Methodology for Measuring the Impact Force of Compaction Rammers

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***Abstract* – In this paper a methodology to measure impact force is proposed. It includes conceptual description of the sequence of the steps, tools needed to carry out the measurement, validation and the post processing of the collected data and automated data acquisition during end-of-line testing. The proposed concept is also putting requirements to the needed equipment.**

***Keywords* – Impact force, compaction machine, rammer, high-speed camera, measurement, guaranteed value.**

1. Introduction

In this paper a methodology to measure impact force is proposed. It includes conceptual description of the sequence of the steps, tools needed to carry out the measurement, validation and the post processing of the collected data and automated data acquisition during end-of-line testing. The proposed concept is also putting requirements to the needed equipment.

Compaction machines (rammers, forward compaction plates, reversible compaction plates and rollers) are used in the construction business to compact and smoot ground materials such as soil, gravel, asphalt, sand, and etc.

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Compaction machines have many characteristics but their performance can be measured by how much the machine compacts the ground material and how fast it does it therefore, this is really valuable information for customers. Controversially for most compaction machines, the presented characteristic is the centrifugal force which means that the main component of the machine is the rotating eccentric mass. The issue here is that the centrifugal force is not fully defining the performance of the machine regarding compaction capability. Centrifuge modeling [1] is a widely introduced method to measure soil stiffness. That type of models use the acceleration of the drum is used as input to determine the stiffness. However, there are machines which do not use eccentric mass components, such as rammers. In this case, the centrifugal force cannot be provided as a machine characteristic which is confusing for the customers. Furthermore, those systems using the centrifuge model are too expensive for the comparatively cheap rammer type of compaction machines. There were previously researches if it is feasible to use that technology on rammer type of machine, but researchers report that it cannot be used for high frequency machines [2].

For all types of compaction machines, one of the main representative characteristics is the impact force they provide. Analytical calculations of this characteristic are not very well known because of the complexity of the machines. In reality, it is much more accurate to measure the eccentric force of the machines. A reference in the literature for such suitable methodology for real end-of-line industrial measurements has not been found. Such methodology will be very useful to compare the performance of different machines in same conditions.

Furthermore, such characteristics which are descriptive of the done compaction work are not followed and not presented in the relevant product standards for rammers and plate type of construction machines EN 500-1 [3] and EN 500-4 [4]. Other characteristics are made mandatory to be followed but they are not referring to the effectivity or the efficiency of the work the machine has performed. Nowadays is also important to take into consideration such characteristic defining performance. Performance of the machine is related to its carbon print, how many passes the machine would make to finish the site, thus how much energy would be needed to finish the site – that can be influencing also the decision of the operator. That is seen as a drawback gap in today′s legislation by the authors of this paper. There is a space to introduce such a characteristic in the market.

2. Actuality of the Problem

One short definition of the process measuring is to compare the unknown value to a known one. Nowadays one of the most shown characteristic of compaction machines is the centrifugal force which might be considered enough to make a choice but in reality it does not represent the actual performance of the machine. For example, same centrifugal force for 2 machines with only difference in the plate area - the machine with smaller plate will have better impact force which will lead to a higher level of compaction. Furthermore, even if the plates are equal in area, the centrifugal force is not one solely characteristic by which to assess performance. In such cases center of gravity would impact - placement of centrifugal component, material, placement and orientation of rubber dampers, so the centrifugal force cannot be used to compare the two machines' performance.

More valuable for the clients would be to choose the product they want by machine's performance. One of the main characteristics of the performance is the impact force and the question of how to measure it stands.

Measurement of the impact force is related to a series of technical obstacles. For example, such types of machines run with 10-12 Hz but the inertia of the conventional sensors is much greater. So the accuracy of the results gathered by such means will not be reliable and always will be less than actually achieved impact force.

