

**Impact of particle shape on friction angle**

N. Stark et al.

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# The impact of particle shape on friction angle and resulting critical shear stress: an example from a coarse-grained, steep, megatidal beach

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## Abstract

The impact of particle shape on the friction angle, and the resulting critical shear stress on sediment dynamics, is still poorly understood. In areas characterized by sediments of specific shape, particularly non-rounded particles, this can lead to large departures from the expected sediment dynamics. The steep slope (1 : 10) of the mixed sand-gravel beach at Advocate Harbour was found stable in large-scale morphology over decades, despite a high tidal range of ten meters or more, and strong shorebreak action during storms. The Advocate sand ( $d < 2\text{ mm}$ ) was found to have an elliptic, plate-like shape. Exceptionally high friction angles of the material were determined using direct shear, ranging from  $\phi \approx 41 - 46^\circ$ , while the round to angular gravel was characterized by  $\phi = 33^\circ$ . The addition of 25 % of the elliptic sand to the gravel led to an immediate increase of the friction angle to  $\phi = 38^\circ$ . Furthermore, re-organization of the particles occurred during shearing, being characterized by a short phase of settling and compaction, followed by a pronounced strong dilatatory behavior and an accompanying strong increase of shear stress. Long-term shearing (24 h) using a ring shear apparatus led to destruction of the particles without re-compaction. Finally, submerged particle mobilization was simulated using a tilted tray in a tank. Despite a smooth tray surface, particle motion was not initiated until reaching tray tilt angles of  $31^\circ$  and more, being  $7^\circ$  steeper than the latest gravel motion initiation. In conclusion, geotechnical laboratory experiments quantified the important impact of the elliptic, plate-like shape of Advocate Beach sand on the friction angles of both pure sand and sand-gravel mixtures. The resulting effect on initiation of particle motion was confirmed in tilting tray experiments. This makes it a vivid example of how particle shape can contribute to the stabilization of the beachface.

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## 1 Introduction

Subaqueous sediment dynamics play a major role in coastline, river and lake development, as well as scour around submerged structures, and coastal hazards such as submarine landslides (Kuehl et al., 1996; Simons and Şentürk, 1992; Bradley and Stolt, 2006; Masson et al., 2006). Despite the widespread interest and ongoing research in this field, the complex system consisting of a number of factors governing subaqueous sediment dynamics and beach dynamics (hydrodynamics, morphology and sediment properties) is still far from being fully understood. Focusing on the sediment properties, the friction angle is known to be a major factor controlling the critical shear stress required to initiate particle motion (Middleton and Southard, 1984; Bagnold, 1988; Kirchner et al., 1990; Soulsby, 1997). The friction angle depends on grain size, sorting, density, particle arrangement, and particle shape (Schanz and Vermeer, 1996; Das, 1990). In particular, the importance of the particle shape with regard to the friction angle and initiation of subaqueous sediment motion was pointed out by Kirchner et al. (1990) for the case of river sediments. Generally, there is still a certain lack of data pertaining to the impact of particle shape on subaqueous sediment dynamics and beach morphodynamics, particularly for the behavior of non-rounded particles.

The mixed sand-gravel beach near Advocate Harbour (Fig. 1) was investigated in the framework of a sediment dynamics experiment in May 2012. Hydrodynamics, large- and small-scale morphology, and sediment distribution were monitored over three weeks. With regard to the latter, a distinct cross-shore zonation varying with the lunar tidal cycle and weather/hydrodynamic conditions was observed (Stark et al., 2013b). However, despite the energetic hydrodynamics at the beach during wind-wave forcing events in particular, the beach slope has remained constant at about  $6.4^\circ$  for decades. Also – and rather surprisingly – following a significant storm wave event, the beachface was dominated by sandy sediments (Fig. 1). Furthermore, these sandy sediments, representing the finest fraction at the beachface with  $d < 2$  mm, were characterized by a strong variations in particle shape, and a high abundance of flat, elliptic particles

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(Fig. 2). As a result, it was hypothesized that the flat, elliptic shape of the sand-sized particles impacts the friction angle, and by doing so, contributes to the stability of the beach. To test this hypothesis, geotechnical laboratory experiments were carried out to determine the behavior of Advocate sand and sand-gravel mixtures during shearing, and a simple physical simulation of sediment mobilization along a tilted tray was conducted.

