	Experiment trial number 3	Average value
Sample mass m_0 $[g]$	6.50	6.50	6.50	6.50
Sample length before vibration L_0 $[mm]$	11.88	11.49	11.78	11.72
Bulk density of the soil before vibration ρ_0 $\left[\frac{g}{cm^3}\right]$	1.73	1.78	1.74	1.75
Vibration time t [s]	60.00	60.00	60.00	60.00
Sample length after vibration L_1 $[mm]$	10.68	10.30	10.61	10.53
Difference in sample length ΔL $[mm]$	1.20	1.19	1.17	1.19
Bulk density of the soil after vibration ρ_1 $\left[\frac{g}{cm^3}\right]$	1.92	1.99	1.93	1.95
Difference in sample bulk density $\Delta\rho$	0.19	0.21	0.19	0.20

3 Mathematical model of the pneumatic launcher shot phenomenon for a system with impulse power supply

The system under consideration is supplied with air with known parameters at the initial moment. The known parameters are pressure, temperature and air volume. The entire shooting process is based on the adiabatic expansion of the air [12]. Air was assumed to be an ideal gas and it is possible to make some simplifications in the calculations. The gas temperature is relatively low below 100^oC so there is no need to consider the change in specific heat at constant pressure $c_p$and volume c_v as a function of temperature. It is possible to use averaged values of these parameters.

The shooting process with a constant gas load can be divided into three periods:

a) In the first period, the pre-chamber is filled to pressure with light gas p_1 and temperature T_1 (Fig. 5).

b) After reaching the expected value of air pressure in the pre-chamber, the equipment operator initiates the shot. From that moment on, the second period is analyzed (Fig. 6). There is a very short moment, and it lasts until the bar-projectile begins to move as a result of the opening of the gas flow from the pre-chamber to the projectile chamber.

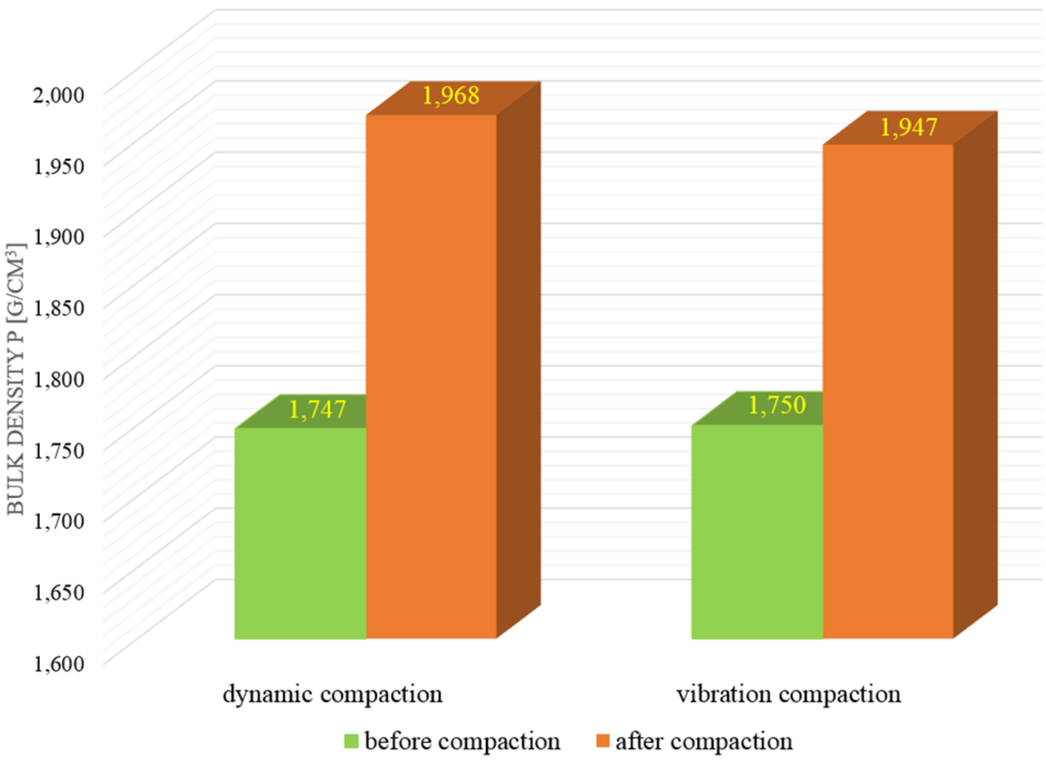

Figure 4. shows a comparison of the results of the analysis of preliminary compaction of a non-cohesive soil sample on the example of dry silty sand for the variant: I) dynamic compaction (with the use of SHPB) and II) vibration compaction (with the use of a vibration shaker).

