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Buoyancy and local friction effects on rockfill settlements: A discrete modelling

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Abstract

Measured displacements in the upstream shell of rockfill dams show some settlements which can reach a few meters with water levels changes, especially during the first impounding, whereas downstream displacements are smaller. Complementary phenomena are responsible for rockfill collapse due to wetting. Here we numerically investigate the effects of buoyancy forces and the decrease in the coefficient of friction with water on a rockfill column maintained by vertical rigid walls and progressively filled with water. Numerical simulations of the settlements of the rockfill column, using the Contact Dynamics method, are presented. Buoyancy forces seem to have only a negligible influence on the granular pile. Decrease in the friction angle of the rock with water induces rearrangements of the medium, all the more as the decrease is significant. These dynamic rearrangements exhibit an irregular temporal evolution of the granular medium which can be characterized by a phenomenon of local "crisis". Analysis of the settlements shows that these two combined effects are not the major cause of the settlements observed in rockfill dams and that they cannot in particular explain the settlements.

Keywords: Rockfill; Buoyancy; Friction; Granular medium; Discrete modelling; Wetting; Collapse

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1. Introduction

Rockfill dams are made up by coarse materials, blocks, whose dimension can reach up to one meter. Observations collected in the upstream shell of rockfill dams show a slow accumulation of deformation over many decades, and a collapse is often noticed when these shells are submerged. A collapse can also be observed on downstream shells in the case of heavy rainfall [1,2]. As the physical local phenomena governing the deformation observed occur at the grain scale, it is important to use a discrete approach to take into account each block in the simulation so as to have an understanding at the particle level. So the choice of a discrete element method allows the study at the grain scale the local phenomena that are not easily measured in conventional experimental tests. This is of real interest to civil engineers who do not possess accurate tools to assess and investigate granular mechanics (no consideration of local blocks' instabilities are available with finite element models).

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Two complementary mechanisms were identified to explain the rockfill dams' settlements [3–6]: (a) lubrication and attrition of asperities; (b) breakage of particles initiated at contact points which can lead to global rock breakage or edge crushing.

The aim of this work is to assess the rearrangements induced in the structure during a water filling procedure. The use of a discrete element simulation appears to be a suitable tool to quantify the localized settlements in the whole structure. This phenomenon is mainly driven by the presence of water that lubricates and enhances crushing and attrition of the asperities at contacts points; this possibly leads to local destabilization in the medium. These local effects are taken into account via the introduction of a wet coefficient of friction, μ_{wet}, which is assumed to be lower than the dry coefficient of friction, as measured by Cambou [7]. Indeed, in an experimental study on friction of natural rocks, Cambou has shown that the coefficient of friction generally decreases in the presence of a liquid. Note that this is not observed for glass beads since Skinner measured an increase of the coefficient of friction when particles are flooded [8]. Nevertheless, the physical phenomena governing the friction between two rocks in the presence of water (see Section 2.2.3) cannot be simply compared to the friction of glass beads which would correspond here to an over-simplified model of the granular medium.

In this work, we propose a two-dimensional discrete modelling of a rockfill pile, flooded by water. Firstly, the numerical study is briefly presented with a description of the discrete element method used, followed by the different actions of water in the intergranular space: buoyancy forces and diminution of the interparticle friction angle are both implemented. Then we focus on the local phenomena taking place when the reservoir is filled with water. The specific influence of each effect is discussed separately. Finally, the results of the discrete simulations are compared with a finite element simulation of a rockfill hydroplastic model [9] which has already been validated.

2. Numerical modelling

2.1. Simulation method

Our simulations are based on a discrete element approach, the Non-smooth Contact Dynamics for short Contact Dynamics [10]. In the Discrete Element Methods, each individual particle is modelled separately and its motion is induced by the interactions with its neighboring particles [11]. Usually, these discrete methods neglect the role of any interstitial fluid filling the space between grains; therefore a collection of grains is entirely driven by the equations of motion and by the contact laws ruling the collisions and the friction between grains.

