Contact maturing in silica sand

Fatigue des contacts dans le sable siliceux

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ABSTRACT: The time-dependent behavior of silica sand after disturbance is a well-documented phenomenon. Engineering manifestation of this effect is encountered, for example, after in-situ compaction of sands. When compacted with vibratory means (or blasting), sands appear to have an almost unchanged (and often slightly lower) resistance to cone penetration immediately after the disturbance. However, the resistance will increase within weeks and months after the compaction process. A hypothesis is advocated in this paper suggesting that delayed fracturing of micro-morphological features on grain surfaces at contacts is a key contributor to the time-dependent response and aging of silica sand. Grain-scale testing was carried out to gain evidence supporting the hypothesis. The results of testing indicate that contacts subjected to constant loads remain active for weeks. The outcome of this process is termed 'contact maturing'. Preliminary tests are consistent with the hypothesis of contact maturing. Numerical simulations of the contact behavior are also undertaken, and the results are illustrated in the paper.

RÉSUMÉ: Le comportement en fonction du temps du sable de silice est un phénomène bien documenté. La manifestation technique de ces effets est rencontrée, par exemple, après compactage in situ de sables par des moyens vibratoires. Une hypothèse est préconisée dans cet article suggérant que la fracturation différée des détails micro-morphologiques sur les surfaces des grains est un facteur clé de la réponse dépendante du temps et du vieillissement du sable de silice. Des essais à l'échelle des grains ont été effectués pour obtenir des preuves qui étayent l'hypothèse. Les résultats des essais indiquent que les contacts soumis à des charges constantes restent actifs pendant des semaines. L'issue de ce processus est appelée 'maturation par contact'. Les tests préliminaires sont cohérents avec l'hypothèse de la maturation du contact. Des simulations numériques du comportement de contact sont également entreprises, et les résultats sont illustrés dans le document. (Traduit par Google.)

KEYWORDS: Static fatigue, grain-scale testing, sand aging.

1 INTRODUCTION

Aging of silica sand is a well-documented phenomenon, yet there is no consensus regarding the primary causes of aging. Two convincing pieces of evidence for aging are the behavior of sand after disturbance and the setup of displacement piles. The former was brought to light in a paper by Mitchell and Solymar (1984), who pointed out that an increase in the cone penetration resistance after compaction by vibratory means (or blasting) does not occur immediately after compaction, but it increases gradually in the weeks and months after disturbance. Evidence for the pile setup can be found, for example, in Chow et al. (1997); an increase in the pile shaft resistance can easily double within a few months of the pile installation.

Various hypotheses have been proposed in the last three decades to explain the observed time-delayed effects in the response of silica sands to loads. Among them was a buildup of bonds at sand contacts due to mineral deposition (Mitchell and Solymar 1984), structuration process (Mesri et al. 1990, Schmertmann 1991, Bowman and Soga 2003), and time-dependent grain fracturing (Lade and Karimpour 2010).

The hypothesis advocated in this paper, suggests that delayed fracturing of micro-morphological features on grain surfaces at contacts, such as asperities and mineral debris, is a key contributor to aging of silica sand. Of primary importance in this hypothesis is the behavior of an intergranular contact under sustained load. To gain evidence supporting this hypothesis, an apparatus was constructed for grain scale testing of time-dependent behavior of individual intergranular contacts.

The results of testing indicate that contacts subjected to constant load remain active for weeks. The outcome of this process is termed 'contact maturing' here. Grain-scale experiments are tedious and demanding; therefore, in addition to testing, a numerical model was developed capable of simulating contact behavior using the distinct element method.

2 CONTACT MATURING HYPOTHESIS

A scanning electron microscope image of an Ottawa sand grain is illustrated in Fig. 1. When grains with a rich surface texture, as in Fig. 1, come into contact and become loaded, the surface asperities become fractured or crushed, leading to comminution of the material.

