A Suggested Method for the Study of Crushed Aggregate Response to Dynamic Compaction

Nikolaos Petropoulos

PhD student, Department of Civil, Mining and Environmental Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden
Corresponding author: e-mail: nikolaos.petropoulos@ltu.se

Dimitar Mihaylov

Researcher, Department of Civil, Mining and Environmental Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden, Phone: +46 (0)920 492447, e-mail: dimitar.mihaylov@ltu.se

Daniel Johansson

Associate Professor, Department of Civil, Mining and Environmental Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden, Phone: +46 (0)920 492361, e-mail: Daniel.Johansson@ltu.se

Erling Nordlund

Professor, Department of Civil, Mining and Environmental Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden, Phone: +46 (0)920 493535, e-mail: Erling.Nordlund@ltu.se

ABSTRACT

Soil improvement by dynamic compaction has been extensively used all around the world in large civil engineering projects. Limited number of laboratory tests has been conducted to study the behavior of soil material under dynamic loading. A suggested method is presented in this paper which includes a new laboratory apparatus and experimental procedure as well as data analysis. The suggested impact machine is a drop hammer type machine, it can host up to 37.5 mm particle size in a coarse-grained aggregate matrix independent of its conditions, i.e. saturated or unsaturated, it is also flexible in terms of weight and size of the drop hammer and the mold. The machine is equipped with accelerometers for continuous monitoring of the sample's behavior during impact. The experimental procedure shows the steps for conducting consistent dynamic compaction tests. It also describes how the measurements should be conducted. These measured quantities correspond to key parameters such as density, angle of repose and compaction. Finally, a case example demonstrates the function of the machine and the analysis of the recorded data.

KEYWORDS: Dynamic compaction, impact tests, experimental apparatus, soil behavior, confined blasting

INTRODUCTION

In sub-level caving mining method, the production blasting is confined, i.e. the blasting is against pre-blasted or waste rock. The particle size distribution of the caved material has a wide range of fractions starting from fine material (size of millimeters) up to coarse fractions (size of meters). During the blast, there is only one degree of freedom for the blasted material, because at the sides of the blast there is only intact rock, which is perpendicular to the blasted material. The result of it is the compaction of the waste material which might affect its characteristics. This effect could be studied in similar manner as the effect of dynamic compaction on soil.

The behavior of soil material when subjected to dynamic compaction in confined conditions is of significant importance since it is part of several engineering areas, e.g. soil foundation, soil improvement, mining engineering etc. The different aspects of the behavior of the soil material can be related, for example, to stability and flowability of the soil. These cases can be found in most civil engineering structures, for instance, slopes or dams. Dynamic compaction is a well-known technique with extensive application in soil improvement. It densifies the soil and increases its load bearing capacity [1]. This method was first introduced by Menard & Broise [2]. This technique can be used as analogue to the proposed impact machine in this paper. Dynamic compaction is based on the drop of a heavy hammer weighing from 5.4 to 27.2 tons and a drop height varying from 12.2 to 30.5 m [3]. Limited number of laboratory investigations have been published in the dynamic compaction field and the application of this method is largely based on empirical approaches, for example pilot tests.

Several researchers have carried out analyses of dynamic compaction data from field measurements. They have investigated the effect of impact loading on various types of soils and proposed prediction models for depth of influence by impact and estimation of the maximum applied stress during the impact.

Scott & Pearce [4] described different approaches to ideally predict the reaction of soil during dynamic loading. The theoretical models presented in the paper were related to linear elastic unsaturated soil, elasto-plastic unsaturated soil, linear elastic soil in a saturated state and saturated compactable soil. The dynamic properties of the material defined the deceleration of the falling weight and the initial stress level in those models by considering for example the specific acoustic impedance and dilation velocity. The reaction of the material during an impact was described in the paper for the different cases. The overall summary of the above tested models was that it was very complex to reach a full solution of the real soil reaction during impact because the forces and motions could not be described by simple elastic or plastic models. Particular cases, e.g. very light impacts, could be reasonably described by the current models.

Mayne & Jones [5] made an attempt to calculate the stresses during dynamic loading. It was assumed that the applied force was a triangular pulse, and the area under the force-time curve was equal to the change in momentum. After the combination of the applied force with the mechanical parameters of the soils such as the shear modulus, vertical stiffness and shear wave velocity, the derivation of the peak dynamic stress beneath the drop hammer was made. The equation was applied on different sets of data from different test sites giving good predictions of the magnitude and duration of the stress during impact.

Poran, et al [6] conducted a study in laboratory scale to investigate the impact behavior of sand by changing impact parameters such as drop height, weight of drop hammer and contact area. The study was based on the Dynamic Settlement Modulus (DSM) concept which correlates density and elastic parameters of a soil mass. The experimental setup was composed of a 1.22 by 1.22 by 1.22 m cubic steel tank filled with sand and a drop hammer with varying diameter i.e. 102 mm, 152 mm and 229 mm. The drop hammers were equipped with piezoresistive accelerometers. The results showed that

DSM could be correlated with sand densification. With the proposed method the influence depth and width of the impact could be estimated based on the drop hammer weight and contact area, drop height and number of blows.

Oshima & Takada [7, 8] conducted experiments on the effect of ram momentum on the compaction of soil and sandy material. There were two sources of data, i.e. field data and laboratory data from centrifuge model tests. The data were analyzed based on the impact duration and kinetic energy. The evaluation of the compaction from the laboratory tests was done with the cone point resistance method. The results showed that the momentum of the ram had a greater effect on the compaction of the tested material than the kinetic energy of the ram.

The above literature review suggests that there are only empirical models or techniques for the estimation of compaction of soil or sandy materials. In this paper, the development of an impact machine capable of hosting coarse-grained aggregate material is proposed. Additionally, there is no “standard” equipment which can be used for detailed investigation of the coarse-grained aggregate response under dynamic loading. This paper describes the development of an impact machine which is equipped with sensors as well as a method for evaluation of coarse-grained aggregate response during confined dynamic compaction in laboratory conditions and the extent of the compacted zone.

EQUIPMENT DEVELOPMENT

The concept behind the impact machine

The development of the impact machine was based on criteria such as safe operation, capability to host measuring equipment and adjust the compactive effort. The conceptual idea behind this machine was similar to that of the Proctor tests and based on the practices for evaluation of compaction characteristics [9, 10] and the standard of the evaluation of aggregate impact value (AIV) [11].

The impact machine was designed to produce compactive effort per blow within the range of the standard and the modified Proctor tests, i.e. 24 - 108 kN-m/m^3 per blow. Hence, the drop hammer had to be heavier than the hammer used in Proctor tests (24.5 and 44.48 N) and AIV tests (14.0 kg) and the drop height had to be increased in order to reach the required compactive effort. It should be mentioned that the proposed impact machine was not designed to measure optimum water content and it does not utilize kneading mechanism to increase compaction. It was designed to study the behavior of loose aggregate material during dynamic loading.

The impact machine was intended to utilize only one blow which impacts the entire surface of the tested material and has only one thick layer as opposed to the Proctor tests which utilizes multiple layers and blows. Therefore the hammer had to have a diameter close to the mold diameter. Additionally, the impact machine should be capable of hosting material with a grain size of up to 37.5 mm as coarse-grained aggregate matrix. The drop hammer and the mold had to be detachable for different experimental setups.

The drop height had to be no more than 1.5 m due to spatial restrictions. An energy accumulator was required to accelerate the drop hammer up to the desired impact velocity which is directly related to the impact stress. According to the above compaction standards, the mold had to have a diameter of about 300 mm. This means that the mold was 8 times larger than the maximum particle size. Safe operation of the impact machine was of utmost importance and it was considered during the design of the machine.