Analytical determination of the impact force on the other hand is also related to some restrictions which make them hard to perform in real life. In the literature, there are described methods which can be used [5] and [6], but they need a lot of input data to build the mathematical models which makes them hard to be used. There are many factors which influence on the compaction. Different factors were researched, for example some researchers focused on how the soil impacts on the efficiency of the machine [5]. In that case mathematical model was developed of the soil, taking into account the soil characteristics. Other focused on how the wight of the machine influences the compaction process [7]. Yet, the achieved compaction is influenced on all of the factors.

A need of methodology to measure the impact force is seen to be needed to be established with the possibility to automate the process with less need of input data.

3. Theoretical Basis

A widely used method to measure impact force is the use of load cells. Although recent research shows load cells are not the state of the art method - depending where the load cells are located during the impact test this could lead to a local increase in the stiffness which leads to a different result. Reported are papers evidencing for the obstacles to use load cells for such application [8]. This method is not uniform. The result of the reported method of CCC continuous compaction control [9] which is proposed on the market is not showing specific achieved value but rather comparing values and putting them under one of three classes – under compaction, best compaction and over compaction.

There are numerous analytical methods by which it is possible to determine the impact force of a certain object. In our case, the object is a complex machine consisting of various mechanisms, damping, and spring systems. In this type of machines there is not only combustion engine but complex hydraulic-mechanic driving system. Add to this the dampening effect of the soil and the analytical model describing all this is complicated and hardly manipulated.

Using simulations is a high-end way to determine the expected impact force, which requires expensive simulation software and skilled personnel. This is close to the scientific methods of investigation.

All those methods are hardly applicable in real industrial production conditions. Implementing such in end-of-line testing is practically impossible or not definitive for the exact produced machine.

Firstly a method for prototype sampling is needed to be developed and based on it a new reliable, easily implemented in end-of-line testing method will be presented. Furthermore, this unified method needs to be able to provide repeatable results.

4. Method

The concept of the method consists of a few bullet components each of which has variations with its pros and cons.

Base

The aim of the developed methodology is to assure repeatability and be used as a unified method to determine impact force. The main component in the whole system, changing significantly its characteristic is the media. For example, if compacted media is soil the result will be affected by the many characteristics soils have - type of soil, grain size, humidity, porosity, contamination of non-uniform materials, and many more. Furthermore, another obstacle to using soil as media is its ability to be overcompacted. A machine can overcompact an area with 3 - 4 passes and any results received after those passes will be unreliable.

There is a need of a material which has similar characteristics to the soil which are not changing for the period of the measurement. In this way, the repeatability of the measured values is secured.

- Touch Moment

The first parameter which needs to be identified in the proposed methodology is to know the moment the running machine touches the compacted media. This is needed because we need to know the depth to which the machine will compact the media - so we need to know in which exact moment the machine would start to compact the media.

This can be assessed by many means, but in this paper, we focused on electrical means - the idea is the first moment of touching is to be indicated by an electrical signal. Electrically conductive foil and spray were considered, which one is to cover the compacted area. Both were considered to be vulnerable to the hits of the machine - the foil can tear apart and the spray's continuity will be broken, both of which events will lead to cut the electrical circuit. That is why more robust material or coating is needed.

A good solution of the issue is to use electrically conductive compacted media and when a touching event occurs the electrical circuit will close and the signal will indicate the event. This is illustratively represented with a light bulb in Figure 1.

- Touch Period

Once the contact occurs between the plate and the media, we need to start measuring to what depth the machine will compact the media and for how much time it will reach from starting position A to the lowest depth compacted B. The way we decided to do that is by using an incremental line installed on the foot of the machine. The specific of those machines makes the foot obvious choice because all other components of the machine are moving relatively to each other - because of the dampers. So the question is how to mark the starting value on the incremental line when the machine is at point A and follow how that marking is changing to point B. The time for the machine to move from point A to point B is a few hundreds of a second - 0.02-0.04 sec. To record and observe this fast process in a reliable way, we need reliable equipment which can meet that speed requirement.