## 2 Methods

Beach samples were gathered along a cross-shore transect in the vicinity of an instrumented frame that was installed for the full three weeks of the experiment. The frame was equipped with a number of different acoustic and other devices estimating flow velocity, bedload transport velocity, wave orbital velocity, wave height and small-scale morphological variations (Hay et al., 2013). Sampling locations along this cross-shore transect reached from the berm down to the low water level, being 10 m apart from one another (Position 181 [berm] through Position 188 [low water level]). Additionally, samples from two fully-submerged sites in about 1.5 m of water depth at low water were collected at sand patches, and close to a reef-like assembly of boulders and rocks. These samples represent surficial sediment samples, and were taken using a small shovel.

The sampled sediment showed a strong variation in grain size distributions ( $d_{50} = 0.3 - 18.5$  mm) along the cross-shore transect, as well as depending on the hydrodynamic conditions (Fig. 1). The finest sediments were found at the fully-submerged sites ( $d_{50} = 0.3$  mm), while the most fine-grained samples from the beachface were characterized by  $d_{50} = 1$  mm. Within the sand-sized fractions ( $d < 2$  mm), strong variations in particle shape with a high abundance of flat, elliptic particles were observed (Fig. 2).

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## 2.1 Geotechnical laboratory experiments

Three different shear devices were used: a small direct shear box for sandy sediments only, a large direct shear box for gravel and sand-gravel mixtures, and a ring shear device for 24 h tests of the sand samples.

### 2.1.1 Direct shear box

The direct shear test is one of the oldest shear test arrangements, and can be found in most geotechnical laboratories (Das, 1990). For the direct shear tests of the sand, a standard-sized small shear box (surface area = 36 cm<sup>2</sup>) was used, and the sediment was filled in loosely and water-saturated. Each sample was tested at three stages of normal stress: 3, 32, and 64 kPa. This is significantly lower than normal stresses usually applied for subsoil testing (as great as 1034.2 kPa after Das (1990)) to account for low normal stresses at the beachface sediment surface. Between the tests, the samples were stirred up to ensure a loose particle arrangement at the start of shearing.

A significantly larger direct shear apparatus (929 cm<sup>2</sup>) was used for shearing the gravel and gravel-sand mixtures. 100 % gravel, 75 % gravel mixed with 25 % sand, and 50 % gravel mixed with 50 % sand were tested at normal stresses of 51, 99, and 149 kPa, which were the lowest normal stresses feasible with the large direct shear apparatus. Similar to the small direct shear box, samples were loosely installed, and stirred up after each test.

The direct shear tests were used to monitor the development of shear stress with horizontal shearing of the sample to determine the shear strength, and subsequent friction angle. Furthermore, any compression or expansion of the samples during shearing was observed.

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## 2.1.2 Ring shear test

Shearing behavior over 24 h was tested using a ring shear apparatus (also called annular direct shear apparatus). Here, an annular specimen (sand or finer sediments only) is sheared, under a given normal stress (92 kPa, being the lowest normal stress the apparatus allowed; 461 kPa, 922 kPa), on a horizontal plane by the rotation of the annular sample relative to a stationary lid (Craig, 1974). This test was mainly conducted to observe long-term dilatatory behavior.

## 2.2 Physical simulation of sediment remobilization

A smooth tray with a hopper feeding sediment onto the tray was arranged in a tank filled with water, and was tilted to angles ranging between 20–40° (Stark et al., 2013a). The angle at which sediment started moving, and average particle velocities were determined via video observations, and via a prototype wide-band coherent Doppler profiler (MFDop) (Hay et al., 2008, 2012a, b). In this study, the main interest was to determine how easily the gravel and sand can be mobilized in comparison to each other, and other gravel types.

## 3 Results

### 3.1 Geotechnical laboratory experiments

#### 3.1.1 Direct shear box

The plots of horizontal displacement versus measured shear stress (Fig. 3) illustrate the different response to applied shear stress for the different loading stages. At the lowest applied normal stress, sample failure occurred at a low value of the applied shear stress. At the second loading stage, we found some stress-vs-horizontal displacement-curves which matched a shear stress path expected in the case of loose

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sediments, and some which already showed a tendency towards a peak shear strength, as expected for denser sand. In some cases, a step-like feature was observed in the stress-vs-horizontal displacement-curves, likely corresponding to processes of re-arrangement of the particles. The same was true for the highest normal load. Here, we additionally observed clear differences between the samples from the beachface, and those from the permanently submerged sites. Analysis of the profiles led to a friction angle of  $\phi \approx 46^\circ$  for the beachface sands and a friction angle of  $\phi \approx 42^\circ$  for the sand from the permanently submerged sites.