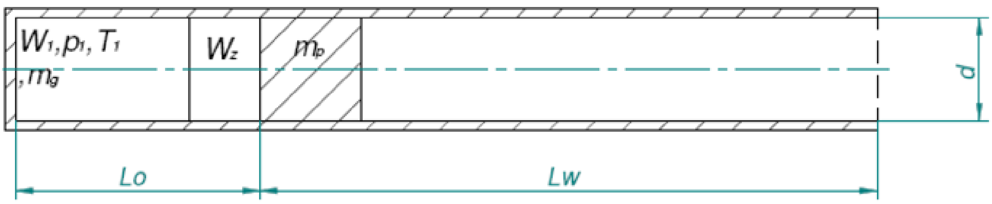

Figure 5. Physical model of the launcher system before turning the compressed air lever - first period of the shot process.

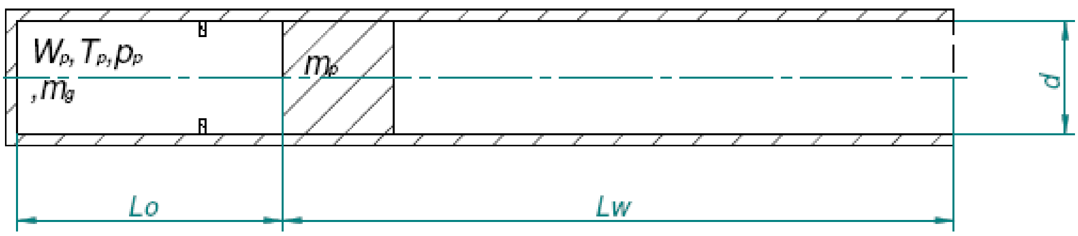

Figure 6. Physical model of the launcher system after opening of the gas flow from the pre-chamber to the projectile chamber – second period of the shot process.

Air parameters in volume $W_0 = W_1 + W_2$ are possible to calculate from the adiabatic equation:

$$p_0 = p_1 \cdot \left(\frac{W_1}{W_0}\right) \tag{1}$$

$$T_0 = T_1 \cdot \left(\frac{W_1}{W_0}\right) \tag{2}$$

These parameters describe the state of the air at the beginning of the bar-projectile movement. Therefore, they can be considered as initial values that are adopted for the calculations of the bar-projectile and the thermodynamic parameters of the gas during the shot.

c) The third period lasts from the moment the bar-projectile begins to move until it exits the barrel (Fig. 7).

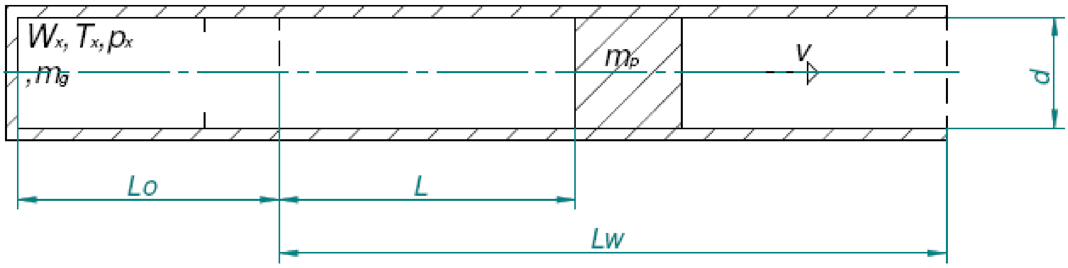

Figure 7. Physical model of the launcher system during the movement of the bar-projectile– third period of the shot process.

The basic equation of the mathematical model of the shot is the energy balance, resulting from the first law of thermodynamics:

$$dQ = dU + dL \tag{3}$$

where:

Q - energy supplied to the system;

U - internal energy of light gases;

L - work done on bar-projectile acceleration.