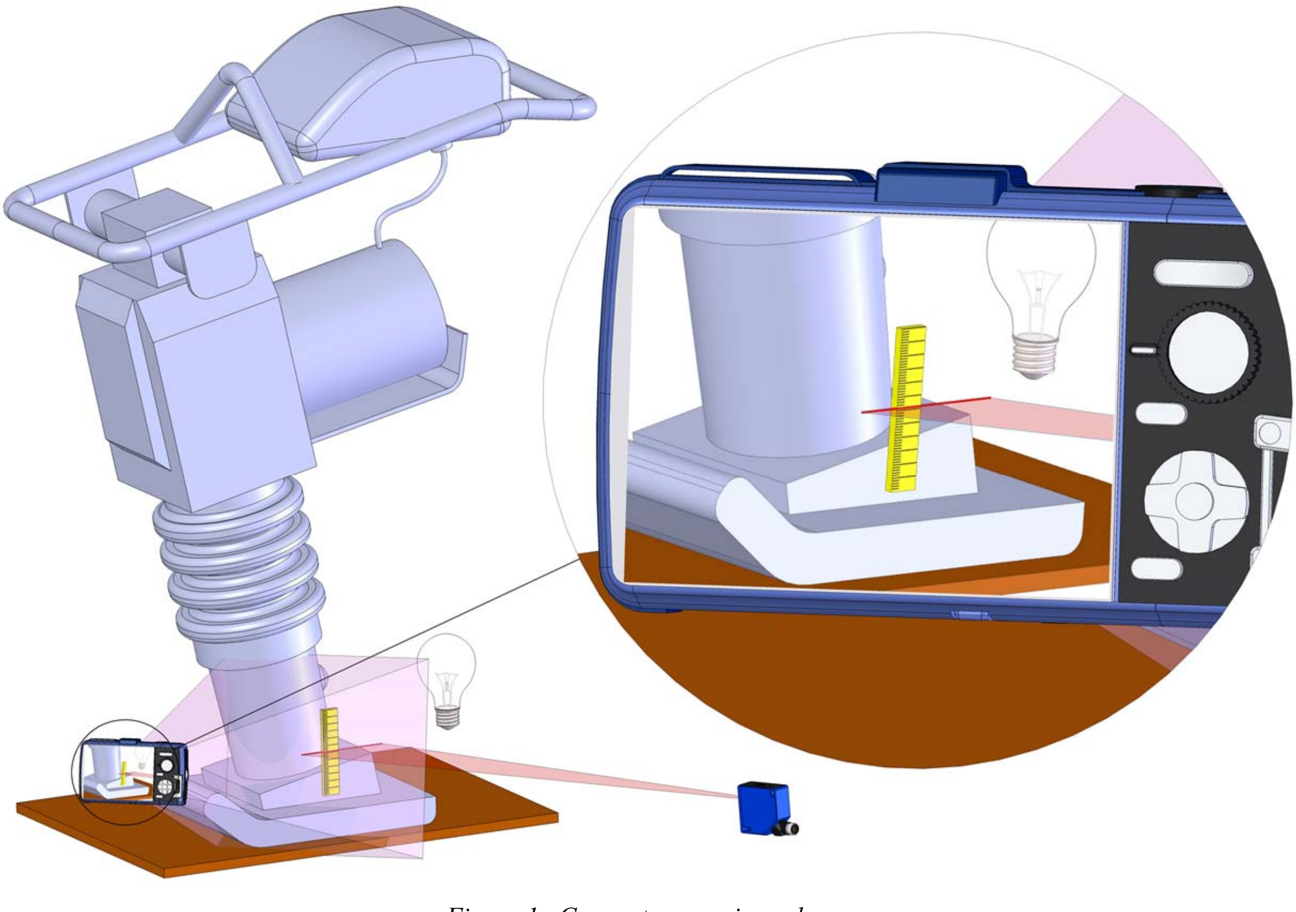

Figure 1. Concept measuring scheme

This is decided to be done via a high-speed camera but this also brings some technicalities to be resolved- parallax, angular and linear misalignment.