In this paper, we only present the main hypothesis of the Contact Dynamics method. This method uses an implicit resolution of the contact forces. It is based on unilateral contact and therefore on impenetrability, which means that particles which are candidates for contact must not cross the boundaries of antagonistic bodies [12]. The bodies are perfectly rigid. The friction at contact is described by the classical Coulomb's law, given μ the contact coefficient of friction, sliding occurs between particles when the threshold $R_t = \pm\mu R_n$ is overcome, where R_t and R_n are the tangential and the normal forces at contact. In Coulomb's law, when sliding occurs, the frictional force remains opposite to the sliding velocity and keeps the value attained at the threshold. These contact laws allow to model multiple collisions between grains. Moreover, a coefficient of restitution can be introduced which controls the velocity of the grains after the collision. In our simulation, this coefficient is set equal to zero so as to remain in a quasi-static situation. Although the events and processes that happen at the surface between several bodies are various and complex, these simple contact laws enable us to reproduce the dynamics of a collection of rigid grains.

2.2. Discrete element model

2.2.1. Major features

To model the rockfill, we have simulated with the Contact Dynamics method a two-dimensional column of rigid circular particles, held in position by two vertical rigid walls and a bottom horizontal base. The initial configuration is generated by a gravity deposition of about 1000 grains. The media is bidisperse and the diameters Φ of the grains are taken equal to 60 cm and 1 m to deal with the real rockfills. The bidispersity of the grain size is introduced to prevent any crystal-like ordering. The mass density of the grains is $\rho_{G\text{dry}} = 2.65$ kg/m^3 per unit length. The dry microscopic coefficient of friction equals $\mu_{\text{dry}} = 1$, a very high value, to take into account the angularity of the blocks. The coefficient of friction at the walls is also taken to be equal to 1. With this set of parameters the granular packing

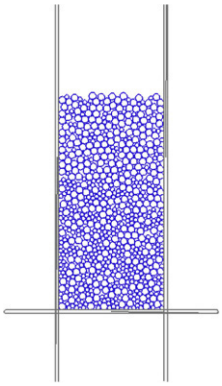

Fig. 1. Column of rockfills prepared by gravity deposition.

prepared by rain deposition under gravity has an initial packing fraction, or compacity, equal to 0.77. The height and the width of the column are respectively $H_0 \approx 31$ m and $L = 15$ m, and its top surface is almost flat as can be seen in Fig. 1. Then, the rockfill column is "virtually" filled with water with a filling velocity $V = 0.1$ m/s. H_w represents the water height in all the following discussion.

2.2.2. Buoyancy forces

The presence of water is first introduced by taking into account the buoyancy forces, which are implemented as follows: a grain entirely submerged has a mass density $\rho_{G\text{wet}} = \rho_{G\text{dry}} - \rho_{\text{water}}$, and for a grain partially submerged, we use for the mass density a linear interpolation with height between $\rho_{G\text{dry}}$ and $\rho_{G\text{wet}}$. Note that the inner porosity of the rock is neglected so that we do not consider any water infiltration in the micropores.

2.2.3. Decrease of the coefficient of friction with water

The second effect of water is introduced by changing the coefficient of friction of the Coulomb's law for a wet contact. A contact friction law with the two different coefficients of friction (dry and wet) is then implemented in the software.

To our knowledge, only a few works have been developed to assess the value of the wet coefficient of friction of rocks. So we do not have a reliable estimation of this coefficient of friction change with water but it is generally believed that the coefficient of friction decreases in the presence of a liquid at the contact points. This decrease has been verified experimentally in limestone, basalt, diorite, etc. [7]. On the contrary the coefficient of friction increases in the case of gneiss or for glass beads as already mentioned. This decrease can be justified by the possible existence of a water film at the contact zone between two blocks which enables a slight lubrication at interparticle contact points. In addition, the decrease of the coefficient of friction can be set off by the breakage of micro-asperities that create some debris on which particles can easily roll. Note that this last phenomenon also exists when the medium is dry. Indeed, a slip motion can infer breakage, attrition and disimpaction of the asperities [13] in such a way that the friction force can drop; then the resistance R_n becomes smaller than the threshold formerly reached to start the slip. This phenomenon is enhanced by the presence of water, which induces physico-chemical phenomena, like corrosion for instance, particularly at high stress points on the grain surface.

Starting from these ingredients, we have carried out numerical simulations to study the influence of each phenomenon in order to estimate each contribution to the settlements measured.