The vertical displacement was characterized by a two-phase behavior that was approximately similar for all sands independent of their origin (Fig. 4). First, a phase of specimen compaction, i.e. a negative vertical displacement, was observed, corresponding to the range of horizontal displacement when also the first plateau in the step-like shear stress profiles was noted. This observation supports the hypothesis of particle re-arrangement and alignment during this phase. After this compaction phase, a strong dilation behavior is characteristic for the Advocate Beach samples, reaching significantly larger positive vertical displacements than the previous negative vertical displacement (Fig. 4).

The gravel tests in the large direct shear box revealed typical shear stress profiles, as expected for loose granular material (Fig. 5), and led to a friction angle of  $\phi \approx 33^\circ$  for the pure gravel sample, while the addition of sand resulted in an increase in the friction angle to  $\phi \approx 38^\circ$ . The vertical displacement was characterized by compaction: no dilation was observed.

### 3.1.2 Ring shear test

The vertical displacement during shearing was investigated in more detail in the 24 h ring shear tests (Fig. 6). Under all three values of normal stress, the specimen expressed the previously described phases of compaction and stronger dilation. However, under the much higher normal stresses tested in the ring shear, it stood out that the magnitude of compaction as well as dilation is governed by the normal stress. Nev-

ertheless, a noticeable compaction followed by a strong dilation was confirmed by the low normal stress measurements in the ring shear apparatus, being likely the test closest to the in situ beach face conditions where normal stresses are low. Afterwards, a stagnation is reached in which the vertical displacement level remains constant, before it comes to another negative vertical displacement, being governed in magnitude by the normal stress stage again. Furthermore, it was observed that over the long-term shearing the sand experienced a process such as grinding. The particle sizes at the shear face were reduced, and in the case of the highest normal stress, down to a mud size level.

### 3.2 Physical simulation of sediment remobilization

In a simple physical simulation, we tested the initiation of particle motion of sand and gravel from Advocate in comparison to each other, and to other commercially available gravel. The Advocate gravel showed a behavior similar to more angular, as well as more rounded gravel (Fig. 7). Deviations depending on shape and size were observed, but will not be discussed in detail in this article. A more distinctively different behavior was observed in the case of the sand. Initiation of particle motion of the Advocate sand did not start until tray tilt angles of  $31^\circ$  were reached, while all gravel size particles started moving at tray tilt angles of  $21\text{--}24^\circ$  (Fig. 7). The predominant “failure” or slipping plane was the tray-sediment interface, likely leading to the initiation of particle motion at lower inclinations than suggested by the friction angles determined in the direct shear tests.

## 4 Discussion

Friction angles of  $\phi \approx 42\text{--}46^\circ$  were determined for the flat, elliptic sand from Advocate Beach using direct shear. Considering that the tests were conducted on loose sand samples, these friction angles were significantly larger than what was expected from the literature: i.e. loose sand (rounded):  $\phi \approx 27\text{--}30^\circ$ ; loose sand (angular):  $\phi \approx 30\text{--}35^\circ$

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(Das, 1990). Instead, these loose samples fall in the high range of dense sand: i.e.  $\phi \approx 40 - 45^\circ$  (Craig, 1974; Das, 1990). The friction angles measured for gravel matched the range that has been observed for loose gravel before (Craig, 1974; Das, 1990; Simoni and Houlsby, 2006). However, mixing the Advocate sand with the gravel led to an immediate increase of friction angles, expressing the opposite behavior than observed in other studies in which rounded to sub-angular sand was mixed with gravel. Both Simoni and Houlsby (2006) and Yagiz (2001) described a steady decrease in friction angles with the addition of sand to the gravel sample, while the Advocate sand led to an immediate increase of friction angle after adding 25 % of sand, but remained constant when adding 50 % of sand. This supported the first observation that the Advocate sand withstood exceptionally high shear stresses in comparison to similar particle sizes of rounded or angular shape before failure.