The relevant equations in this process can be expressed as:

- heat (energy) supplied to the system:

$$Q = c_v \cdot m_g \cdot (T_0 - T_n) \tag{4}$$

- internal energy of gas

$$Q = c_v \cdot m_g \cdot (T - T_n) \tag{5}$$

- external gas operation:

$$L = \varphi \cdot m_p \cdot \frac{v^2}{2} \tag{6}$$

where:

T - current temperature value;

T_0 - initial temperature value;

T_n - reference temperature;

m_p - mass of the bar-projectile;

m_g - air mass;

v - bar-projectile speed;

φ - secondary work factor [11] calculated from the equation:

$$\varphi = K + \frac{1}{3} \cdot \frac{m_g}{m_p} \tag{7}$$

for the case under discussion $K = 1$

Taking into account the above energy balance can be written as:

$$c_v \cdot m_g \cdot (T_0 - T_n) = c_v \cdot m_g \cdot (T - T_n) + \varphi \cdot m_p \cdot \frac{v^2}{2} \tag{8}$$

By transforming this equation with respect to temperature T:

$$\begin{aligned} c_v \cdot m_g \cdot (T_0 - T_n) &= \varphi \cdot m_p \cdot \frac{v^2}{2} \\ T_0 - T &= \frac{\varphi \cdot m_p}{c_v \cdot m_g} \cdot \frac{v^2}{2} \\ T &= T_0 - \frac{\varphi \cdot m_p}{c_v \cdot m_g} \cdot \frac{v^2}{2} \end{aligned} \tag{9}$$

Further transformations with respect to pressure to the next form of the above equation:

$$\begin{aligned} R \cdot T &= R \cdot T_0 - \frac{\theta \cdot \varphi \cdot m_p}{m_g} \cdot \frac{v^2}{2} \\ m_g \cdot R \cdot T &= m_g \cdot R \cdot T_0 - \theta \cdot \varphi \cdot m_p \cdot \frac{v^2}{2} \end{aligned} \tag{10}$$

From the Clapeyron equation:

$$p \cdot W = m \cdot R \cdot T \tag{11}$$

By using this relationship, equality is created:

$$p = \frac{m_g \cdot R \cdot T_0 - \theta \cdot \varphi \cdot m_p \cdot \frac{v^2}{2}}{W} \tag{12}$$

where:

$W = W_0 + dL$ - current volume value;

θ - ratio, $\theta = K - 1$.

The remaining equations of the mathematical model are related to the dynamics of the bar-projectile motion:

- equation of motion resulting from the second law of dynamics:

$$\frac{dv}{dt} = \frac{p \cdot s}{\varphi \cdot m} \tag{13}$$

- speed equation:

$$\frac{dL}{dt} = V \tag{14}$$

Equations (12) - (14) allow to describe the shot process a pneumatic gas system with a constant mass of gas introduced into the system.

4 Comparison of the numerical and experimental characteristics of the work of the pneumatic launcher

The mathematical model presented in the previous chapter was used to develop the performance characteristics of the pneumatic launcher included in the split Hopkinson bar test stand (shown in Fig. 8), which is located at the Department of Military Engineering and Infrastructure (Military University of Technology in Warsaw).

Figure 8. View of the pneumatic launcher (purple marking) as an important element of the SHPB test stand.

Table 3. Summary of the characteristics of bar-projectiles

	Bar-projectile		
	Type 1	Type 2	Type 3
Length [mm]	99.10	199.40	249.80
Weight [g]	234.91	353.72	491.04
Diameter [mm]	19.92	19.97	19.96
Material	Steel C350		
Youngs modulus E [GPa]	200		
Wave propagation velocity c_0 $\left[\frac{m}{s}\right]$	5000		

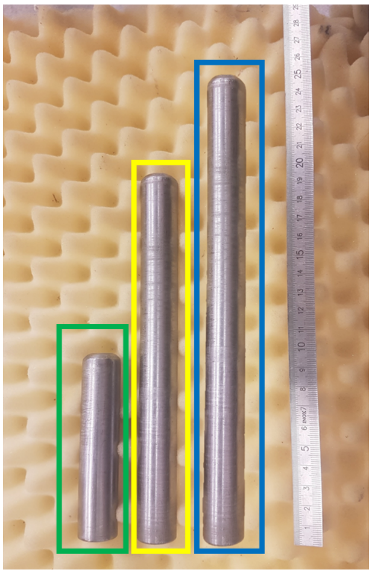

Figure 9. Bar-projectiles used for the analysis - 100 mm (green marking), 200 mm (yellow mark), 250 mm (blue mark)