3. Numerical results

3.1. Influence of the buoyancy forces

Only a few models are used to simulate reservoir filling of dams. And, to our knowledge, none of them has simulated precisely the local effects of the hydrostatic forces on the whole structure. To do so, the rockfill column is slowly filled with water at a velocity $V = 0.1$ m/s. To analyze the rearrangements in the medium, we have

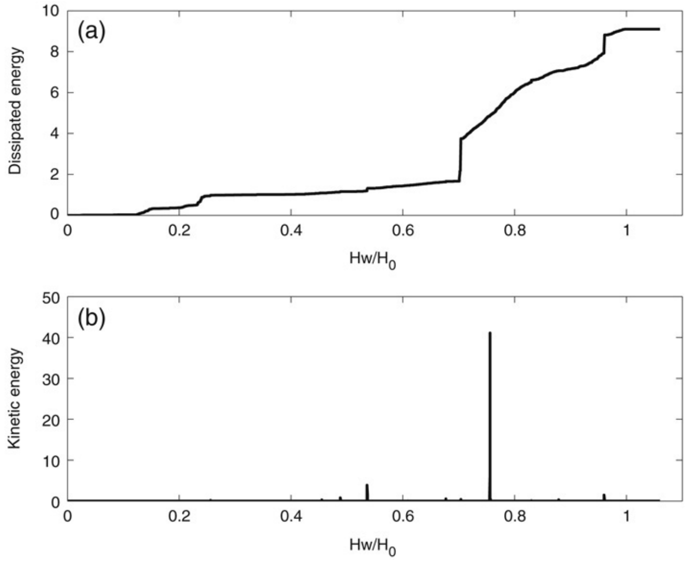

Fig. 2. Evolution during water filling of (a) the energy dissipated by contacts and of (b) the kinetic energy (both energies are expressed in Joules).

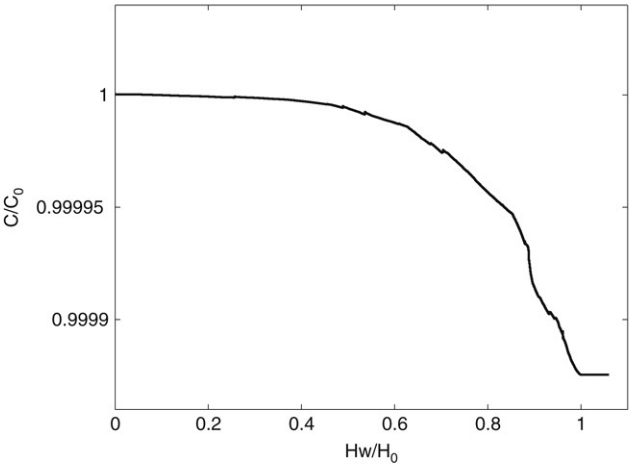

Fig. 3. Evolution during water filling of the ratio between the compacity C and the initial compacity C_0.

evaluated the energy dissipated by the contacts. This energy is the sum over all contacts i of the product of R_{ti}, the tangential reaction at contact i, with V_{ti}, the corresponding velocity of the contact:

$$E_D(t) = \sum |R_{ti} V_{ti}|. \tag{1}$$

As can be seen in Fig. 2(a), the evolution of E_D is irregular while water is progressively filling the column. This irregular evolution is also visible in the fluctuations of the kinetic energy presented in Fig. 2(b). These fluctuations reflect the succession of dynamical destabilizations of the column. The kinetic energy is composed of a translational and a rotational component, and the destabilizations are both due to particle translations and rotations.

Although we can observe some signs of reorganization while filling, these fluctuations are sparse and their intensity is quite low. As one observes the evolution of the packing fraction of the medium, Fig. 3 shows that the granular packing tends to dilate while filling. But note that the variation is at the same order of magnitude than the numerical precision. It is therefore difficult to conclude about it. The coordination number, which represents the mean number of contacts by particle also decreases while filling. This is in accordance with the previous result but here again the difference between the initial coordination number and the final one is hardly significant (3.26 vs 3.2). Finally, we can

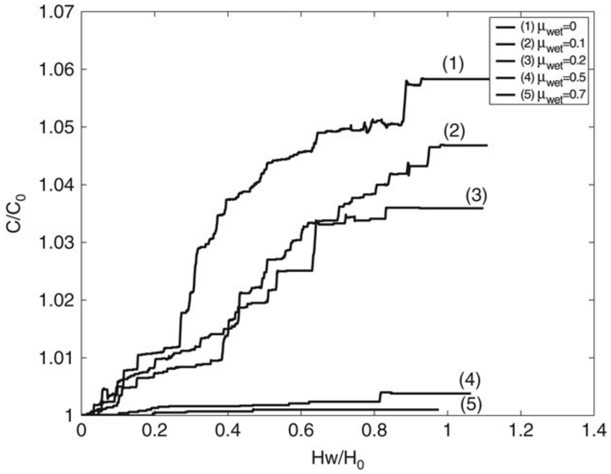

Fig. 4. Evolution during water filling of the granular column compacity for various values of μ_{wet}.