The vertical displacement plots, determined using the small direct shear box and the ring shear apparatus, indicated that the samples underwent different phases of arrangement during shearing. In the following, we propose a concept of particle rearrangement during the shearing process that may explain the observed vertical displacement and failure shear stresses (Fig. 8). Under first shearing, the loose and unaligned particles, rearrange and align corresponding to their shape. This would lead to a denser state of particle packing, explaining a first increase in shear stress and negative vertical displacement. With increasing shear stress, the particles may be erected, again guided by their elongated shape, allowing for higher shear stresses and a strong dilatatory behavior (Fig. 8). This arrangement was so strong and final (possibly in an arrangement similar to shingles on a roof) that particles were rather destroyed by grinding than re-arranged again (Fig. 8) during long-term shearing.

These results indicated that the Advocate sand is characterized by high friction angles which arise from a distinct particle shape, and resulting rearrangement during shearing. The flat, elliptic sand can potentially resist higher shear stresses before failure, and possible sediment mobilization at the beachface.

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This was also confirmed by a simple physical simulation in which the sand was exposed to the tilting of a smooth tray. The experiment was part of a larger investigation of particle velocity and particle motion in bedload transport of different particles sizes (Stark et al., 2013a). The tray tilt angle at which mobilization of the sand particles occurred did not match the determined friction angles, which can be explained by the smooth surface of the tray. Nevertheless, a clearly delayed mobilization at much higher angles than the tested gravel was observed, confirming that the Advocate sand was resistant to the initiation of particle transport.

In summary, the geotechnical laboratory experiments and the physical simulation of sediment remobilization confirmed that the flat, elliptic sand from Advocate can resist strong shear stresses, offering a valid explanation how the sandy particles remained at the beachface during significant wave action. This also suggested that this sand could play a significant role in the long-term stability of Advocate Beach.

The application of geotechnical laboratory experiments to investigate sediment behavior under shear stress proved to be a suitable and useful approach to study the response to applied shear under controlled conditions. Nevertheless, some issues have to be considered. First, the collected samples hardly represent the in situ texture at the beachface, in particular in a submerged state, and under active flow and wave action. This is a well recognized issue regarding sediment sampling in the field of subaqueous sediment dynamics (Blomqvist, 1991; Larson et al., 1997; Edwards and Glysson, 1988). Specifically loosely arranged surface samples have to be considered significantly disturbed after retrieval, transport and storage. Instead of trying to preserve the original state, we decided to account for this by installing the sample in the shear boxes in a very loose, not consolidated and fully water saturated state, aiming for conditions representative of submerged beachface surface sediments which are frequently re-arranged by bedload transport processes. As we observed the re-arrangement of the loose, unaligned particles during shearing, we argue that the laboratory-prepared samples mimicked the in situ conditions of recently and loosely deposited sediments which are exposed to increasing shear stress in the swash and surf zone fairly well. How-

ever, in future experiments it should be aimed for cutting samples out of the beachface in an approximately undisturbed state and during different tidal phases to confirm the conclusion drawn from highly disturbed samples.

A second issue is the applied normal stress. Standard direct shear tests aim for determination of shear strength and friction angle with regard to slope stability and structure stability. This implies that usually the behavior in deeper sediment depths is targeted rather than the uppermost sediment surface (Craig, 1974; Das, 1990). We addressed this issue by applying the lowest normal stresses possible. In the case of the large direct shear box and the ring shear, the use of lower normal stresses than standard would have impacted on the operation of the shear boxes, and was rejected. In the case of the small direct shear box, it was feasible to test at very low normal stresses. However, there are concerns as to whether failure stress and friction angles can be properly determined at low stress levels in a shear box (Bruton et al., 2007). For the case of fine sands, Lehane and Liu (2013) demonstrated that a conventional direct shear can indeed be applied at low stress levels, but that corrections might be required, particularly at normal stresses below 10 kPa. In the present study, no corrections were applied because most of the tests were performed at normal stresses significantly above 10 kPa, and the sands tested here were significantly coarser and differently shaped than in the study by Lehane and Liu (2013) so that it is not clear if those corrections could be directly applied. Furthermore, the other shear tests (applying standard loads) as well as the physical simulation of sediment remobilization supported our observations. Nevertheless, further investigation is needed to better determine how standard geotechnical laboratory experiments should be utilized for the investigation of subaqueous and beach sediment dynamics, including the development and inclusion of suitable corrections.