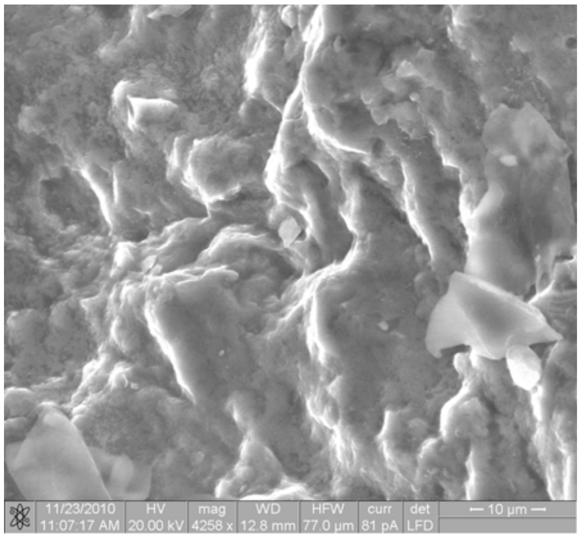

Figure 1. Scanning electron microscopic image of the surface of an Ottawa 20-30 sand grain.

However, the proces of fracturing at the contact does not stop at the end of loading; rather, it cotinues with decreasing frequency. The underpinning of this presumption comes from rate process theory and fracture kinetics (Glasstone et al. 1941, Krausz and Krausz 1988, Bažant and Pang 2007).

The central component of the hypothesis is the delayed fracturing of the textural features at contacts (Michalowski and Nadukuru 2012). This time-dependent fracturing occurs at constant load, and gives rise to the evolution of contacts over time, with an increasing number of "contact points" at individual nominal contacts between grains. This process is identified as the key cause of rate effects and aging in silica sand.

3 GRAIN-SCALE TESTING

In order to gain insight into sand time-dependent contact behavior, an apparatus was constructed that allows loading individual grains with forces of the order of newtons, and measuring the response of grains under sustained loads.

3. 1 *Apparatus*

Testing for time effects in grain response is distinctly different from testing for immediate response of grains to increasing loads (Cavarretta et al. 2010, Senetakis and Coop 2013). When a contact between two grains is investigated, the measured response is always a combined response of the grains studied and the two contacts of the grains with the loading platens, including the response of the glue used for mounting the grains.

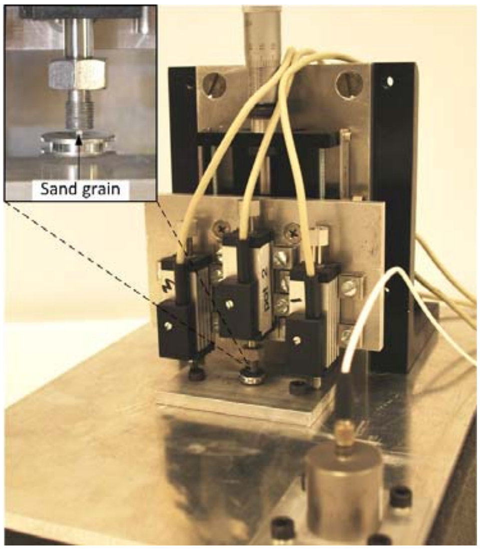

Figure 2. A view of sand-grain testing apparatus.

To eliminate these uncertainties in measurements, a test setup was arranged with one grain, loaded with two steel (relatively smooth) platens. The response measured is a simultaneous response of two contacts with two flat surfaces. While this is not equivalent to one contact between two grains, the response measured is indicative of the contact behavior. The advantage is in eliminating the influence of the mounting glue necessary in two-grain tests, and the uncertainties associated with the orientation of the contact between two grains.

An image of the apparatus is shown in Fig. 2. Its essential part is a potentiometer with a calibrated spring that is mounted on a stage with one degree of freedom in the vertical direction. The grain is placed between one steel plate mounted on the arm of the potentiometer and one mounted on the base of the apparatus. The required force on the grain is induced with the calibrated spring in the potentiometer. Once the required force is reached, the potentiometer measures the time-dependent convergence of the two steel platens which is the result of static fatigue at the contacts and some creep of the grain's core mineral.

Although the stage has only one degree of freedom, the tolerances in the rails may allow for minute rotation. Two other potentiometers are mounted symmetrically on the stage to detect any non-symmetric movement of the stage, which would have an effect on the measurements.

