# Dissemination of Weak Waves in Granular Materials Under Short-Term Impulse Loads

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**Abstract.** The results of experiments with dry high-silica sand are presented. Multiple point impacts have been revealed to improve waveguide properties of the material because a conductive channel, containing force "chains", is formed there. Quasistatic alternating shears condition the change in the particle packing; destroy "chains", and deteriorate the channel conductivity. Further multiple impulse loads lead to restoration of the "chains" and conductivity of the channel.

## Introduction

One of the main properties of powder, granular and granulated materials is multiplicity of their forms of equilibrium, i.e. similar boundary conditions are met by diverse disseminations of inner stresses. It is possible because conditions on the contacts between particles are in form of inequalities. That is why the behavior of material is generally nonlinear and nonholonomic, i. d. the response of material to outward loads can essentially depend on the whole antecedent history of its deformation.

Let us consider this property on the example of wave dissemination in granular materials. The experiments were carried out in dry high-silica sand; the average grain was ~0.3 mm.

## 1. Methods of experiments

The first difficulty arising when carrying out experiments is to get quite homogenous samples of granular materials. Here, to avoid data scattering samples are to be almost identical in all experiments. To get homogenous packing we used a movable case of a uniform shear machine [1]. As the material is filled up in the case initial particle packing has a number of defects, vacancies, arches, dislocations etc. If the sample is subjected to the cyclic alternating shear, dry friction among the particles is replaced by the pseudo-viscous one and a lot of defects are eliminated. Quite homogenous closed packing is formed; its properties are stable in all the experiments.

The uniform shear machine (Figure 1) consists of a case with three movable and one fixed side walls and a square bottom with the side of 250 mm, transforming into a parallelogram under the shear. Under the cyclic shear parameters of the packing get stabilized within the first dozens of cycles. For the purpose of experiments the samples were deformed within 30 cycles with the range of shear angle

±1.5 degree. As the state close to the stationary one had been attained, cyclic deformation was stopped.

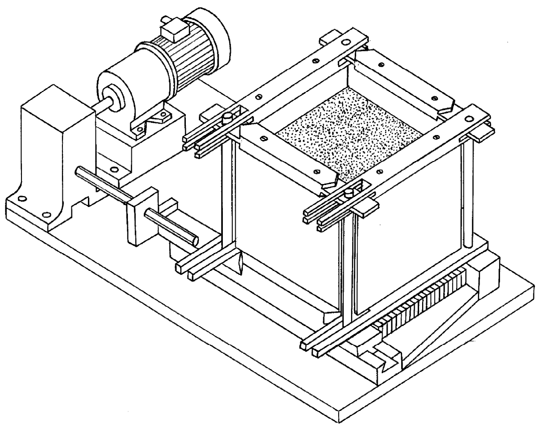

**Figure 1**. The overview of the uniform shear case

The single point impact of the physical pendulum calibrated against energy and located on the vibroplatform, which was on the fixed wall of the case and submerged into the granular material generated the wave in the material (not shown in Figure 1). The length of the pendulum was 300 mm; a steel ball was 35 g. Impact energy (E) was calculated according to the deflection angle from the equilibrium and amounted to 0.175; 0.350; 1.40; 2.45; 3.50; 4.55 $J{\cdot}10^{-3}$ in experiments.

Impulses of acceleration were measured by two accelerometers. Accelerometer 1 was stationary fixed on the vibroplatform (it generated the initial reference impulse). Accelerometer 2 was placed in the granular material in front of the vibroplatform and at a particular distance from it. The axis of sensor sensibility was oriented towards the dissemination of longitudinal waves in the sample (in the direction of impact). Impulses of acceleration were registered by digital oscillograph Agilent 1000 Series. The oscillograph triggering was performed from the front of the reference impulse. Processing of signals involved assessment of the change in their parameters as soon as they had passed through the granular material with respect to the distance length and impact energy. The mean speed of wave dissemination was calculated according to the time of pulse delay.

## 2. The results of experiments

Figure 2 *a* outlines the impulse acceleration registered by accelerometer 1, a and Figure 2 *b* impulses registered by accelerometer 2, the number of impacts was growing (numbers of impacts are given under oscillograms).

While passing from the reference impulse (Figure 2 *a*) to the first impulse one can see in Figure 2 *b*, that its amplitude is decreased by 1200 times and its duration is grown by 8 folds as compared with the initiating pulse. Comparing curves 1 – 19 one can conclude that impulses are transformed, as well as their forms, amplitudes and duration (the time of impulse passing $\Delta t$ through the granular material (delay time) is shown along the x-coordinate axis).