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## 5 Conclusions

Three different types of laboratory tests were performed to assess the behavior of sediments from Advocate Beach during shear: Geotechnical direct shear tests and ring shear tests, as well as simple physical simulations of sediment transport initiation. The sediments ranged in size from sandy particles to gravel, and the sand-sized fractures were characterized by a high abundance of flat, elliptic grains. The study was part of a larger effort targeting beach dynamics at Advocate Beach, Bay of Fundy, Nova Scotia. It was found that the geotechnical laboratory methods offer important insight into the soil mechanical processes under shear stress and sediment resistance to shear, impacting directly on the sediment dynamical behavior at the beachface. Particularly, it was proposed that the flat, elliptic shape of the Advocate sand undergoes a specific process of particle re-arrangement and alignment that results in a significant increase in friction angles. This strengthens the sand against shearing processes, likely contributing to the stability of the sand at the beachface against wave action.

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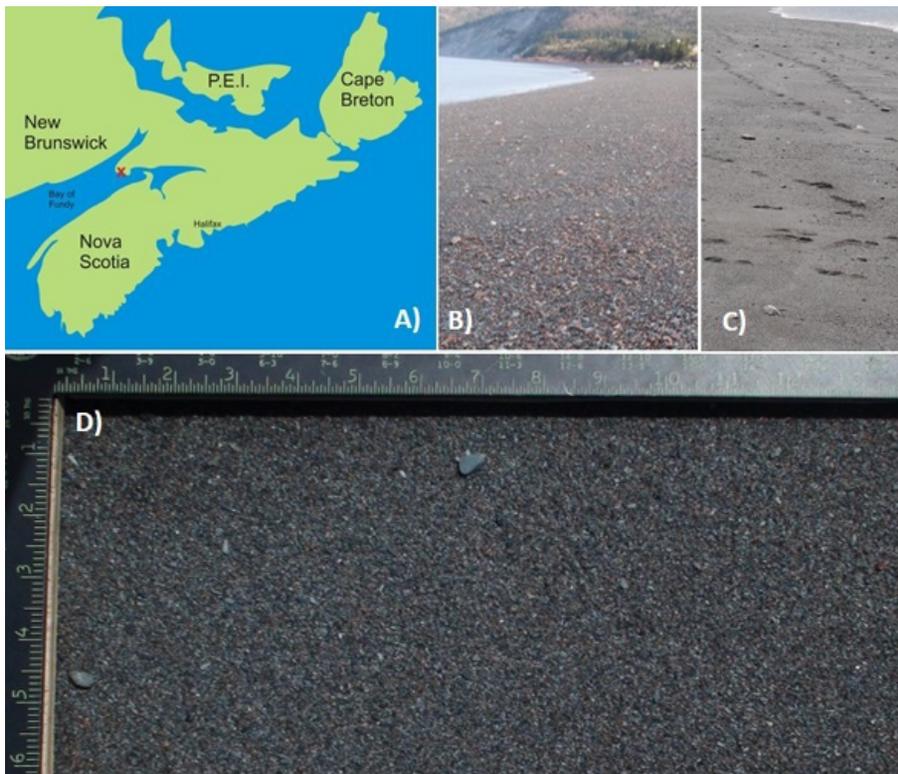
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**Fig. 1.** (A) The location of Advocate Harbour at the Bay of Fundy between Nova Scotia and New Brunswick, Canada. (B) Image of the beachface at low water during calm weather conditions. (C) Image of the beachface at low water after a storm event. (D) Image of the surficial sediments after a storm event (scale in inches).

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**Fig. 2.** Example of flat, elliptic sand particles.