Purpose of the impact machine

The impact machine had to allow several parameters of a coarse-grained aggregate sample to be measured to study the reaction of the sample under dynamic loading. These parameters were bulk density, angles of repose and compaction.

The angle of repose had to be measured before and after the impact of the drop hammer on the surface of the sample. The angle of repose is an important property which defines the flowability and the stability of a granular material.

The final measurement was the degree of compaction at different positions in the sample which is directly related to the volumetric change of the sample due to the impact. Compaction involves all the above mentioned parameters which dictate the behavior of a coarse-grained aggregate sample during dynamic loading. The maximum and final compaction can be measured by analyzing the data from the sensors.

There are methods, e.g. centrifuge model, Proctor tests and cone resistance methods to measure all the above parameters (density and compaction) but none of these methods can measure the history of these parameters during the impact. The main issue with these methods is that they can be used for relatively fine materials, e.g. clay and sand. This impact machine was designed to host materials with up to 37.5 mm particles size. The purpose of this impact machine was to dynamically study the reaction of coarse-grained aggregate upon impact and to measure the maximum displacement of the sensors during the impact which can be used to calculate the density and compaction.

The kneading mechanism, which extensively used in impact tests, was intentionally omitted since the purpose of this study was to study the material reaction to a single blow. The optimum water content of a sample was out of scope for this impact machine. However, the reaction of a wet material to impact can be studied.

Development of the impact machine

Different designs were considered including pneumatic, hydraulic and mechanical systems which can accelerate the drop hammer to the desired velocity within the given drop height. The first two are complicated and require sophisticated elements. It was therefore opted to use the mechanical solution. However, the selection of the energy accumulator also needed to be resolved. The solution to this problem was to use elastic cords (shock cords or bungee cords).

The next step was to design the metal parts according to the mentioned design criteria. Consequently, the selected mold had an inner diameter of Ø298.9 mm with 12.5 mm wall thickness and 350 mm height. The gap between the mold and the drop hammer had to be smaller than the maximum particle size. Hence, the diameter of the drop hammer was Ø270.0 mm which gave a radial gap of 14.45 mm. The weight of the drop hammer was 35.5 kg in all the tests. Only one parameter was used to define the applied compactive effort; the impact velocity. As mentioned before, the drop hammer was designed in a way that its weight could vary according to the desired setup; hence its minimum weight was 15.5 kg.

The drop hammer and the mold had to be fully aligned and centered. This condition was achieved by utilizing a support and a guiding structure. The solution was to have three guiding points, the first two were two vertical pipes (Ø60.3 by 8.0 by 2500 mm) to act as guides and the last was the main body of the holder (Ø42.4 by 5.0 by 2700 mm) of the drop hammer (Figure 1). The figure shows a simplified view of the impact machine as well as the main elements.

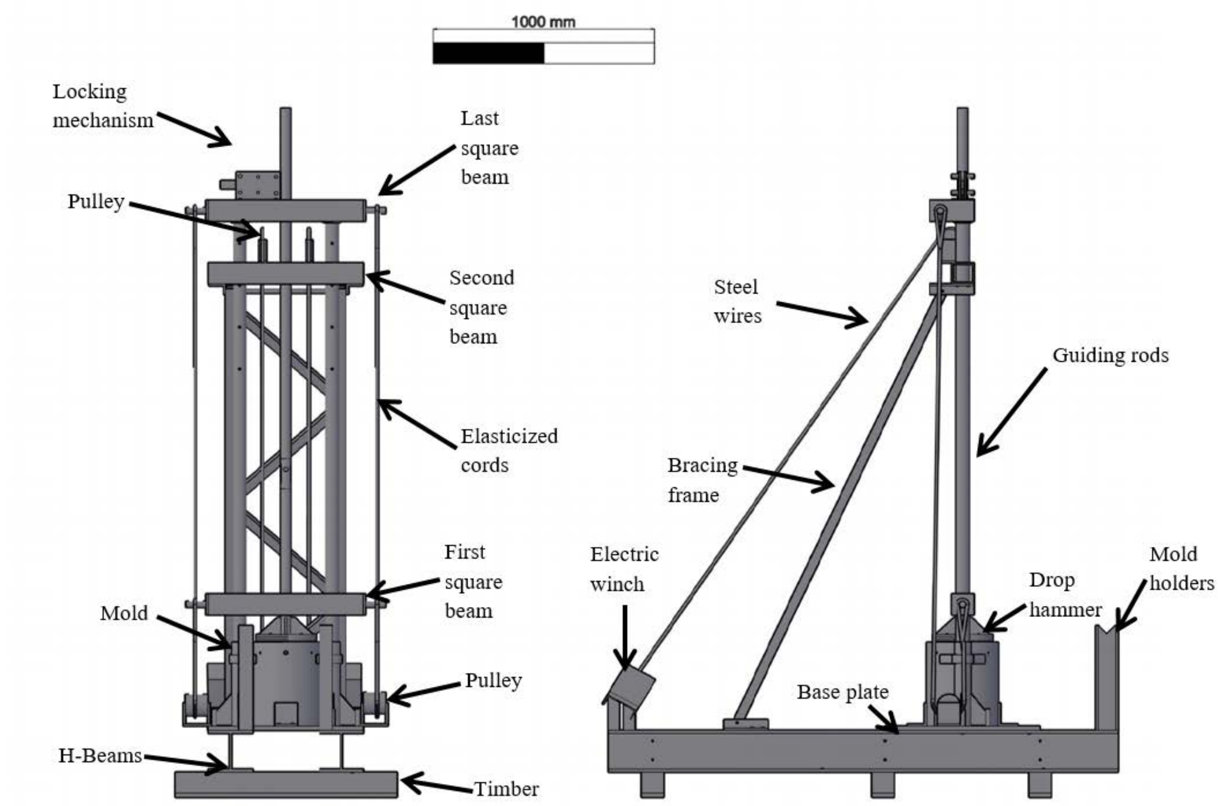

Figure 1: The impact machine

The main body of the impact machine is composed of (it is described from the bottom to the top):

- A timber structure composed of a plank, fabric layer and a square timber beam to act as damper minimizing the impact on the floor. This timber structure has dimensions of 100 by 100 by 1000 mm and it was bolted to the floor by means of drop-in anchors which were cemented.
- Two H-beams (HEB 200) used together with the anchors as inertia mass and foundation for the entire system. The beams were connected to the timber structure. Two threaded rods were connected the two beams together in order to prevent excessive bending during the impact. On each H-beam, there was a holder for placing the mold to ensure safe preparation of the test and to measure the angle of repose before and after the impact test.
- A base plate (700.0 by 700.0 by 20.0 mm) where the mold fitted with connection parts for the guiding pipes and one aluminum 4-grooved pulley per side to pass through the elastic cords. This defined that the maximum number of cords could be up to 4 per side.
- The mold (Ø 298.9 by 350 mm) was bolted on the base plate by means of two steel corners (80.0 by 100.0 by 10.0 mm). These two corners also acted as adjustment elements to ensure the alignment of the mold with the drop hammer. Eight holes were drilled (Ø12), 50 mm from the top of the mold, to allow air to escape during impact; this was to avoid cushion effects prior to impact. The volume in the mold for the sample was 0.021 m^3.