To explain the effect let us consider the results of the study on micro-mechanism of granulated material deformation. Paper [2] presents photoelastic analysis of stresses and deformations in conditions of uniform shear in photosensitive broken glass simulating a granular material. Papers [2, 3] point at formation of force chains with maximal contact stresses along them in the material. New additional force contacts are generated if outward load is growing due to micro-rotations and displacement of particles. Therefore, the load-carrying capacity of the structure gets improved. As the result of further increase in loads the generated structure gets destroyed, the resistance of material is deteriorated; and stresses are relieved. The results of study on the sliding behavior under the edge shear of a crack filled with granular material are presented in papers [4, 5] in view of the mechanism of force chains. Advancing and transformation of acoustic waves in high-silica sand are studied in [6, 7, 8].

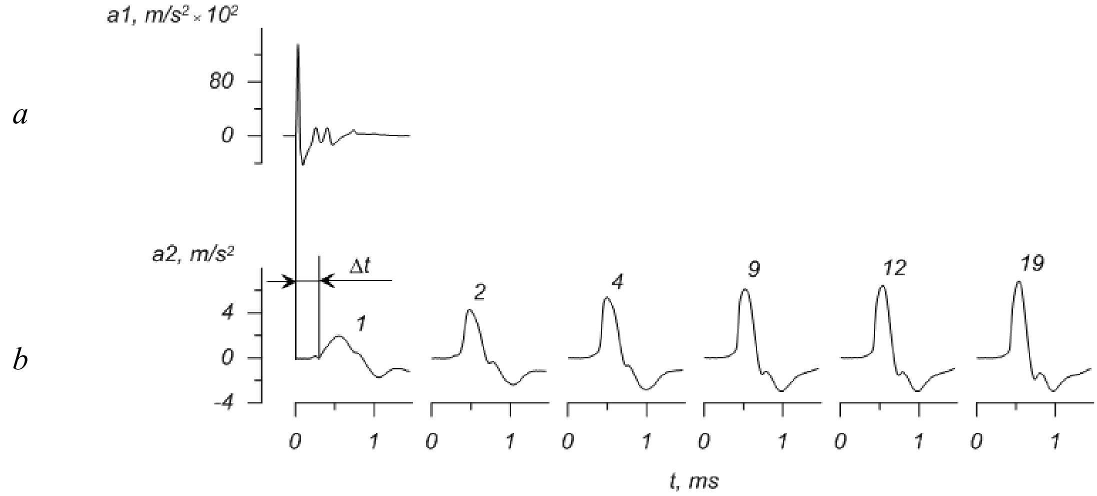


**Figure 2.** The change in the form of impulse signals under iterative impacts of constant energy *E*=4.55·$10^{-3}$ J

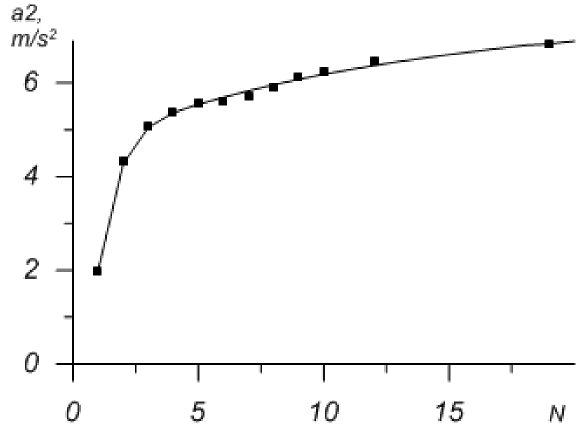


**Figure 3.** The change in the signal amplitude at the end of the distance *L*=45 mm in conditions of growing impacts

In the case under consideration each impact conditions a compression wave in the material towards accelerometer 2 from the vibroplatform. Deformations are accumulated with each impact. That is why we have all reasons to assume that particles approach each other and generate stable contact combinations, aligning towards the wave dissemination. As the number of impacts increases, contacts of this kind are multiplied. Here, the conductivity of the material rises too. Energy is transferred both through harder force chains formed under deformation and weakly loaded contacts with more relative slippage of particles. Therefore, a conducting channel is formed in the material under iterative impact loads. Increased pulse duration and reduced amplitude in the unformed conducting channel are possible because of losses in weak contacts. High-frequency components of impulse oscillations are subjected to the strongest influence. In [9] it is revealed that weak contacts as compared with the strong ones have a demodulating property – an ability to weaken or absorb high-frequency components of the signal spectrum. The form of signals and a simple rule «the broader the impulse is, the narrower is the spectrum» enables drawing a conclusion that weak contacts have a dominant influence on signal transfer in the unprepared granular material. As one can see in Figure 2, further impact improves the conductivity of the channel. New force chains formed of weakly loaded contacts support passing through high frequencies, becoming apparent in increased amplitude *a* 2 and reduced pulse duration *τ* 2 to a constant value.