3. 2 *Time-deflection curves for loaded grains*

Tests were performed on the Ottawa sand grains (grain size in the range 0.6 – 0.84 mm). Results of preliminary testing are presented in Fig. 3.

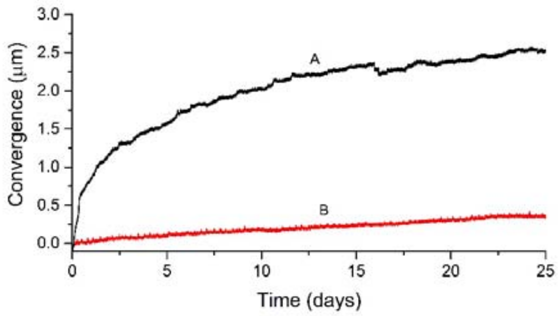

Figure 3. Time-convergence curves for grains of different surface roughness: (a) RMS = 621 nm, and (b) RMS = 29 nm.

The curves show the convergence of the platens loading the grain. This convergence was monitored with the frequency of 1 Hz, while the grain was loaded with a constant force of 2.4 N. The difference between the two grains, for which the tests are presented in Fig. 3, was in the surface roughness. The roughness was measured by the root mean square (RMS) of the surface elevation. The grain in the upper-curve test had a surface texture characterized by RMS = 621 nm, and the grain in the lower-curve test had RMS = 29 nm (very small roughness).

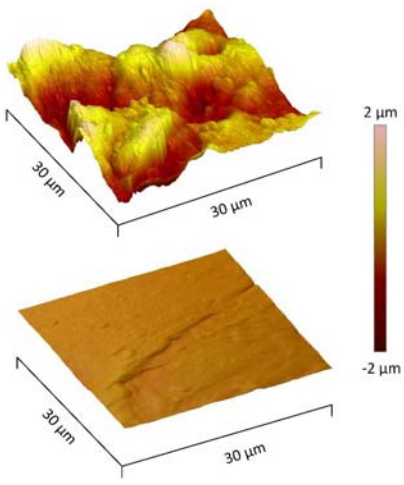

Figure 4. Atomic force microscopy scans of grains in tests A and B: (a) RMS = 621 nm, and (b) RMS = 29 nm.

The response of the grains to loading is a combined response of two contacts with the loading platens and the creep response of the core material of the grain. Creep of the grain starts immediately after loading the grain, but the displacement (convergence) owed to contact maturing occurs at a much higher rate in Test A (high roughness). This is because the surface features in Test A are subjected to fatigue, whereas the surface in Test B is almost devoid of major asperities on the scale of hundreds of nanometers. This is illustrated in Fig. 4.

The rate of convergence is almost constant in Test B with very low roughness. In this case, the creep of the mineral core of the grain is likely to have accounted for a large portion of the convergence.

The tests revealed that the surface roughness plays a primary role in the time-dependent response of the grain to sustained loads. This is consistent with the hypothesis that contact maturing is the key factor contributing to time effects and aging in silica sand.

4 MODELING OF A CONTACT

Testing of contacts is a tedious process, so a model was developed to analyze the response of a single contact to loads. This model can be used in numerical testing of the influence of various contact geometries on the time-dependent response to sustained loads.

4. 1 *Distinct element model of a contact*

The distinct element method (DEM) was selected as a tool to simulate the static fatigue at the interface between rough surfaces of silica sand grains. Here, unlike in the typical application of DEM, the distinct elements are the building blocks of a single grain. These "sub-particles" are bonded together with bonds susceptible to *stress corrosion cracking*.