- A drop hammer was composed of a centered pipe (Ø42.1 by 5.0 mm) and a set of attachable steel disks (10 kg each) for regulating the weight. The current setup involved three disks with a layer of fabric in between to act as wave suppressor. The centered pipe was composed of two parts which could be connected together with a steel rod and four pins. The upper part of the centered pipe could be locked in place by the lock/release mechanism. If a change of the drop hammer was necessary, these four pins could have been removed to attach another drop hammer.
- The first square beam (100.0 by 100.0 by 5.0 mm) was equipped with Teflon® rings ensuring smooth sliding of the beam along guiding pipes. At both ends of the beam there were two hooks for hosting a set of cords. There was a hole in the middle of the beam for passing through the support pipe of the drop hammer and two holes for attaching steel cables to lift the drop hammer.
- The second square beam in which the bracing structure was attached. Two pulleys were also attached on top of it for guiding the steel cables which connected the electric winch (installed at the rear part of the machine) and the first square beam. The steel cables were fixed in place by pins in the first square beam.
- The last beam stabilized the guide pipes, support pipe for the drop hammer and provided a floor for the lock/release system. Additionally, at both ends of the beam two hooks were welded for hosting the other end of the elastic cords.

The impact machine was also equipped with extra parts which could help the user to easily operate the machine. These parts included (i) an electric winch, installed at the very back of the machine, which lifted the drop hammer together with the first square beam up to the locking position, (ii) a set of rubber pads in both guide rods which controlled the deceleration of the first square beam and prevented the beam to hit the mold, (iii) an auxiliary tool designed to install and remove the mold from the impact machine. This tool was composed of an engine hoist attached to the edge of a pallet truck. A counterweight was placed behind the engine hoist on the pallet truck to balance the weight of the mold.

Since some parts of the machine could reach high velocities, safe operation of the machine was of significant importance. The lock/release mechanism was the key element for safe operation and was designed with great care. It was mainly composed of three heavy duty roller bearings (capacity 21.6 kN) installed at the points where the maximum applied force was expected, moreover four medium duty ball bearings (capacity 2.85 kN) were also installed for providing smooth rolling of the latch. Additionally, there was a spring which pushes the steel latch against the opening in the rod. The moving range of the latch was regulated by two stoppers. In the drop hammer rod a heavy duty roller bearing was also installed. The mechanism was bolted on the top square beam which was reinforced at the bolting points. When the impact machine was in full tension (approximately 4.2 kN), the lock/release mechanism required around 80 N of pulling force to release the drop hammer. The latch was long enough to always be in contact with the heavy duty roller bearings in the locking mechanism.

The machine had only two moving parts during the impact; the drop hammer and the first square beam with the cords attached. The falling sequence was initiated when the drop hammer was released and the first beam was accelerated by the cords, and then, the beam accelerated the drop hammer to the desired impact velocity.

Laboratory evaluations were carried out to define the diameter and the required elongation of the shock cords (Figure 2). The optimum diameter and elongation were Ø12 mm and up to 100 %, respectively. This configuration resulted in a tensile force of about 250 N. The cords had to have a residual tension after the impact in order to minimize the bounce of the drop hammer. Thus the working range of the cords was from 20 % to 100 % elongation. This working range had to fall within the safe region of the cord as a breakage of a cord might lead to increased chance of personal injury, especially when the cords were tensioned. The elastic cords after each test were inspected for weaknesses and replaced after 10 tests with new cords. The reason for the replacement was to maintain the impact velocity and safety.

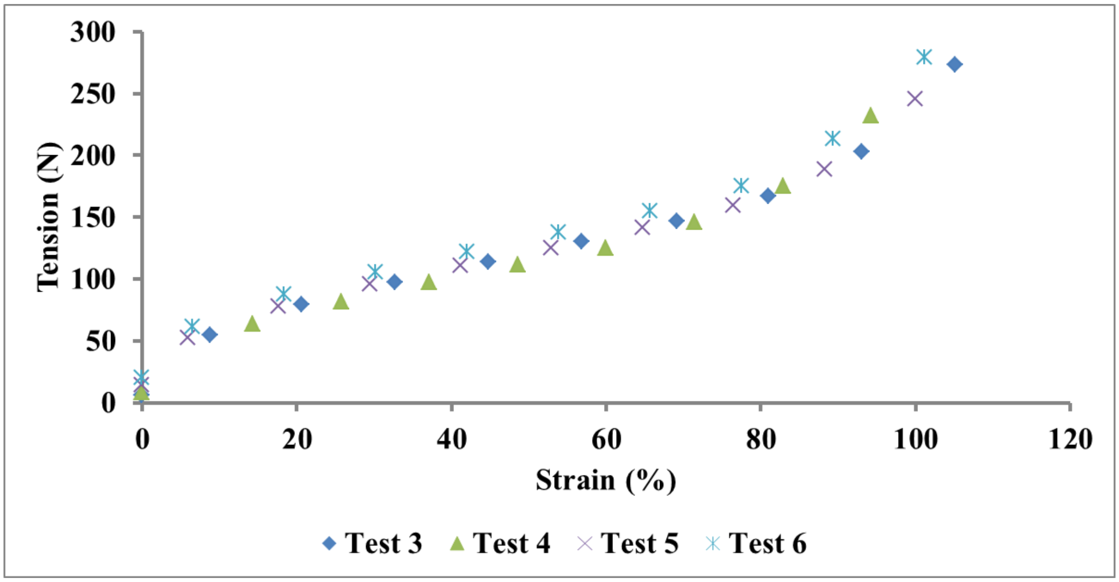

Figure 2: Elastic cords performance

The shock cord behavior was tested under several loading/unloading cycles as well as when the cord was tensioned for long periods of time (Figure 3). For this analysis, the cord was extended to maximum elongation resulting in a peak tensile force of 1000 N. After this force, the elastic cord acted as a regular rope and at this extension there was an irreversible deformation of the cord. However, this magnitude was far above the proposed working range. The number of attached shock cords regulated the impact velocity that could be achieved.

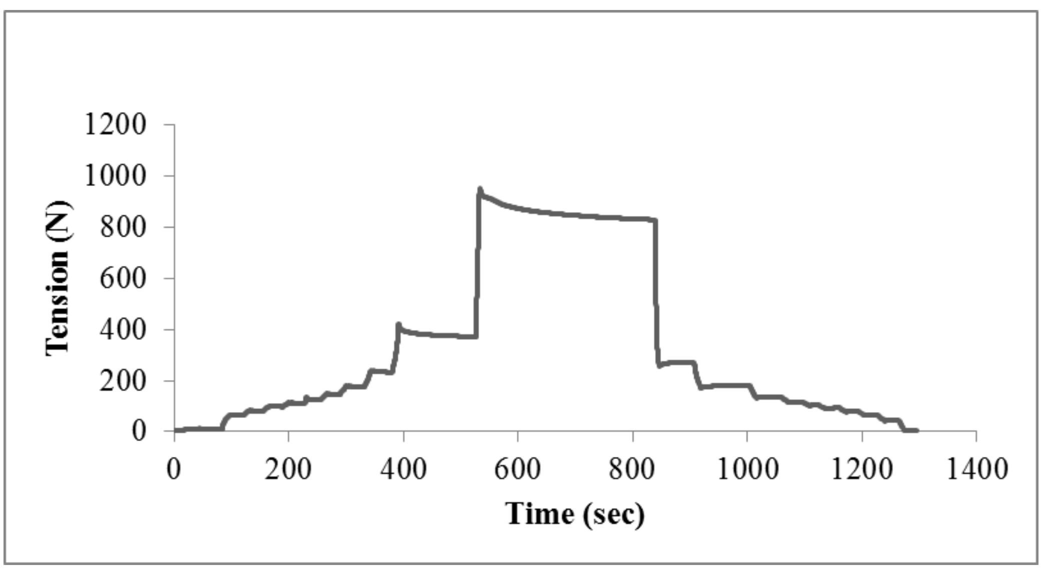

Figure 3: Loading/unloading cycle

Measuring equipment

The measurement of the impact velocity by itself did not provide enough information regarding the behavior of the tested material and the mechanisms involved in this process. The impact machine was equipped with velocity sensors and accelerometers detecting the impact velocity and the deceleration/acceleration at the moment of the impact, respectively.