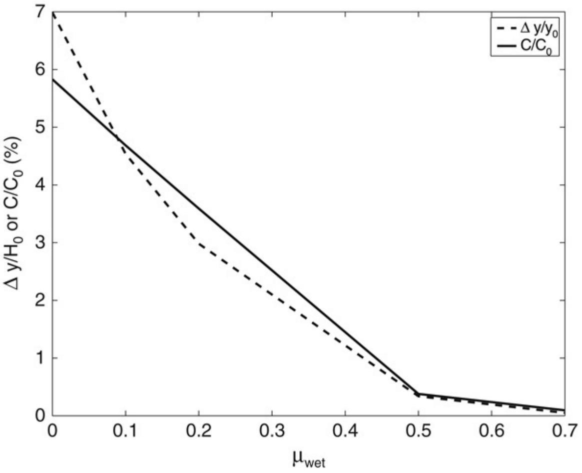

Fig. 5. Variation during water filling of the final compacity and the final settlement for various values of μ_{wet}.

conclude that, during water filling, buoyancy forces alone have almost a negligible effect on the global settlement of the granular column.

3.2. *Influence of a decrease of the coefficient of friction with water*

In this section we investigate the effects of a decrease in coefficient of friction with water so as to assess their role in the settlements of the whole structure. Then, in our simulation, we introduce a wet coefficient of friction μ_{wet} for the contacts situated below the moving water level. Five values of μ_{wet} are used: 0, 0.1, 0.2, 0.5, and 0.7. The last two values are more realistic compared to the high initial value of μ_{dry}. The other ones permit to amplify the phenomena of sliding and rearrangement in the granular packing.

The results presented here take also into account the buoyancy forces, so as to illustrate the more relevant physical case. Therefore, the following handles the influence of the hydrostatic pressure when it is coupled to the coefficient of friction decrease with water.

First of all, a diminution of the volume (per unit length) of the sample is noticed with the decrease of the friction angle as the column is filled up by water. As could be expected, the volume diminution shown in Fig. 4 is all the more pronounced that the wet coefficient of friction is low. This increase of the compacity is directly related to a settlement of the column crest as observed in Fig. 5. We can note that the results displaying compacity and settlement

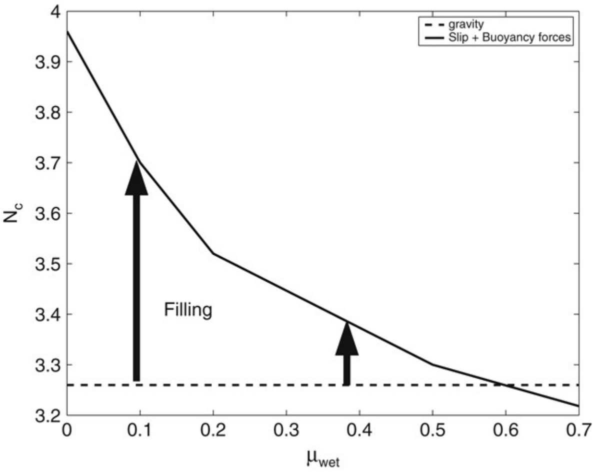

Fig. 6. Variation during water filling of the final mean coordination number for various values of μ_{wet}.

