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On the Origin of Sand Injectites in Bahrah Area, Northern Kuwait Bay: A Fluid Dynamic Numerical Modeling

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Abstract

This work aims at describing from a fluid dynamic point of view the occurrence and the origin of sand injectites outcrops observed in two sites within the Bahrah coastal plain area, northern Kuwait Bay, through analogies with the knowledge on spouted beds. For non-cohesive systems, the channel formation can be easily reproduced through Eulerian–Eulerian computational fluid dynamics (CFD) simulations. When a certain fluid inlet velocity is set, the fluid breaks through the bed of particles creating the central channel. Cohesiveness, most likely present and relevant in the field of interest, was introduced by simulating the fluid–sand multiphase system with the CFD software adapted to satisfactorily describe previously reported field observation. To simulate such systems, the volume-of-fluid (VOF) method yielded the best results. In fact, cohesiveness can be taken into account through the Bingham model, which introduces additional parameters to estimate, and these parameters determine whether the fluid can create a central vertical channel or diagonal cracks. The CFD simulations proved to be a valid tool to reproduce laboratory-scale observations and may further explain the mechanisms behind these enigmatic formations, confirming the role of fluid–solid drag in the creation of the injectites. Future works will address further development of this approach and the application on larger scales.

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Keywords

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1 Introduction

The origin and properties of sand injectites have been investigated by scientists for centuries, with many aspects still being unclear (Hurst et al., 2011). Two recent works have focused on those that can be observed in the Bahrah coastal plains, northern Kuwait Bay, pointing out their features and differences through various analyses (Al-Hajeri et al., 2020, 2021).

Several geological phenomena, including sand injectites, are caused by fluid–solid transport phenomena. The underlying physical mechanisms are similar to those that can be found in different fields, such as fluidization in chemical engineering. Thus, similar modeling strategies may be useful to obtain numerical predictions that would not be possible to achieve experimentally. Fluidization has often been reproduced through computational fluid dynamics (CFD) simulations, based on the numerical solution of local balance equations. Different techniques permit reproducing the solid phase, with advantages and disadvantages (Guo & Yu, 2017; Moliner et al., 2019a; Pan et al., 2016), also for the case of soils (Zhou et al., 2019).

Experimental observations from the literature can be relevant in the context of sand injectites formation: Nermoen (Nermoen, 2010) shows a comparison of the different behaviors of non-cohesive and cohesive solid particles when subjected to a fluid flow. This is comparable to the discrepancies between Site 1 and Site 2 reported in the previous papers about the Bahrah injectites (Al-Hajeri et al., 2020, 2021). Cohesive forces are common in soils, complicating the simulation setup. Several approaches have been

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proposed, whose validity depends on the origin and intensity of the forces (Xu et al., 2022). This preliminary work investigates the application of such approaches to a physical configuration that may be useful in understanding the origin of the Bahrah injectites, reinforcing the hypotheses on their origin.

2 Methods

We performed the simulations with the well-known commercial program Ansys Fluent. For the sake of brevity, the equations of the various models are not included here but can be found in the program's guide or in previous publications. The expected fluidization pattern resembles that of spouted beds (Moliner et al., 2017), which are often simulated via CFD, with both discrete- (Marchelli et al., 2019) and continuum-based (Moliner et al., 2019) methods for solids. Since the involved particles are very fine, the latter are more appropriate due to the lower computational requirements (Moliner et al., 2019). Non-cohesive particles are often simulated through the reliable and established kinetic theory of granular flows (KTGF) (Moliner et al., 2019). This approach can be modified to include cohesive forces (Zhong et al., 2020), but depending on the mechanism, the volume-of-fluid (VOF) approach may be more suitable (Chen et al., 2014; Wang & Song, 2019), especially when the solid medium is so compact that the fluid cannot pass through it. In this case, the two phases can be considered as immiscible. Cohesiveness can thus be included in the viscosity, often through the Bingham approach (Nogami & Yagi, 2004), which was employed here.

