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Scaling of particles and equipment by experiments of an excavation motion

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ABSTRACT

Designing more efficient excavating equipment in bulk handling is a complex task as accurate analytical models for the interaction between bulk material and equipment are rare. Particle based simulations of bulk material executed by Discrete Element Method (DEM) offer an approach in evaluating the performance of prototypes. However, due to their high computational costs, these simulations often require the use of particles larger than in reality. Until now it is uncertain to what extent this simplification affects the predicted performance of the equipment, as literature on this topic is scarce.

This work investigates the effect of scaling particle and equipment size on the performance of an excavation motion characteristic for excavating equipment such as grabs, reclaimers and bulldozers. This performance was assessed by comparing the required excavating force for different sizes of the equipment and different particle sizes using experiments. First the applicable scaling laws were derived and, based on those results, an experimental setup was built for measuring the force required to excavate material using a bucket geometry. Glass beads were selected as representative material, since they can easily be obtained in several sizes. For comparison also experiments with gravel and iron ore were performed. The effect of scaling particle and equipment size was studied by using three scaled combinations of particles and equipment (scales A, B and C), and by separately changing the excavating speed and particle sizes of the glass beads.

Based on the tests it can be concluded that the scale factor is not constant during the excavating motion and that the derived scaling law (force ~ (characteristic length)^3) is not representative for scaling the excavation motion. The current scaling used one single factor for every bucket dimension, it is therefore recommended to investigate different scaling approaches by taking into account the different dimensions separately. In addition, the experiments revealed that there was no effect of the particle size (d) and blade thickness (t) ratio on the measured energy required for excavating with the smallest scale buckets (A and B), however for the largest scale bucket it is worthwhile to further investigate this in the region of $d/t > 1,5$. This is specifically of interest when scaling particles in DEM simulations to reduce computational time by increasing particle sizes.

1. Introduction

Scaling is a widely used concept in engineering and mainly used to predict the outcome of full scale behavior by performing experiments on a small scale model. The results of these small scale experiments are then converted to full scale. However, in the field of bulk solid properties and the interaction with equipment however, scaling is not as well implemented as in other engineering fields.

Full scale experiments are seldom performed in bulk handling, mostly because of the high costs. Nevertheless the results are required for gaining knowledge and validating small scale experiments, experimental tests and design methods, and DEM simulations as stated by Lommen et al. [1]. Of particular interest is the scaling of an excavating motion that represents digging and penetration motion characteristic for grabs, reclaimers and bulldozers for non-cohesive materials, as these processes depend on the particle size according to Gebhardt [2].

For silo design several researches on scaling were carried out. Wojcik et al. [3] demonstrated that, as a consequence of scaling errors, recommendations for the design based on results obtained with small scale experiments, could turn out to be wrong in full scale. Four different silo inserts, varying in size and location, were tested at full scale. The authors compared their work with various experiments with inserts in silos at small scale presented in literature. They found that small scale results of stresses cannot be transferred directly to full scale as a result of size effects. These are primarily caused by the pressure level, but also due to difference in the size ratio between the particles and the silo, as well as the difference in particle size distributions.

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Beverloo et al. [4] was the first who experimentally investigated the outflow rate of silos extensively, leading to the well-known Beverloo equation. This empirical relation for non-cohesive materials expresses a relation between the outflow rate, orifice size and particle size. Johanson [5] discusses scale-up parameters for silos, to obtain knowledge for meaningful small scale experiments. With numerical examples the author showed that in the most cases when using the same bulk material in small scale as in full scale, it is not possible to keep the ratio of major principal stress and unconfined yield stress constant both in small and full scales. Hereby small scale experiments can produce completely different behavior than exhibited in the full scale silo. The author also states that to assure the same dynamical effects during outflow in the model silo as in the full scale silo, the acceleration of the bulk solids must be the same.

Behavior of cohesive bulk solids in scaled silos can only experimentally be investigated with the aid of a bunker centrifuge, as a result of the strength which cohesive materials gain under compression [6–8]. This is left out of consideration here as this research focuses on non-cohesive materials.

For material flowing down a plane such as in transfer chutes, Augenstein et al. [9,10] and Pouliquen [11] investigated scaling of particle size, bed thickness, inclination angle and roughness of the plane. Their research resulted in empirical scaling laws and an empirical relation for the friction coefficient between the granular layer and the rough bed as a function of the mean velocity and the bed thickness. The material consisted of quasi monodispersed glass beads and the authors indicated that the effect of angular particles should be further investigated.