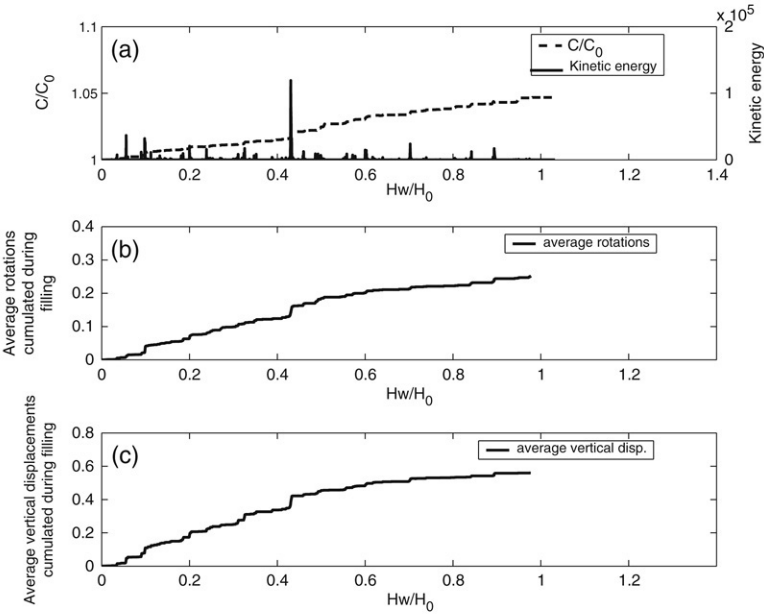

Fig. 7. Evolution of (a) the kinetic energy and the compacity, (b) the average rotation and the mean vertical displacement of particles (c) cumulated during the filling procedure.

evolutions are in good agreement. The final coordination number N_c, presented on Fig. 6, follows the same tendency that therefore underlines the contraction of the media.

In addition, an irregular evolution is observed here again. It appears that there is a succession of intermittent events which correspond to local destabilizations owing to the mobilization of friction between particles, leading to some kind of dynamic "crisis" where grains rearrange themselves in some zones of the column. Even if almost unrealistic, the case of a low wet coefficient of friction, namely $\mu_{\text{wet}} = 0.1$, gives a good insight into this phenomenon as can be seen on Fig. 7.

During water filling, the compacity as well as the mean rotation and the vertical settlement of the particles evolve by discrete steps, directly correlated with the kinetic energy peaks. This "crisis" activity can also be illustrated by the occurrence of numerous critical contacts, or sliding contacts, which reach the Coulomb threshold, μR_n with $\mu = \mu_{\text{dry}}$ or μ_{wet} depending on the water height. This kind of phenomenon has already been studied by Staron [14], in a granular

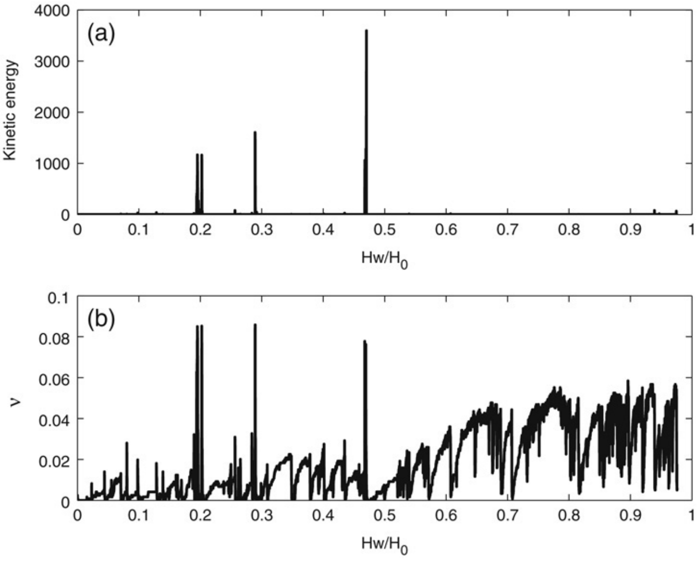

Fig. 8. Evolution during water filling of (a) the kinetic energy in comparison with (b) the critical contacts of the system for $\mu_{\text{wet}} = 0.7$.

bed, initially horizontal and tilted with a constant rotation rate, to analyze avalanche precursors. Such a critical contact cannot sustain any further shear force increment and can eventually lead to a local reorganization by slip motion or to the disappearance of the contact. The evolution of the critical contacts is described by their density ν, as defined by Staron, $\nu(H_w) = N_{\text{crit}}/N_{\text{tot}}$ where N_{crit} and N_{tot} are respectively the number of critical contacts and the total number of contacts within the granular packing at any given water height H_w. Fig. 8 shows, for a more realistic value of the wet coefficient of friction, namely $\mu_{\text{wet}} = 0.7$, the variation of the density of critical contacts during water filling, in comparison with the evolution of the kinetic energy of the system. Note that with a low value of μ_{wet}, the corresponding threshold induces a high number of critical contacts during almost all the flooding, making it difficult for the critical contacts to be correlated with the peaks of kinetic energy.