Figure 3 shows changing amplitude of the signal at the end of the distance according to the number of impacts *N*, as one can see, as soon as 19 impacts had been done, the amplitude was increased nearly by 3.5 times. The delay Δ*t* was quite the same and amounted to 192 μs, being in line with the mean speed of wave dissemination *V*=234 m/s, as the number was changed. After 20 – 25 impacts the state of the channel is distinguished by insignificant further change in its conductivity.

Let us consider the effect of impact energy on basic parameters of wave dissemination in the formed channel. Figure 4 *a* outlines the curve of changing signal delay with respect to the impact energy, which shows the delay Δ*t* is reduced 0.39 to 0.28 ms, being in line with increasing speed of wave dissemination *V* 115 to 160 m/s as the energy grows. Pulse duration *τ*2, shown in Figure 4 b grows slightly and gets constant as the impact energy is increased. The growth in pulse duration alongside with the increase in energy points at deteriorated material conductivity.

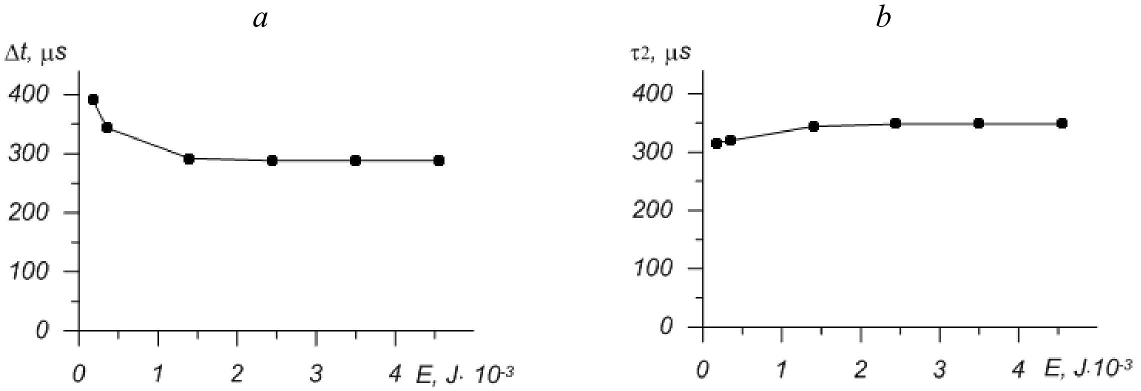


**Figure 4**. Time of pulse advancing (*a*) and duration (b) at the end of the distance in respect to the impact energy

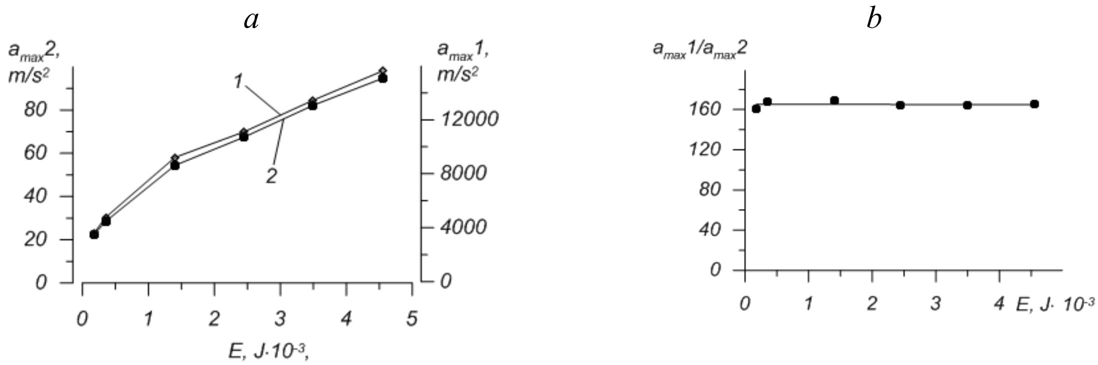


**Figure 5.** The change in maximal amplitudes of impulses (*a*) and their correlations (b) according to the impact energy on the distance *L*=45 mm