The instrumentation could provide static and dynamic data of the impact process. The measuring instruments which were installed on the impact machine were 3 shock ICP® miniature piezoelectric uniaxial accelerometers (PCB 350B03, 10000 g). Two probes were installed on the mold for measuring the terminal velocity and trigger the logging units. A high-speed video camera was used for monitoring purposes as well. The installation positions of the instrumentation were (Figure 4) as follows:

- Accelerometer (1) was installed on the drop hammer in direct contact with the impact surface. This accelerometer measured deceleration of the drop hammer during impact.
- Accelerometer (2) was installed at 50 mm from the surface in the sample to record the displacement at this point.
- Accelerometer (3) was installed at 150 mm from the surface to record the displacement deeper in the sample.
- Two velocity probes (4) were attached on the mold to measure the impact velocity.

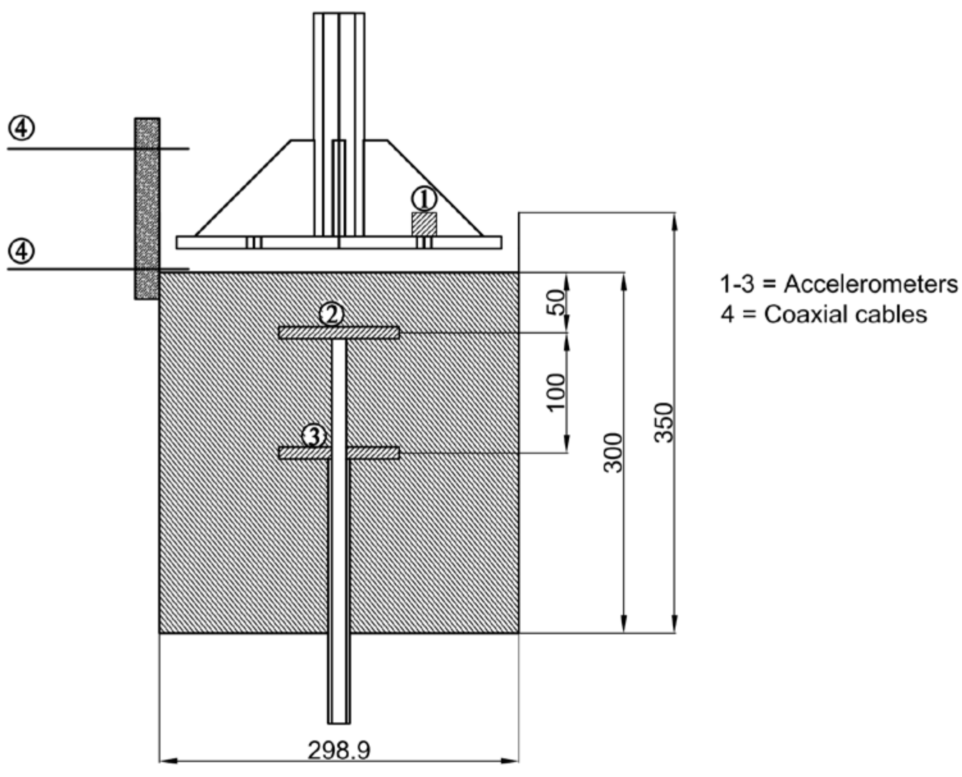

Figure 4: Location of the sensors in the mold

The selection of accelerometers as instrumentation was based on the dynamic nature of the data. The intention was to dynamically observe the impact of the drop hammer on the surface of the tested material. Additionally, the utilization of accelerometers provided the measurement of the duration of the pulse of the applied force.

A new instrument had to be developed in order to host the accelerometers which could be installed in the sample. This instrument was a telescopic device with two platforms (Figure 5). The platforms were made of aluminum due to similar density with the sample and were machined in order to make room for the accelerometers. The platforms were aluminum disks (Ø80 by 16 mm). Each platform was connected with a copper pipe. The pipe dimensions were chosen, so the copper pipe (Ø12 by 320 mm) from the first platform could pass through the lower copper pipe (Ø18 by 220 mm) which was attached to the second platform.

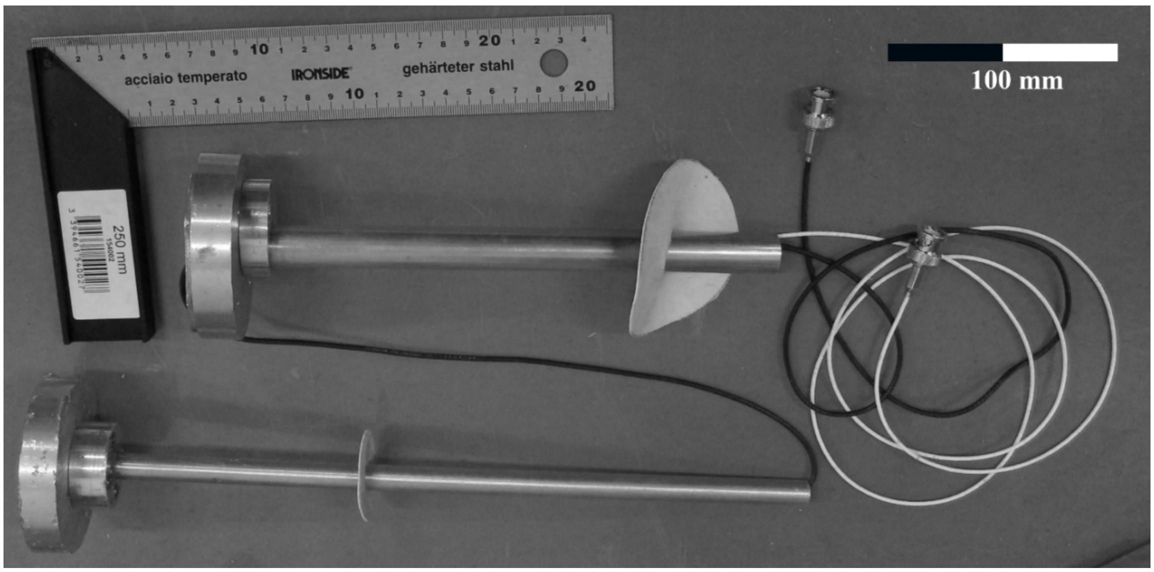

Figure 5: Telescopic system

The telescopic instrument passed through the mold and the base plate. Then, it was possible to measure in a static way the exact initial position of the instrument in the mold before the impact when the mold was already installed in the impact machine.

The impact velocity was monitored by means of two probes. There were two coaxial cables installed at the top of the mold, and there was 100 mm distance in between. The edge of the cables were unshielded, thus when the core touches the shield, the circuit is closed. The cables were connected with a pulse box producing two spikes, i.e. one for each cable, when the cables were short-circuited by the drop hammer. As the distance between the cables and the time span between the spikes were known, the impact velocity could be calculated. Moreover, the first spike triggered the logging units.

All of the sensors were connected with two data acquisition systems, i.e. National Instruments logging unit with sampling rate 250 kS/s and Tektronix oscilloscope 2024 with sampling rate 315 kS/s. An experimental procedure was developed in order to achieve consistent testing. The sample preparation was based on standard practices as described below.