Parallax should be considered on how to be prevented as an optical effect. As the indicative line is on the machine itself then we needed somehow to have the pointer on the line. There were 2 proposed ways – to have a physical pointer closely placed to the incremental line or a laser line; and here is where the parallax effect made the choice for us - if it was the physical pointer then the parallax effect would have been observed. So, we naturally chose the laser line.

- Description Step-by-Step

The equipment chosen above will be used in the below consecutive steps in order to measure and determine the impact force.

The procedure starts with:

- Mounting the incremental line on the foot of the machine. The machine is put onto the chosen media;
- The high-speed camera should be positioned in such a way to clearly see the incremental line;
- Furthermore, when the machine is at position A and the machine makes first contact with the media this event should be timely noted by the camera - there should be a contact indicator. The laser line should be mounted in such a manner that the machine does not affect the stability of the source of the laser. It should be stationary mounted and the source can be mounted at a great distance from the running machine. The laser pointer (laser line) should always be pointing on the incremental line even when the machine is running;
- The machine is started;
- On the slow motion frames, the moment when the machine reaches position A should be visible and should be able to count the distance which the machine travels until it reaches position B - this frame which indicates the lowest point reached by the foot. The time for which the machine goes from A to B is recorded in the video.

Now we have the time and the distance between positions A and B.

The impact force can be calculated and we have given the input data:

$$F = 2\sqrt{2gh}\frac{m}{t}, N, \qquad (1)$$

where:
F is the impact force, N;
g is gravity, m/s^2;
h is the distance between A and B, m;
m is the mass of the machine, kg;
t is the time for the machine to reach position A to position B, s.

This way the impact force can be defined for each hit of the machine.

- Guaranteed Value

In order to assure that the received impact force value will be always in some guaranteed range different calculation statistical methods can be used. That is important because the measured value will vary due to various factors - errors from the measurement, inhomogeneity of the compacted media, human factor - machine operator, error due to the specificity of the working mode of the machine, and testing environment. An example of errors of measurement would be the lost information between frames which the slow motion camera could catch due to the limited frame per second characteristic of the camera.

For the purpose of this paper, the below statistical calculation method was used in order to determine the guaranteed values of the impact force.

The uncertainties of the impact force $u(F)$, in Newtons can be estimated by the standard deviation σ_{tot}:

$$\sigma_{tot} \approx u(F), N. \qquad (2)$$

This standard deviation is expressed by the standard deviation of reproducibility of the method σ_{ro}, in Newtons. That can include the different measurement characteristics such as uncertainties of instruments – the camera, the ruler line, etc. The standard deviation of uncertainty due to instability of the operating and mounting conditions of the source under test σ_{omc}, in Newtons:

$$\sigma_{tot} = \sqrt{\sigma_{ro}^2 + \sigma_{omc}^2}, N. \qquad (3)$$

There is an open discussion on factors which would influence the deviation of reproducibility. If those were known we could have calculated this factor for the total deviation. Yet, as they are unknown in this paper we suggest the round robin test for determining the standard deviation of reproducibility of the method. It should be carried out in accordance with ISO 5725 [10]. This requires the compaction machine under test to be determined under reproducibility conditions. That would require the test to be carried out by different testing measuring equipment, different distance rulers, the exact position of where the machine hits the floor is always different from the previous time. Such round robin test would provide us with the total standard deviation $\sigma_{tot,i}$ for just that individual compaction machine with which the round robin test was carried out. The obtained total standard deviation for this individual machine would be the reproducibility standard deviation of the method itself since it would include all uncertainties that are foreseeable for the given type of soil.

To determine the uncertainty associated with the instability of the operating, assembly conditions for one particular compaction machine σ_{omc} the test should include the same person, same compaction machine, same location, with special provisions to control as much as feasible the machine to hit the same position with each jump, same measuring equipment, and same measuring instruments.