4. 2 *Parallel-Bonded Stress Corrosion model (PSC)*

This model is based on proposals of Potyondy and Cundall (2004) and Potyondy (2007). The bond between particles has a diameter $\overline{D}$ and can transfer forces as well as moments (including torque). If a tensile stress above threshold σ_a is induced in the bond as a result of moment loads, the stress corrosion cracking process begins. Consequently, the size of the bond reduces; the rate of the bond reduction is described by

$$\frac{d\overline{D}}{dt} = \begin{cases} 0 & \text{if} \quad \overline{\sigma} < \overline{\sigma}_a \\ -\beta_1 \exp\left[\beta_2 \dfrac{\overline{\sigma}}{\overline{\sigma}_c}\right] & \text{if} \quad \overline{\sigma}_a < \overline{\sigma} < \overline{\sigma}_c \\ -\infty & \text{if} \quad \overline{\sigma} > \overline{\sigma}_c \end{cases} \quad (1)$$

where $\overline{D}$ is the parallel-bond diameter (width in 2D); $\overline{\sigma}$ is the maximum tensile stress acting on the parallel-bond periphery; $\overline{\sigma}_a$ is a threshold stress below which the stress-corrosion ceases; $\overline{\sigma}_c$ is the parallel-bond tensile strength; β_1 and β_2 are two rate parameters that can vary with environmental factors (temperature, moisture, and chemical environment).

4. 3 *2D demonstration*

To demonstrate the capability of the model, an interface between two plane particles (of circular and rectangular shapes) was modeled, Fig. 5. The model comprised of 23,190 sub-particles, and the upper grain had a diameter of 0.6 mm.

The model was loaded with a force of 12 N, which led eventually to the breakage of the bottom grain. This simulation demonstrates that the contact evolves, the number of contact points increase within the nominal contact, leading to a firmer interface, i.e., higher contact stiffness. This is likely to propagate through the spatial scales to produce an increase in the macroscopic small-strain stiffness, a clear manifestation of aging in sand.

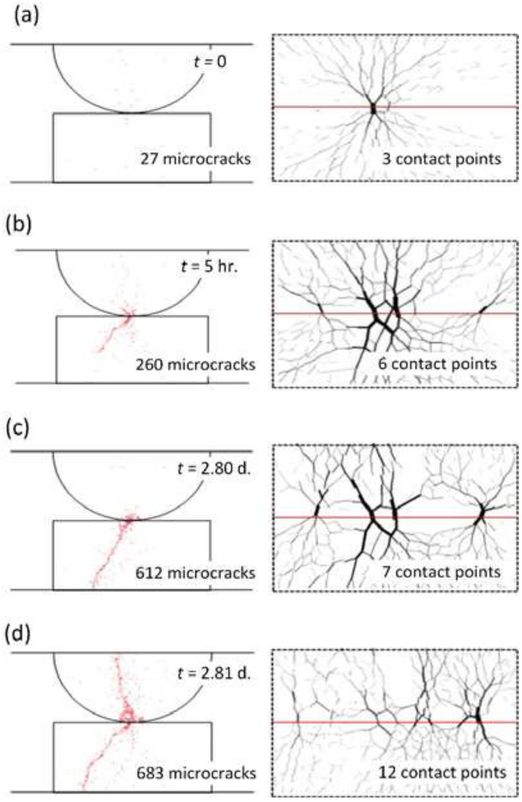

Figure 5. Evolution of a contact between two grains: sequential development of cracks shown in the left column, and an increase in the number of contact points within the nominal contact area is illustrated in the right column with clearly marked force chains crossing the interface.

4. 4 *3D Simulation of a contact*

The PSC model was calibrated using Test A. Figure 6 illustrates the calibration simulation of the half-grain in contact with a rigid plate. Model parameters were chosen such that the calculated convergence matched the measured one (calibration process). The contact was loaded with a force of 2.4 N and this constant load continued for 25 days, reaching half the convergence measured in Test A (the physical test yields the convergence associates with two contacts).

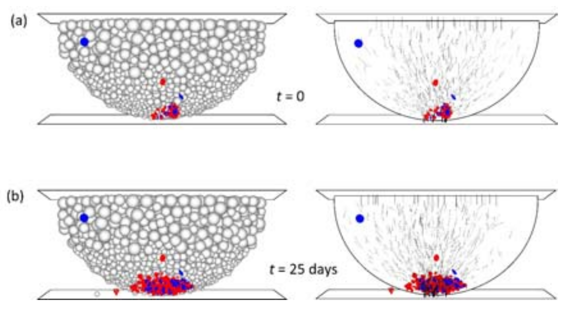

Figure 6. The calibration test. Time-dependent fracturing and evolution of force chains: (a) immediately after application of the load (2.4 N): zero convergence, 95 micro-cracks, 6 force chains across contact area, and (b) after 25 days: deflection 1.25 µm, 496micro-cracks, 10 force chains across contact area.