Let us analyze impact transfer through granular material in conditions of fixed length *L*=45 mm. Figure 5*a* shows maximal amplitudes of acceleration *a*1 and *a*2 (curves 1 and 2, respectively) according to impact energy, and Figure 5 b outlines its correlation. One can see amplitudes of acceleration change proportionally, and their correlation is stable in the range under consideration and amounts to 164; that is in line with wave attenuation by 99.4%. The situation is different if the distance between sensors is changed (Figure 6). The dependence on impact energy is becoming apparent slowly. The higher it is, the longer is the distance covered by the wave, and the stronger is attenuation. This dependence agrees with one given in [10].

This dependence can be accounted for the flowing force along the force chains including separate particles in the conductive channel. The process of their formation is highly influenced by the amplitude of iterative impulse impact. Repetitively applied short-term loads with a small amplitude is the reason for activation of unloaded and weakly loaded contacts, which enlarge the number of force chains in the channel; whereas big amplitudes destroy this structure and build a new one with fewer contacts and lower conductivity, consequently.

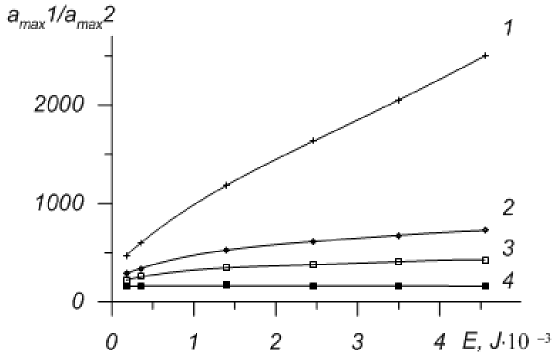


**Figure 6**. Reference signal attenuation after passing through different distances *L*, mm: *1* - 180; *2* - 100; *3* - 80; *4* - 45 with respect to impact energy

The property of channel conductivity is also significant in this respect and it comes to light when passing from one impact energy to the other. The experiments have revealed: if the channel is formed by weak short-term loads, the further effect of high loads alongside with the growing number of impacts results in decrease of the amplitude *a*2 (change of higher to lower conductivity in the channel); provided that the channel is the result of high loads, the further effect of weak loads alongside with their growing number leads to gradual amplitude rising (change of lower to higher conductivity in the channel).

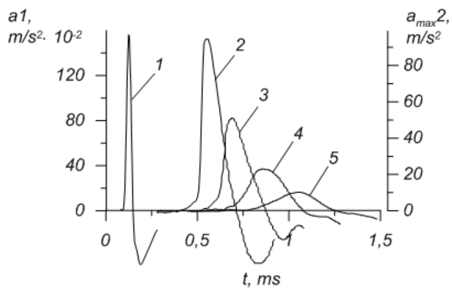


**Figure 7**. Impulses of acceleration for four distances *L*, mm: *2* – 45; *3* – 65; *4* – 100; *5* – 150 and reference impulse *1*

Figure 7 presents the reference impulse 1, measured by accelerometer 1 and impulses of acceleration, measured by accelerometer 2 on various distances *L*. The velocity curve of wave passing through the channel formed by impacts with energy $E$=4.55·10$^{-3}$ J with respect to the distance length *L* is shown in Figure 8*a*, and the curve of maximal wave attenuation – in Figure 8 *b* in the same experimental conditions. One can see the speed of wave passing was doubled as the distance was increased. It is possible because acoustic properties of the material get improved due to the effect of low-amplitude deformations arising on the long length, the deformations result from signal attenuation as the distance gets longer (Figure 8*b*). The presented below results are obtained for dry high-silica sand with porosity

$P = (V_{por}/V_{total})\cdot 100\% = 33.6\%$,

where $V_{por}$ – volume of pores in the total volume of the material $V_{total}$.