Experimental procedure

The impact machine was validated based on numerous trials in order to find the best fitted procedure which gave the necessary results for the material evaluation. The procedure involved static measurements as well as dynamic measurements before, during and after the impact of the drop hammer on the sample.

The preparation started by placing and locking the mold on the holders. A thin fabric layer was placed at the bottom of the mold which defined the boundary conditions by minimizing the compressive wave reflections. These reflections might else exaggerate the heave of the sample after impact. The telescopic system was installed at the proper height of the mold which was 50 mm below the surface of the tested material. The telescopic system was suspended in the mold during filling it. The first 50 mm of the tested material was used to prevent a direct impact of the drop hammer on the first platform resulting very high acceleration.

The verticality of the telescopic system had to be ensured, otherwise a vector of the acceleration would be recorded and consideration needed to be taken to the high friction between the telescopic system, the mold and the base plate. Else the system would give erroneous results. For this setup, a spirit level was used.

The next step was the filling of the mold with the coarse-grained aggregate material. The material was sieved according to ASTM C136/C136M-14 [12]. The material that passed a 37.5 mm sieve opening could be used in the impact machine. The sample was weighed before filling the mold. Then, the mold was filled with the sample material using a soil scoop up to the same level as the first platform to avoid disturbing the telescopic system. Aluminum foil was used to minimize segregation effects; the choice of aluminum foil was based on its flexibility, density and strength. The last 50 mm of the filling material was sieved separately and placed in the mold. During the validation process, a minor change in particles size distribution was observed in this part of the filling material. The remaining material was weighed to calculate the mass of the used material in the mold. This information was used to calculate the bulk density of the material before the impact.

The required height of the tested material was defined by an empirical formula proposed by Menard & Broise [2] and is expressed in the form

$$d = n \cdot \sqrt{W \cdot H_{eq}} \quad (1)$$

where, d is the depth of improvement, W is the weight of the tamper (in t), H_{eq} is the equivalent drop height (see below) (in m) and n is an empirical factor.

The empirical factor was calculated based on the validation tests and it was approximately 0.6. Thus the required height of the tested material was calculated 300 mm considering the maximum equivalent drop height. Additionally, it was equivalent to one diameter of the drop hammer and the ratio of the diameter of the mold and the height of the sample was equal to one.

The angle of repose could be measured when the filling process was done by tilting the mold by utilizing a rotary angle meter. It was worth noting, that there was an influence of the curvature of the mold. It resulted in an overestimation of the angle of repose. Thus, this technique could be used as relative measurement of the angle of repose and to measure the difference before and after the impact only. After this measurement, the sample was restored in the mold and the surface was flattened to maximize the contact points between the drop hammer and the surface of the sample. The mold was, then, tightly bolted in the machine to eliminate rebound of the mold during the impact.

The static measurement of the telescopic system could be done to define its exact position in the material before the impact. The system was connected with the amplifier and with the logging units. The next measurement was to define the exact distance between the flattened surface of the material and the top of the mold. The installation of the velocity probes on the mold followed.

The drop hammer was connected to the first square beam with a pin. The first square beam was lowered at a level where the drop hammer did not touch the velocity probes and the elastic cords were attached. The number of cords depended on the desired impact velocity. After the attachment of the cords the operator should stay at least 2 m from the impact machine for safety reasons, i.e. the cord length if it snapped. The first beam was lifted up by the electric winch to the point where the drop hammer was locked in place. A final check of the logging units was performed. The pin and the steel cables were detached from the beam. The high-speed video camera was turned on and the drop hammer was released.

After the impact the above described measurements were repeated. The high-speed video camera was turned off and the final height of the telescopic system was measured (static measurement). The difference between the measurement of the height of the telescopic system before and after the impact gave the final displacement of the system which could be correlated with the final deformation of the sample at the two measuring points. It was not the maximum deformation as the sample rebounded elastically after the impact.

The attached cords were removed, the drop hammer and the steel wires were attached again to the square beam and both were lifted to the locking position. The distance between the surface of the material and the top of the mold were measured to calculate the final deformation at the first 50 mm of the material. This could be combined with the static measurements from the telescopic system to observe how the bulk density and deformation changed with respect to depth. Then the mold could be removed from the machine but before this the telescopic system had to be disconnected from the amplifier. The mold was placed on the holders for measuring the angle of repose.

The first part of the material was removed by using a soil scoop and progressively removing material until the aluminum foil was revealed. This part of the sample was sieved to observe the difference in particle size distribution due to the impact. Then, the telescopic system was removed and the rest of the material in the mold was dumped in a bucket. When the mold was totally empty it was ready for the next test preparation.

RESULTS AND DISCUSSION

The above described impact machine and experimental procedure were tested with dry material. Figure 6 illustrates a typical example of the produced spikes by the velocity probes; the distance between the two spikes was 100 mm. Based on this information the compactive effort can be calculated (Eq2):

$$\text{Compactive effort}=\frac{(\text{no. of blows})\times(\text{no. of layers})\times(\text{weight of drop hammer})\times(\text{drop height})}{\text{volume of material}} \quad (2)$$

The drop hammer weighed 35.5 kg and the sample volume was 0.021 m^3. The number of blows and number of layers were equal to one since only one blow was used and only one layer was considered. The only parameter that changed was the drop height. However, the drop height depended on the velocity, hence the equivalent drop height had to be calculated based on the equations of motion which means (Eq3):

$$H_{eq}=\frac{v^2}{2g} \quad (3)$$

where v is the impact velocity measured by the velocity probes, g is the gravitational acceleration and H_{eq} is the equivalent drop height. In (Figure 6), the calculated equivalent height is 6.01 m.

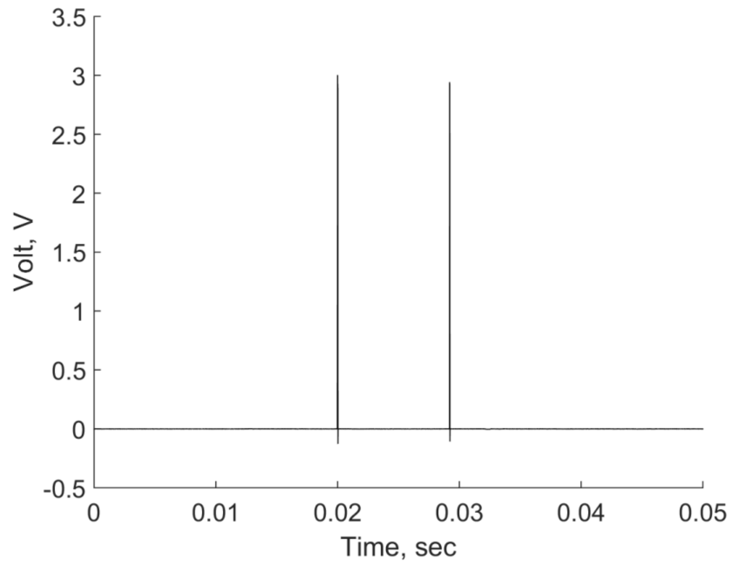

Figure 6: Velocity probes (10.86 m/s)

The recorded accelerations were used to calculate the level of impact stress using the second Newton's law of motion (Eq3).

$$\sigma(t) = \frac{F(t)}{A} = \frac{m \cdot a(t)}{A} \quad (4)$$

where *σ(t)* is the applied stress during the impact, *A* is the surface of the drop hammer, *m* is the mass of the drop hammer and *α(t)* is the deceleration of the drop hammer with respect to time.