The local destabilizations already mentioned for the kinetic energy of the granular column can be observed once again for the density of critical contacts with rapid fluctuations during water filling. In addition, these fluctuations are in accordance with the kinetics energy peaks and correspond to dynamical rearrangements, or local crisis, where particles can slide one over the other or lose contact. Critical contacts are then, in a major part, renewed while filling even though their density seems to increase during the simulation.

A last question concerns the localization of these dynamical rearrangements in the internal structure of the granular column. We here compute pile granular rearrangements during a peak of kinetic energy, where activity is the more intense. Four times are chosen to describe the peak, as plotted in Fig. 9(a): t_1 and t_2 are chosen respectively before and just before the peak, t_3 corresponds to the maximum of the peak and finally t_4 is chosen just after the peak. We have computed the average rotation and vertical displacement by layers of particles for each time. The reference time t_1 corresponds to $H_{\text{water}} = 13.05$ m. Each layer is taken equal to $2\Phi_{\max}$, where $\Phi_{\max}$ is the maximum grain diameter. The column is then composed of 16 layers, each layer corresponding to an equivalent altitude in the column. Concerning the localization of these dynamical rearrangements, in Fig. 9, it clearly appears that their major part occurs at the water level and above it. So once they have already undergone rearrangements and been settled, the layers below the water front do not evolve anymore.

Studies of the column filling, taking into account only the decrease of the coefficient of friction have also been carried out. The results reveal the same kind of behavior, namely the existence of dynamical rearrangements, crisis and irregular kinetics. Nevertheless, when combined with the buoyancy forces, this decrease of the coefficient of friction with water leads to a higher compaction of the granular medium. This can be seen in the evolution of the column packing fraction in Fig. 10 for $\mu_{\text{wet}} = 0$ and 0.2 (note the few differences in the case $\mu_{\text{wet}} = 0.1$). Consequently, it appears that the presence of an additional external force, here buoyancy force, enhances the possibilities of particles rearrangements, and therefore enables a higher settlement of the pile. It is however difficult to conclude in both cases that $\mu_{\text{wet}} = 0.5$ and $\mu_{\text{wet}} = 0.7$ when the increase of compacity undergone by the medium is very slight.

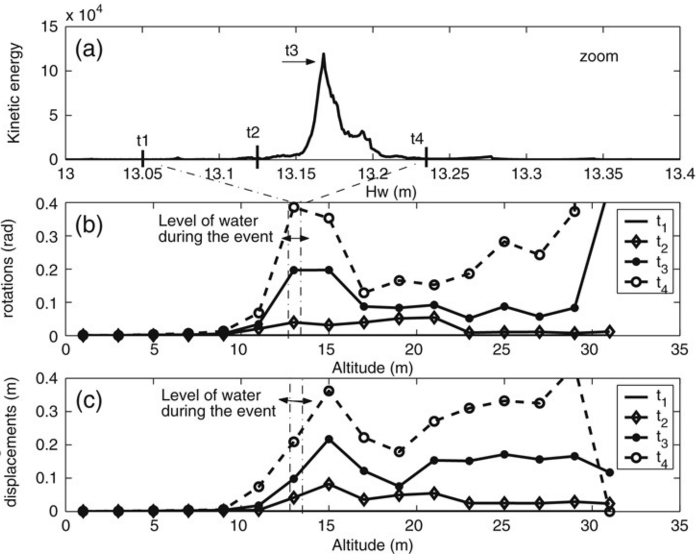

Fig. 9. Evolution during a peak of kinetic energy (in (a)) of (b) the mean rotation and (c) the mean vertical displacement for $\mu_{\text{wet}} = 0.1$.