Recent research by Coetzee and Els [12] on excavation equipment states that analytical methods used to model soil–tool interaction [13–17] are limited to infinitesimal motion of the tool and the given geometry of the problem. These methods are not expected to be valid for the analysis of the subsequent stages of advanced earth digging problems, according to Maciejewski and Jarzębowski [18]. The analytical methods are based on Terzaghi's passive earth pressure theory and assumptions of a preliminary soil failure pattern [19]. Complicated tool geometry (such as buckets) and large deformations cannot be modeled using these methods (Karmakar and Kushwaha [20]). This also means that these analytical models cannot be used for scaling the interaction between material and equipment. In addition these methods cannot account for the effect of particle size on the digging performance.

The experimental and numerical research of Coetzee [12] investigated the performance of a bucket for a single particle size distribution and a single blade geometry and an unknown blade thickness. For the specific situation of digging or penetration process in bulk handling or earth moving no other literature on the effect of particle scaling, equipment scaling and equipment performance was found.

Poschel [21] claimed that small scale experiments, in which only the particle size and the equipment geometry are scaled with the same scaling factor, might cause wrong results. For similar dynamical behavior, also particle properties have to be scaled such as Young's modulus and density, causing a practical problem of selecting the appropriate material. They have demonstrated this only with one numerical simulation of one specific case: material sliding of an inclined slope.

However, from literature it can be concluded that for scaling physical bulk solid handling experiments there is no widely adopted theory available. In addition, it remains unclear to what extent results from previous research will be valid for different types of granular processes such as excavation of granular materials, where the penetration interaction between equipment and particle plays an important role.

This paper investigates the effect of scaling both particle size and equipment size on the equipment performance. An excavating motion characteristic for grabs (Fig. 1a), bulldozers and reclaimers was selected as representative motion for the closing range of a grab (Fig. 1b). As shown in the figure, in practice the grab is lowered in open position onto the bulk material (top) and from there will be gradually closed

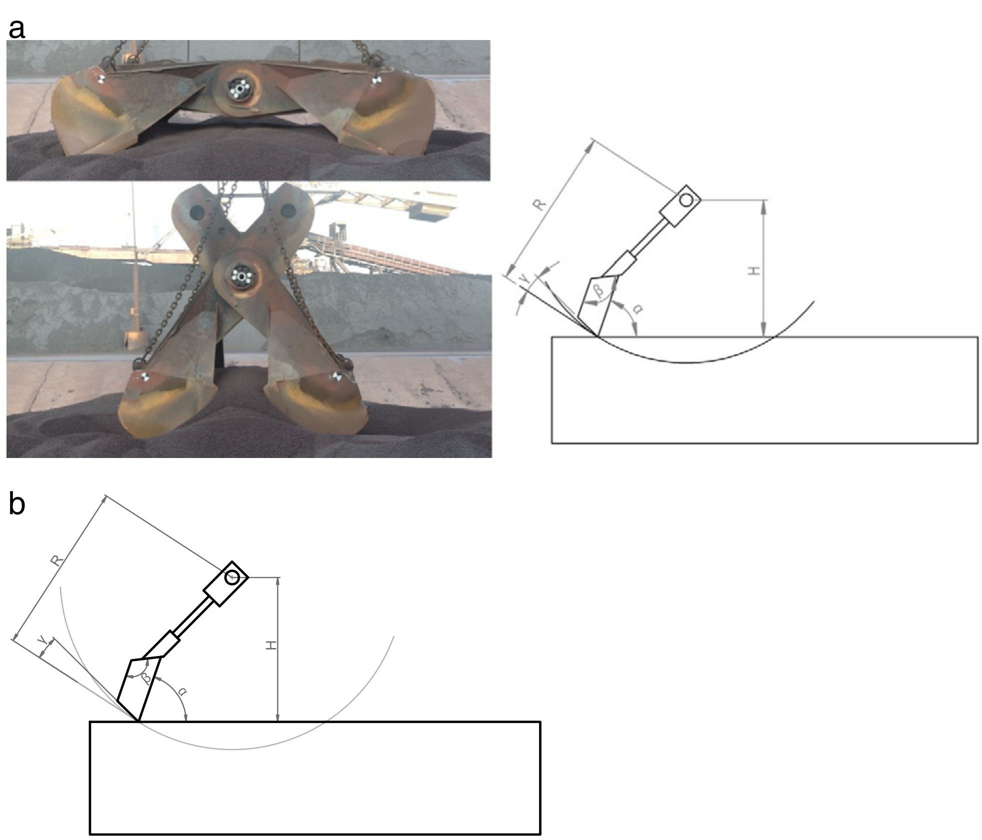

Fig. 1. (a) Grab in industrial practice (top: initial position, bottom: excavating while closing); and (b) chosen excavating motion around a fixed pivot point.