Once the standard deviation of reproducibility and repeatability are calculated the total standard deviation is calculated. In this paper, the guaranteed impact force F_{gua} of any machine is chosen to be calculated by the formula below. This calculation is guaranteeing that any machine from the same type produced would have compaction force at least as much as the guaranteed for the given material being compacted. Different types of soils would affect greatly the resulting compaction force.

$$F_{gua} = F_{av} - \sigma_{tot}, N, \quad (4)$$

where F_{av} would be the averaged impact force of 5 different machines of the same type.

- Validation

In order to validate the results, a validation process is established. In order to do so, we proposed to compare the indicated by the above method depth in which the working machine achieved to a static load. The proposal consists of loading only the plate of the machine which weight we have measured in advance with weights and keep loading it until the same depth is achieved as it was achieved when the machine was working. This final load should be applying the same force as what was measured by the proposed methodology above - by applying that final load we consider the validation process finalized. This loading with the weights is compensating for all forces which have acted when the machine was running - gravity, the inertia of the mass, and the weight of the machine itself.

5. Conclusion

This paper proposes a method how to measure the impact force of any individual compaction machine, specifically rammer type. It proposes statistical calculation that would guarantee that any machine from the produced type would have at least the guaranteed level indicated by the guaranteed compaction force. The method can be used for end-of-line testing for validation of the production.

The testing method and the resulting guaranteed compaction value can be used as marketing material and to compare the efficiency of different models of machines available on the market.

References

[1]. Pistrol, J., Villwock, S., Völkel, W., Kopf, F., & Adam, D. (2016). Continuous compaction control (CCC) with oscillating rollers. *Procedia Engineering*, *143*, 514-521. https://doi.org/10.1016/j.proeng.2016.06.065

[2]. Arkadiusz, K., Jan, M., & Sebastian, B. (2022). Monitoring soil state during compaction process using a vibrating rammer and a plate compactor. *Journal of Terramechanics*, *100*, 61-72. https://doi.org/10.1016/j.jterra.2022.01.002.

[3]. EN 500-1:2006+A1:2009, Mobile road construction machinery. Safety Common requirements. Retrieved from: https://www.en-standard.eu/bs-en-500-1-2006-a1-2009-mobile-road-construction-machinery-safety-common-requirements/ [accessed: 18 May 2022].

[4]. EN 500-4:2011, Mobile road construction machinery. Safety Specific requirements for compaction machines. Retrieved from: https://www.en-standard.eu/bs-en-500-4-2011-mobile-road-construction-machinery-safety-specific-requirements-for-compaction-machines/ [accessed: 18 May 2022].

[5]. Debeleac, C., & Oproescu, G. (2009). Non-linear Behaviour of a Soil Compaction Equipment. In *Proceedings of the EURO-Mini Conference* (p. 114). Vilnius Gediminas Technical University, Department of Construction Economics & Property.

[6]. Schindler, C., Schwickert, M., & Yang, X. (2012). Dynamic behaviour of a vibration tamper by multi-body simulation. *International Journal of Heavy Vehicle Systems*, *19*(3), 225-243. DOI: 10.1504/IJHVS.2012.047914.

[7]. Morariu-Gligor, R. M. (2014). Study of the influence of plate compactor weight on its functioning. *Acta Technica Napocensis-Series: Applied Mathematics, Mechanics, and Engineering*, *57*(2).

[8]. Bethe, K. (1994). Optimization of a compact force-sensor/load-cell family. *Sensors and Actuators A: Physical*, *42*(1-3), 362-367. https://doi.org/10.1016/0924-4247(94)80013-8.

[9]. Chen, C., Hu, Y., Jia, F., & Wang, X. (2022). Intelligent compaction quality evaluation based on multi-domain analysis and artificial neural network. *Construction and Building Materials*, *341*, 127583. https://doi.org/10.1016/j.conbuildmat.2022.127583

[10]. Standard, I. S. O. 5725-2.(2019) Accuracy (trueness and precision) of measurement methods and results—Part 2: basic method for the determination of repeatability and reproducibility of a standard measurement method. *International Organization for Standardization, Geneva, Switzerland*. Retrieved from: https://www.iso.org/standard/69419.html?browse=tc [accessed: 20 May 2022].