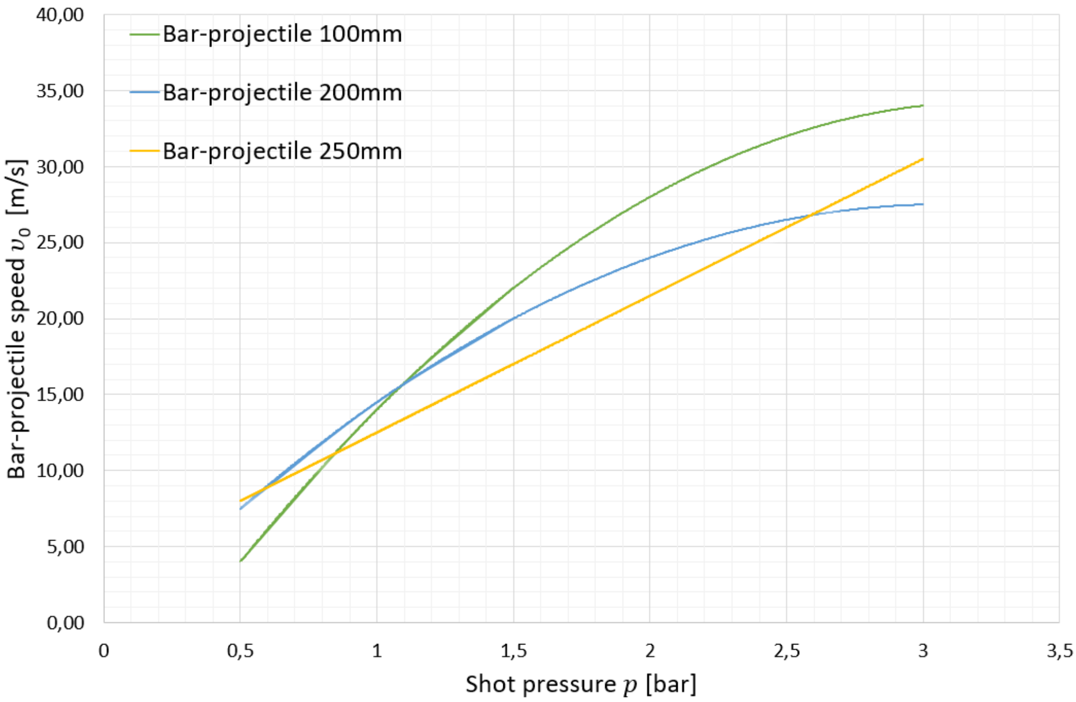

Figure 10. Characteristics of the velocity change at the moment of the bar-projectile impact $v_0$as a function of the initial supply pressure p.

The presented launcher is powered by compressed air with a maximum pressure of 8 bar. The launcher throws bar-projectile of various dimensions - their length is variable and depends on the conditions of the experiment that is carried out on the split Hopkinson bar stand. In the analyzed study, the pneumatic system was used to throw bar-projectile of the following lengths: 100, 200 and 250 mm (Fig. 9). The detailed parameters of these bar-projectile are shown in Table 3.

For all types of bar-projectiles (1, 2 and 3 type), the characteristics of the impact velocity change as a function of the supply pressure were determined. The analysis was carried out in terms of the initial pressure p from 0,5 to 3,0 bar. The results of these analyzes are shown in Fig. 10. The presented characteristic is the result of numerical calculations made in the Matlab environment on the basis of a system of differential equations developed on the basis

a) b) c)