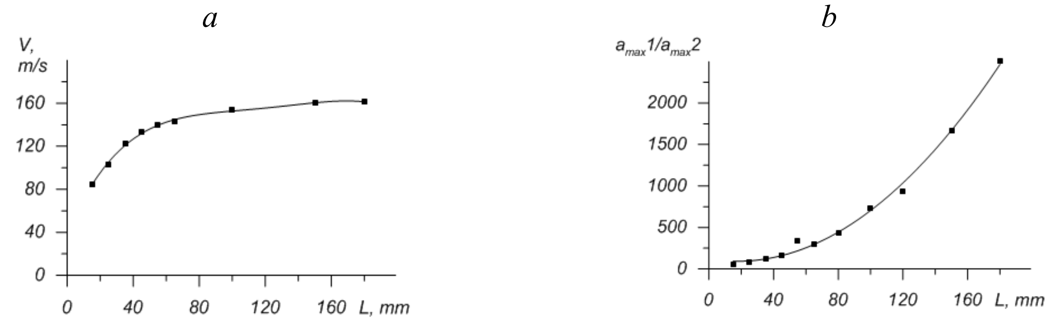


**Figure 8.** The speed of longitudinal wave passing (*a*) and its attenuation (*b*) in respect to the distance length under constant impact energy $E$=4.55·10$^{-3}$ J

Let us consider the resistance of formed force chains to external actions. The disturbance was obtained via deforming the sample by alternating cyclic shear with the angle range $\alpha$=±1.5 degrees.

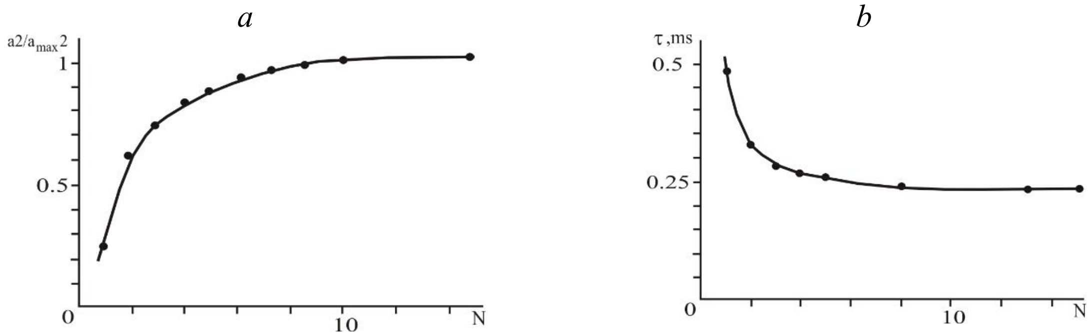


**Figure 9.** Dimensionless ratio of amplitudes (*a*) and pulse duration (b) at the end of the distance L=45 mm under constant impact energy $E$=3.5·10$^{-3}$ J according to the number of impacts

The small angle shear conditions slight expanding of the material. The maximal change in the volume was 0.2%, but the porosity got almost restored when the case came back in position $\alpha$=0. One can think there is no significant change in material properties after a cycle of shear. However, the experiments demonstrated acoustic parameters of sand were rather sensitive to changes arising in particle packing. Similar results concerning other experiments are presented in papers [11, 12, 13]. After being disturbed prevailing conductors made of force chains with strong contacts were destroyed in the conductive channel. The experiments have revealed while the wave is passing through the new structural material amplitude $a2$ goes down sharply. This decline approximates to 70% for the first impact as if compared with the previous maximal amplitude $a_{max}2$. The prior conducting state of the packing can be obtained rather simply via affecting it by some iterative impulses. Figure 9*a* outlines the diagram presenting how the channel conductivity is being restored – dependences of dimensionless ratio of the amplitudes at the end of the distance $L$=45 mm to the serial number of the constant energy impact $E$=3.5·10$^{-3}$ J. The relation equal to the one presented in the diagram is in line with completely restored conductivity.

The Figure shows that maximal prior conductivity of the channel has been restored after 15 sequential impacts. In view of experiments $N$ does not depend or is weakly dependent on the impact energy in the range under consideration. Enormously widened spectrum of frequencies to be passed as each impact improved the conductivity of the channel, resulted in double reduction of pulse duration, which amounted to the range $\tau 2$ = 520÷260 µs (Figure 9*b*) in this experiment.

## 3. Conclusions

We have considered low intensive acoustic waves passing through dry high-silica sand under weak impacts. Multiple short-term loads applied up to 20 times are the reason for formation of a channel distinguished by high conductivity of disturbances, advancing from particle to particle along the force

IOP Conf. Series: Materials Science and Engineering **127** (2016) 012011 doi:10.1088/1757-899X/127/1/012011

chains. The formed chains are irresistible to shear deformations of the sample in general, but can get restored after multiple impacts.

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