The calibrated model was then used to simulate a contact between two grains. 10,775 sub-particles were used to build the model. The threshold tensile stress $\overline{\sigma}_a$ from calibration was found to be 7 MPa, and the rate parameters β_1 and β_2 were 6.4×10^{-19} m/s and 30, respectively. The outcome of the simulation is shown in Fig. 7.

The initial and the final stage (after 25 days) are presented in Figs. 7(a) and 7(b), with illustration of the force chains across the contact nominal area. As the process of maturing progresses, the distribution of forces across the contact become more uniform in magnitude

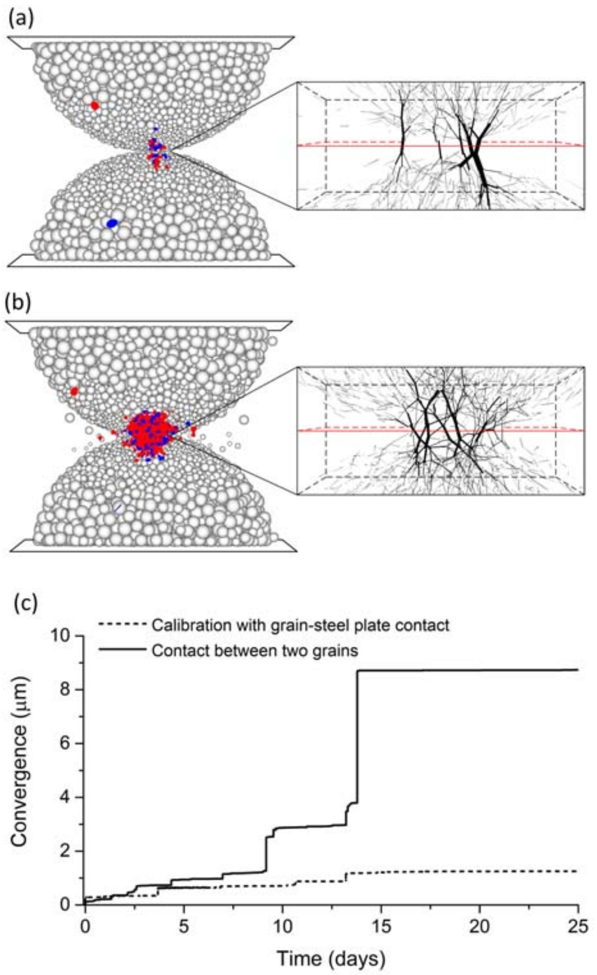

Figure 7. Two-grain simulation: (a) initial stage with 78 fractures, (b) 968 cracks after 25 days, and (c) time-deflection functions for the calibration simulation and the simulation of an inter-granular contact.

The dashed line in Fig. 7(c) is the calibration curve with a grain-steel plate contact, and the solid line shows the simulation of a contact between two grains. A major multiple fracturing occurred at about 14 days causing a sudden large deflection.

A parallel-bonded stress corrosion model appears to be an effective tool to simulate the time-dependent process of contact maturing

5 CONCLUSIONS

The contact fatigue hypothesis advocated in the paper is consistent with grain scale tests. The tests indicate that a response of a silica sand contact to loads is time-dependent. Contacts rich in micro-morphologic features (asperities) undergo a process of fatigue, giving rise to time-delayed response. The time-dependent increase in the number of contact points within a nominal contact area leads then to an increase in the contact stiffness, and an increase in the small-strain stiffness for the granular assemblies. The latter is a well-known effect of sand aging.

The dinstinct element method was found to be a useful tool for modeling a single grain. It is particularly useful in simulations of the time-dependent behavior of contacts, after implementing the stress corrosion (parallel bond) model.

Time effects exhibited by silica sands are the results of the processes at the inter-granular contacts and the system interactions between grains in granular assemblies. Grain-scale studies are needed to both improve understanding of the nature of rate effects and aging in sands, and to make engineering predictions of sand behavior after compaction and after other types of disturbance.

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