The testing methodology and evaluation of the test results is demonstrated by the following example: The sample was a dry coarse-grained aggregate according to ASTM D2487-11 [13] with 0 – 32 mm particles size (d_{30} = 3.3 mm, d_{60} = 25.3 mm) and bulk density 1666 kg/m^3. The density was measured by the weight of the material and its occupied volume in the mold.

The signals were recorded from three accelerometers installed on the impact machine. The raw signals (Figure 7) contained high frequency components which were related to ringing effect of the drop hammer, particle scratching on the telescopic system and friction due to sliding of the drop hammer and first square beam along the guide pipes.

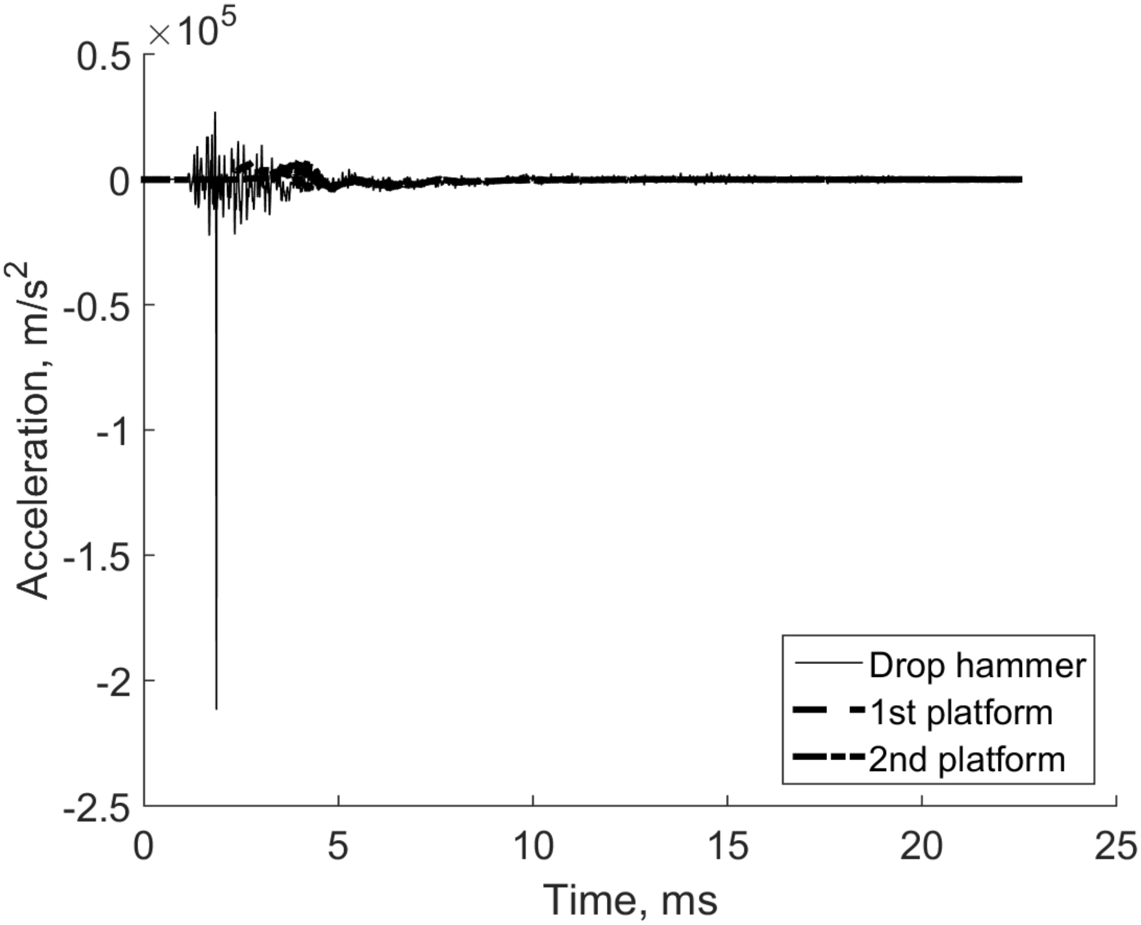

Figure 7: Compactive effort 99 kN-m/m^3 without filtering

Consequently, the signals have been filtered with a low-pass 8th order Butterworth filter of 5 kHz to minimize these effects. After the application of the filter, the signals had the form as shown in Figure 8. It shows the calculated stresses from the impact at approximately 99 kN-m/m^3 compactive effort and at different vertical positions in the sample. In this figure, the entire movement can be observed, i.e. impact and rebound of the drop hammer.

Similar records, as in Figure 8, have been observed in the field from dynamic compaction tests and reported by [3-6, 14]. At the beginning of the record there is a sharp pulse reaching the maximum applied force. After the peak point, the reflections from the wall and the bottom of the mold are shown. There is also an oscillation of the sample, as shown by the recordings from the accelerometers in the telescopic system, before the signals become steady.

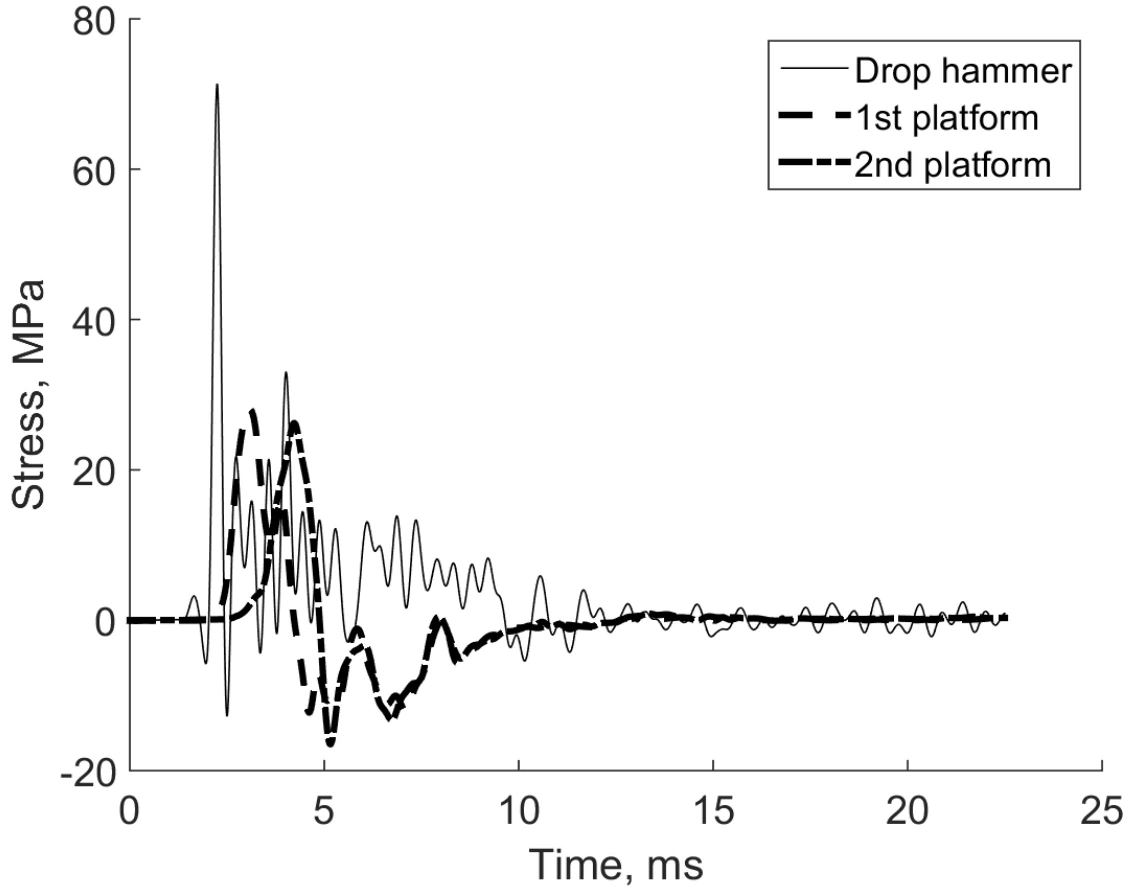

Figure 8: Compactive effort 99 kN-m/m^3 with filtering

The desired quantity was the deformation of the compacted material (it is the same as the drop hammer displacement). A double integration of the above signals (in the acceleration form) can be performed to derive the displacement. As can be seen in Fig 9, the impact duration is 7.55 ms. The results of the different sensors are shown at Figure 9 and Fig 10.