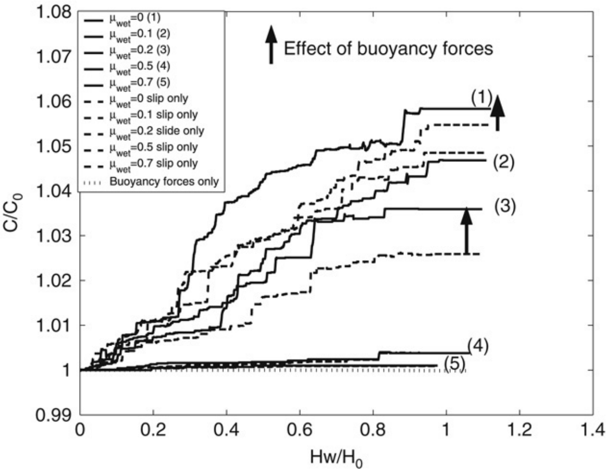

Fig. 10. Comparison of the compacity computed with the decrease of the coefficient of friction alone (dotted lines) and combined with the hydrostatic pressure (bold lines).

This diminution of the overall volume can also be observed on the evolution of the coordination number, since the coordination number calculated with both effects is slightly lower than the one calculated only with the increase in coefficient of friction in water.

4. Discussion

It is important to remind that the scope of our study was, in the first instance, to understand and analyze physical local phenomena when a column of rockfill is filled up with water. This kind of study is of immediate interest for civil engineers who wish to assess the settlements induced by the filling. This model needs therefore to be compared with other studies. The model chosen in the literature is termed the hydroplastic model [9]. This finite element model, which takes into account the presence of water in the media and the grains crushing, predicts settlements in accordance with the observation in the field. This model predicts 0.5% settlements (Fig. 11). Our model overestimates this settlement when μ_{wet} is very low (0, 0.1, 0.2). In addition, it is important to remind that our simulations do not take into account grains breakage which is however the main cause of collapse [2]. Our simulations should then predict settlements

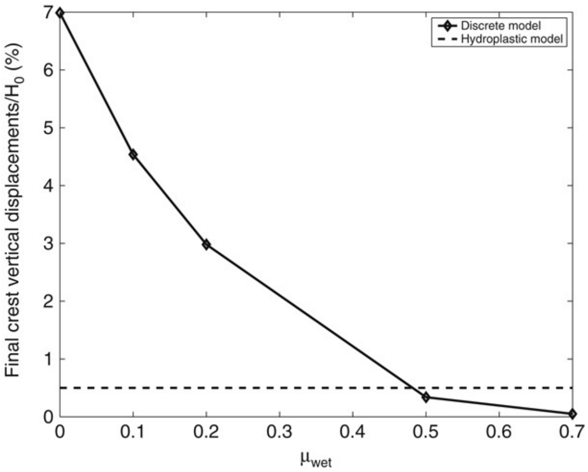

Fig. 11. Comparison of the settlements predicted by the discrete element model and by the hydroplastic model.

lower than 0.5% since we do not consider here all the effects induced by water. In short, 0.5% must be the total settlements generated by all the water effects. Consequently the model underestimated on a phenomenological way the real physical phenomena of rockfill in contact with water. So relevant values of μ_{wet} correspond necessarily to $\mu_{\text{wet}} > 0.5$. This back analysis validates experimental results found by Cambou [13] which have shown only a small decrease of the coefficient of friction with water.

5. Conclusion

This work proposes a micro-mechanical study to account for the role of water in the collapse of a flooded rockfill column via the influence of buoyancy forces and of a coefficient of friction decrease with water. The discrete approach allows access to phenomena that take place at the grain scale and therefore enables detailed study of the dynamics of the grains. The simulations have brought out the occurrence of a succession of local destabilizations undergone by some particles, also mentioned as dynamical "crisis", and localized at and over the mobile water front. These rapid rearrangements give rise to significant fluctuations of the kinetic energy and of the density of critical contacts, as well as to an increase of the mean particles displacement and rotation. Buoyancy forces alone seem to have an almost negligible role. Then we introduced a microscopic wet coefficient of friction, lower to the microscopic dry coefficient, to account for both attrition and lubrication of the grains at contact. This parametrical study has permitted to amplify the local physical phenomena. The influence of this decrease in coefficient of friction on the rockfill settlements can only be underlined for very low values of μ_{wet} which are not relevant to our study. This is in agreement not only with experimental and numerical results found in the literature, but also and above all, with the idea that rock breakage may be the major cause of rockfill collapse. In particular, the time dependent behavior of the rockfill, observed in situ for long periods, underlines that there can be a delay between the water invasion and the local reorganisation of the grains. Such a delay is likely to be due to fracture at work that propagates progressively into the grain. In the work that will follow, our model has to be improved to account for this breakage process at the grain level.

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