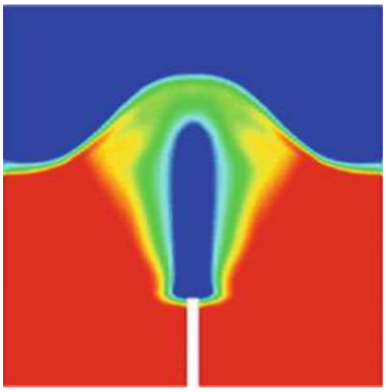

Fig. 1 Volume fraction of sand and air in a non-cohesive case; red is where sand reaches its maximum volume fraction (0.6), whereas blue is 100% water

The simulations focused on a 2D case, with a 7 m width and a 12 m height, meshed with squared cells with dimensions of 1 cm and a fluid (air or water depending on the case) entering the volume vertically upward from a 10-cm nozzle at the center of the base. The simulations began with a bed of sand (density 2500 kg/m^3 and diameter 0.25 mm) settled at the bottom, with an initial height of 6 m, and were run until a steady state was reached (typically a few seconds).

3 Results and Discussion

For the case of non-cohesive particles, Eulerian–Eulerian simulations employing the KTGF seem adequate to reproduce the expected behavior of the solid bed. As an example, Fig. 1 shows the results of a simulation of this kind, which is similar to the fluid dynamic regime of a spouted bed (Moliner et al., 2019). The mathematical treatment for this case is straightforward as the literature is abundant. The values of the fluid superficial velocity or its pressure, combined with the solids properties, are usually enough to verify whether it is sufficient to break through the bed of solids and create a channel, which can be verified through either empirical correlations (Moliner et al., 2017) or simulations (Marchelli et al., 2017).

For the cohesive case, various approaches were tested; Fig. 2 shows a selection. The VOF approach seems more adequate to represent the less ideal cases, in which cohesive forces are so strong that hinder the upward movement of the flow. Conversely, with the KTGF, the fluid is always able to pass through the bed of particles, which always has a non-null porosity. Cohesive particles are more challenging

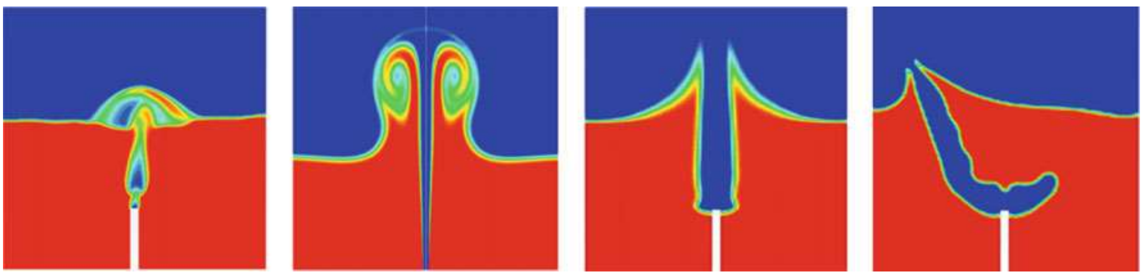

Fig. 2 Volume fraction of sand and air in cohesive cases, which from left to right are: KTGF air–sand simulation with the approach of Zhong et al. (2020); KTGF water–sand simulation with a null restitution coefficient; VOF water–sand simulation with low cohesive forces; VOF water–sand simulation with high cohesive forces

but more interesting from a modeling point of view, as it is a much more unexplored topic. The combination of the VOF method and the Bingham approach seems to be the key to reproduce some peculiar formations that involve asymmetrical shapes. On the other hand, the large number of input parameters may be detrimental for a field in which experimental observations and measurement are limited, so it is fundamental to limit the modeling complexity as much as possible.

4 Conclusions

CFD simulations are able to confirm our initial speculations about the analogies between the geological phenomena that lead to the formation of the Bahrah sand injectites and spouted beds. The theoretical and empirical knowledge on spouted beds can be fruitfully applied to the formation these injectites, whose formation process can be simulated by different CFD techniques. The flexibility and detail of these simulations may prove to be useful in future studies to show the influence of several phenomena and operating variables, helping to shed more light on these enigmatic formations.

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