The maximum deformation of the drop hammer sensor after the impact was 42 mm, as can be seen from Fig 9, although this value was the maximum deformation and not the final, because, the tested material recovered its elastic compression.

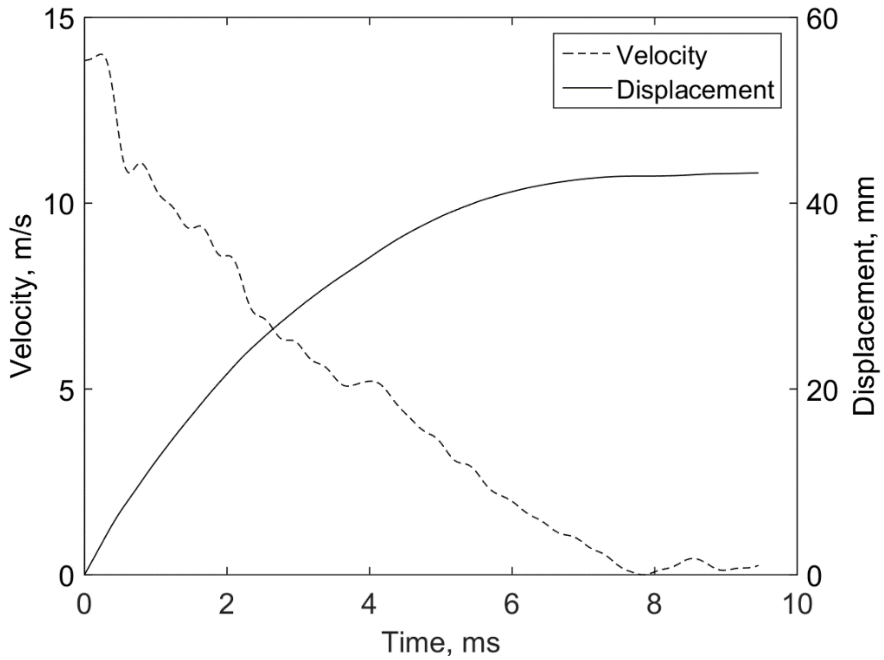

Figure 9: Impact velocity and displacement from the drop hammer

The maximum displacement can be calculated by the double integration of the signals from the 1st and 2nd platform of the telescopic system. The results are shown in Figure 10. The displacement for the first platform was 17 mm and for the second platform 11 mm. These two values indicated the displacement of the accelerometers within the sample.

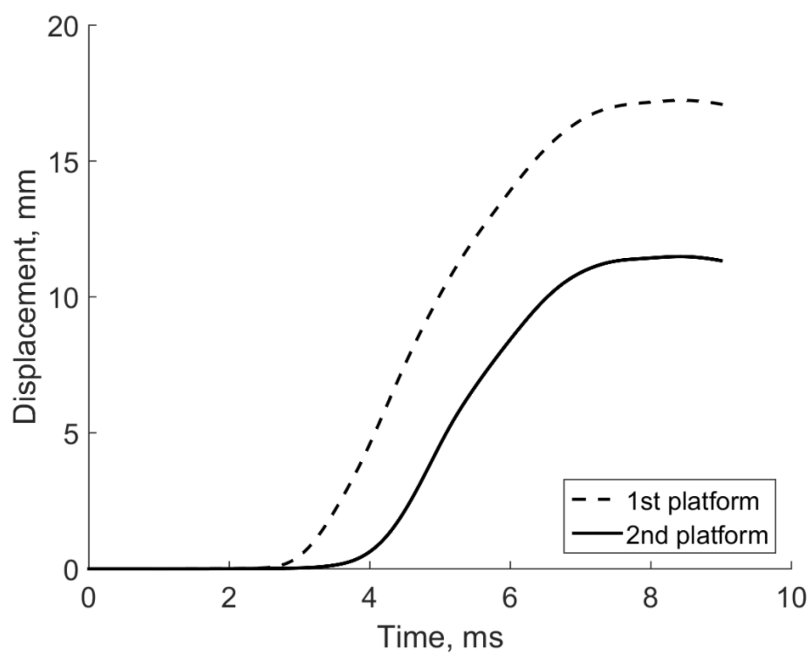

Figure 10: Displacement from the sensors in the telescopic system

Figure 11 shows the static measurements of the distance between the tested material and the top of the mold before and after the impact test. The surface of the tested material was flattened (no load was applied) prior to impact test in order to increase the maximum contact surface during the impact. In this example, the difference of the measured distance was 13 mm.

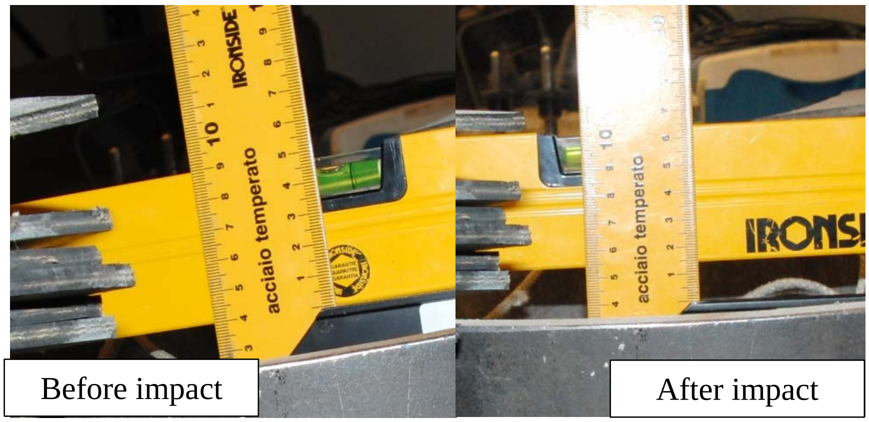

Figure 11: Static measurements at the surface of the tested material

The static measurements provided the final deformation. The difference between the maximum and final deformation showed the elastic rebound of the material.

The combination of the dynamic and static measurements indicated that the elastic rebound of the sample was approximately 69 % of the maximum deformation and only 31 % remained as residual deformation for the material between the drop hammer and the first platform. This shows that the major part of the deformation is elastic. The density calculation required the final displacements which were recorded by the telescopic system.

The calculation of the distance of between the sensors after the impact was performed according to the following equation (Eq5).

$$K = y - x_1 + x_2 \qquad (5)$$

where, K is the distance between the sensors after the impact, y is the distance of the sensors before the impact, x_1 is the measured displacement of the sensor closer to the impact surface and x_2 is the measured displacement of the sensor below.

The final displacements were measured as shown in Figure 11. The inner copper pipe belongs to the first platform and the outer copper pipe belongs to the second platform. The results, in this example, were for the first platform 4 mm and for the second platform 1 mm. The elastic rebound for the first and the second platform (measuring points) was 76 % and 91 %, respectively. This information shows that the influenced zone is between the two platforms, in other words, it was slightly longer than a radius of the drop hammer.