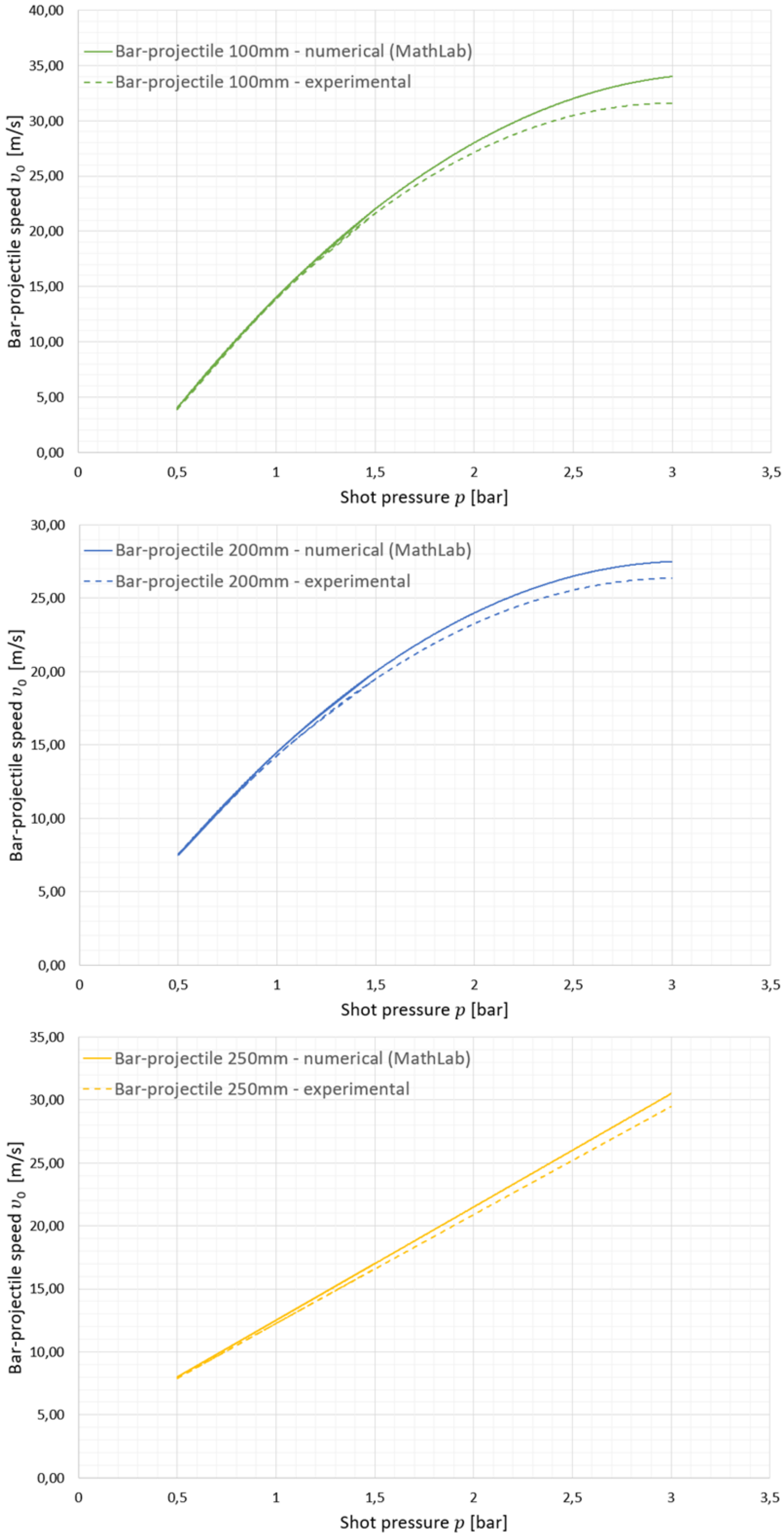

Figure 11. Comparison of the experimental and numerical results in the form of graphs for bar-projectiles: a) 100 mm, b) 200 mm and c) 250 mm.

of the equations: gas state in the battle space (equation 12) and motion (equation 13 and 14).

The publication [10] analyzes the characteristics of the impact velocity change as a function of the supply pressure on the basis of the conducted physical experiment for the same bar-projectiles. A comparison of the experimental and numerical results was made in the form of graphs for bar-projectiles: 100 mm - Fig. 11a), 200 mm - Fig. 11b) and 250 mm - Fig. 11c). There is a visible convergence of results between the numerical analysis in Matlab environment and the physical experiment for each bar-projectile case.