The change in density along the vertical measurement axis was calculated using the final displacement. This gave a density of the first 50 mm of the tested material of 2380 kg/m^3. For the next 100 mm of the material, the density was 1700 kg/m^3 and for the last part, the density was 1677 kg/m^3. The compaction could be also calculated based on the final displacements which were 30 %, 3 % and 0.6 % for the three measurement points.

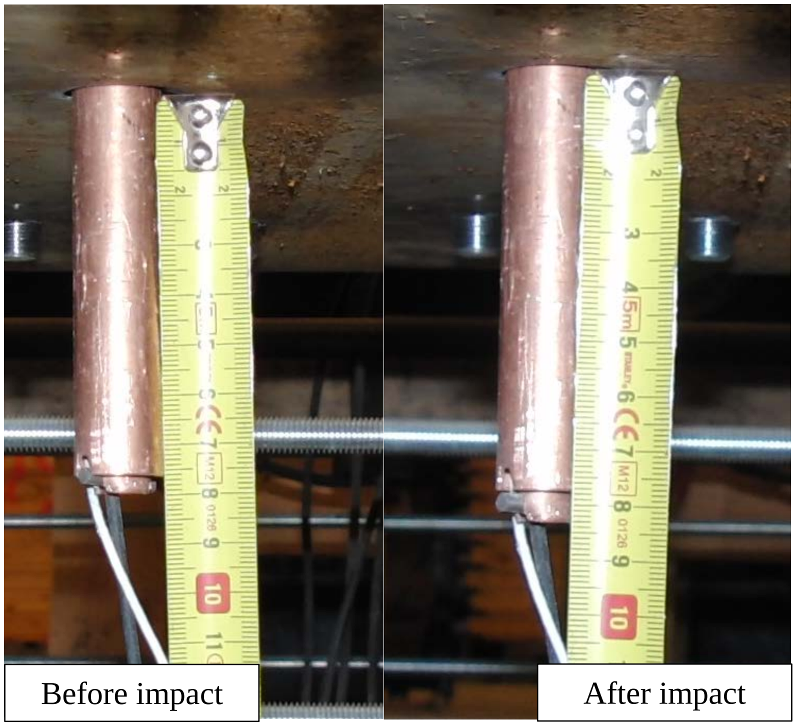

Figure 12: Final deformation measured from the telescopic system

The last measurement was the angle of repose which was measured as shown in Figure 13, i.e. similar to the revolving cylinder method but with different rotation axis. The initial angle of repose was measured with an angle meter when the material started rolling and, in this case 58^{o}. The final angle of repose, in this example, was measured to 74^{o}. The difference indicated particle interlocking resulted from the increased number of contacts between the particles. Compaction in much slower rates utilizing California Bearing Ratio method (CBR) indicated changes in the angle of repose of similar magnitude [15].

Figure 13: Angle of repose measurement

The new suggested method shows wide applicability in many subjects where the study of the behavior of granular material under dynamic loading is required. Of course, different configurations can be used for studying different types of granular materials at different conditions, i.e. dry or wet.

CONCLUSIONS

The machine and method were designed to measure valuable properties which define the quality of soil or coarse-grained aggregate material and its stability. These properties are compressibility in terms of elastic and plastic deformation, density, extent of compaction zone, angle of repose. There are methods for evaluating all the above parameters but all of them measure the final values and after an impact, e.g. density and compaction. This set-up allows dynamic monitoring of the changes in density and compaction during the impact of the drop hammer on the sample in laboratory conditions. Moreover, it allows the measurement of the impact duration which might have an effect on the compaction process, as indicated by the literature.

The above described example shows the potentials of the machine for detailed studies of aggregate behavior. The impact machine can be used for examining the different existing theories and models for estimating how the material properties change during dynamic compaction. Additionally, the results from this machine can be used for numerical modelling purposes.

The proposed impact machine and the new method give reliable and consistent results for granular material behavior. Different types of aggregate materials can be used since the impact machine can host material with up to 37.5 mm particles size. The samples can be unsaturated or saturated. The impact machine can be modified in terms of drop hammer weight and shape, and the impact velocity.

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REFERENCES

1. Chow, Y., Yong, D., Yong, K., and Lee, S., 1992, "Dynamic Compaction Analysis," *J. Geotech. Engrg.*, Vol. 118 No. 8, 1992, pp. 1141-1157, 10.1061/(ASCE)0733-9410(1992).

2. Menard, L. & Broise, Y., 1975. "Theoretical and practical aspects of dynamic consolidation" *Geotechnique*, 25(1), pp. 3-18.

3. Lukas, R. G., 1995, "Dynamic Compaction – Geotechnical Engineering Circular No. 1", *U.S. Department of Transportation, Federal Highway Administration*, Washington, D.C., FHWA-SA-95-037.

4. Scott, R. A. & Pearce, R. W., 1975, "Soil compaction by impact," *Géotechnique*, Vol. 25, No. 1, 1975, pp. 19-30, **http://dx.doi.org/10.1680/geot.1975.25.1.19**

5. Mayne, P. and Jones, J., Jr., 1983, "Impact Stresses During Dynamic Compaction," *J. Geotech. Engrg.*, Vol.109, No. 10, 1983, pp.1342-1346, 10.1061/(ASCE)0733-9410(1983).

6. Poran, C. J., Heh, K. S. & Rodriguez, J. A., 1992, "Impact behavior of sand," *Soils and Foundations*, Vol. 32, No. 4, 1992, pp. 81-92, **http://doi.org/10.3208/sandf1972.32.4_81**

7. Oshima, A. & Takada, N., 1994, "Effect of ram momentum on compaction by heavy tamping", *13th International conference, Soil mechanics and foundation engineering*, New Delhi, India, Balkema, pp. 1141-1144.

8. Oshima, A. & Takada, N., 1998, "Evaluation of compacted area of heavy tamping by cone point resistance", *International conference, Centrifuge 98*, Rotterdam, Balkema, pp. 813-818.

9. ASTM D 1557, 2012, "Standard test methods for laboratory compaction characteristics of soil using modified effort (2700 kN-m/m^3) ", *ASTM International*, West Conshohocken, PA, **www.astm.org**

10. ASTM D 698, 2012, "Standard test methods for laboratory compaction characteristics of soil standard effort (600 kN-m/m^3) *"*, *ASTM International*, West Conshohocken, PA, **www.astm.org**

11. BS 812-112:1990, 1990, "Testing Aggregates. Method For Determination Of Aggregate Impact Value (AIV) ", *BSI Standards Limited*, *British Standards Online*, EBSCOhost.

12. ASTM C136/C136M-14, 2014, "Standard test method for sieve analysis of fine and coarse aggregates", *ASTM International*, West Conshohocken, PA, **www.astm.org**

13. ASTM D2487-11, 2011, "Standard practice for classification of soils for engineering purposes (Unified soil classification system)", *ASTM International*, West Conshohocken, PA, **www.astm.org**

14. Chow, Y. K., Yong, D. M., Yong, K. Y. & Lee, S. L., 1990, "Monitoring of dynamic compaction by deceleration measurements", *Computers and Geotechnics*, Vol. 10, No. 3, 1990, pp. 189-209, http://doi:10.1016/0266-352X(90)90035-T.

15. Al-Hashemi, H. M., & Bukhary, A. H., 2016, "Correlation between California Bearing Ratio (CBR) and angle of repose of granular soil", *Electronic Journal of Geotechnical Engineering*, 2016 (21.17), pp 5655-5660. Available at **www.ejge.com**.

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