5 Conclusions

The paper analyzes the issue of initial compaction of a non-cohesive soil sample. For this purpose, samples of dry silty sand were used. Dry sand has two phases - a solid phase and a gas phase (air). In the two-phase model variant, the influence of the initial compaction process is particularly visible - the air voids are densified and the value of the soil volumetric density increases. Two different compaction methodologies were used for the analysis: I) dynamic compaction (using SHPB) and II) vibration compaction (using a vibrating shaker). A better result of the compaction process was obtained for dynamic compaction (small difference in the result - both methods obtained comparable results). The advantage of this method is the use of the same station in the compaction process, which is then used to conduct the experiment. The key issue is to select the lowest possible value of the initial pressure from the pneumatic launcher to accelerate the bar-projectile. In the analysis, the value of the initial pressure was 0.5 bar - at lower pressure values, the bar-projectile did not hit the soil sample due to the low speed and friction of the bar-projectile side against the inner wall of the barrel. It is necessary to select the lowest possible initial pressure - too high a pressure value will cause the bar-projectile to hit the sample at high speed and destroy the soil skeleton of the sample (the purpose of the impact should be the compaction process with the least possible damage to the skeleton). Additionally, a detailed methodology of the vibration compaction process (with the use of a vibration shaker) was shown, along with a description and photographs of the following stages.

The paper also includes a numerical analysis of the calibration of the pneumatic launcher, which is a component of the SHPB test stand. Calibration calculations were performed in the Matlab environment on the basis of the system of difference equations. The analysis was carried out in the range of the initial pressure from 0.5 to 3.0 bar for three different variants of the bar-projectile length: 100 mm, 200 mm and 250 mm. The result of the numerical analysis was compiled for comparison with the experimental analysis (previously published in another paper). The numerical and experimental characteristics of the pneumatic launcher obtained a high agreement of the results.

References

1. Baryłka, A. Zagadnienie zdatności obiektów budowlanych do użytkowania w problematyce inżynierii bezpieczeństwa tych obiektów. *Inżynieria Bezpieczeństwa Obiektów Antropogenicznych* **4** (2019).
2. Baryłka, A. & Bąk, G. Wpływ pożaru zewnętrznego na wytężenie obudowy schronu wykopowego. *Inżynieria Bezpieczeństwa Obiektów Antropogenicznych* **3-4** (2018).
3. Chmielewski, R., Kruszka, L., Rekucki, R. & Sobczyk, K. Experimental Investigation of Dynamic Behavior of Silty Sand. *Archives of Civil Engineering* **LXVII,** 481–498 (1 2021).
4. Mishra, S., Chakraborty, T. & Basu, D. High Strain Rate Stress-Strain Response of Soils—A Review. *Japanese Geotechnical Society Special Publication* **3,** 80–85 (2015).
5. Omidvar, M., Iskander, M. & Bless, S. Stress-strain behavior of sand at high strain rates. *International Journal of Impact Engineering* **49,** 192–213 (2012).
6. Papliński, A. Assessment of threat arising by closed – volume explosions of fuel-air mixtures. *Safety Engineering of Anthropogenic Objects* **4** (2021).
7. Sobczyk, K., Chmielewski, R. & Duda, K. The concept of a prefabricated structure for protection of critical infrastructure facilities. *Biuletyn WAT* **LXII,** 173–196 (2 2018).
8. Sobczyk, K., Chmielewski, R., Kruszka, L. & Rekucki, R. Strength Characterization of Soils' Properties at High Strain Rates Using the Hopkinson Technique - A Review of Experimental Testing. *Materials* **15,** 274 (1 2022).
9. Sobczyk, K., Chmilewski, R. & Kruszka, L. The Concept Of Experimental Research On The Behavior Of Sand Cover Material For Protective Shelters For Civilians. *Safety Engineering of Anthropogenic Objects* **1** (2020).
10. Sobczyk, K., Kruszka, L., Chmielewski, R. & Rekucki, R. Performance characteristics of Hopkinson's set-up pneumatic launcher. *Acta Polytechnica* **61,** 552–561 (2021).
11. Torecki, S. *Balistyka wewnętrzna* (Wydawnictwo WAT, Warszawa, 1980).
12. Wiśniewski, S. *Termodynamika Techniczna* (Wydawnictwo Naukowo-Techniczne, Warszawa, 1980).