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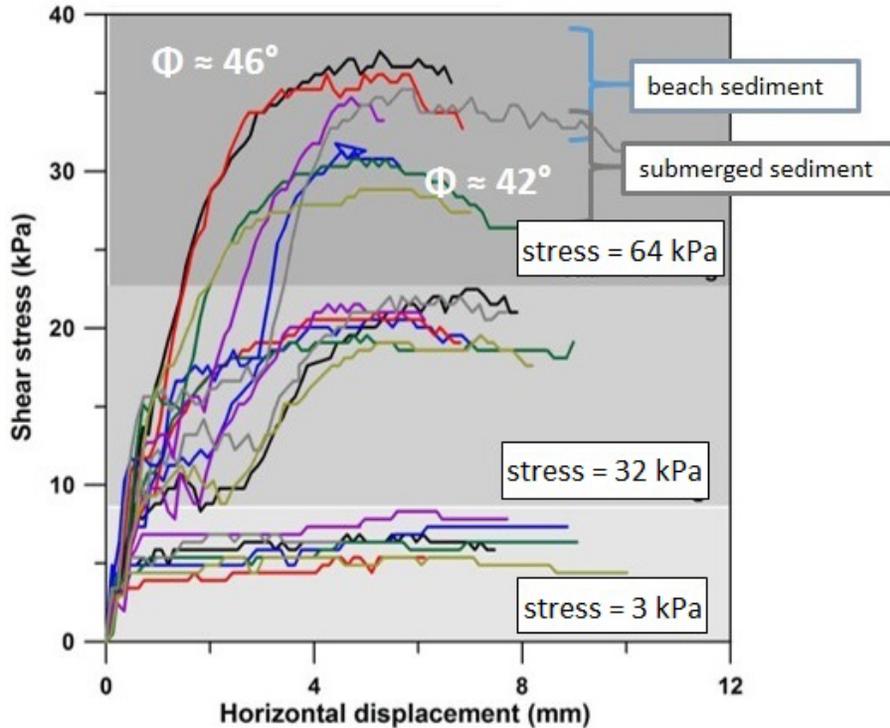
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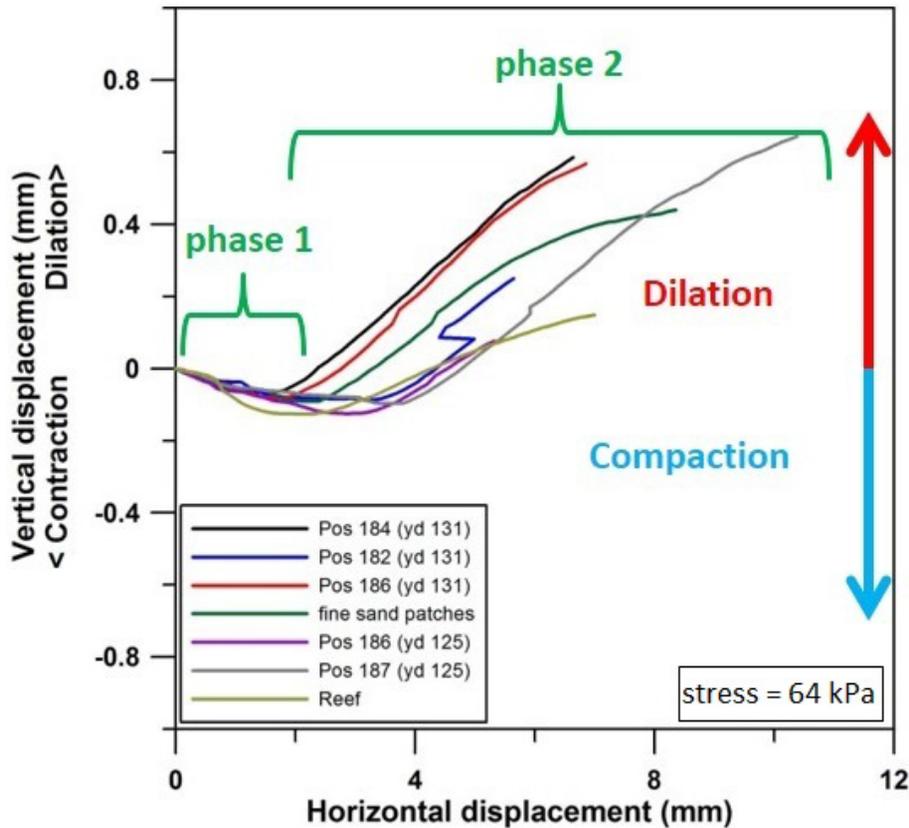
**Fig. 3.** Horizontal displacement versus shear stress of samples with a grain size  $d \leq 2$  mm measured in the small direct shear box. The different stages of normal stress are indicated by different gray shades. At the highest loading stage, a difference in the shear stress path between the beachface sediments and samples from permanently submerged sites can be observed, leading to differences in the friction angle  $\phi$ .

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**Fig. 4.** Horizontal displacement versus vertical displacement of samples with a grain size  $d \leq 2$  mm measured in the small direct shear box under the highest normal stress. First a short phase of compaction was observed, before a strong dilation was monitored.

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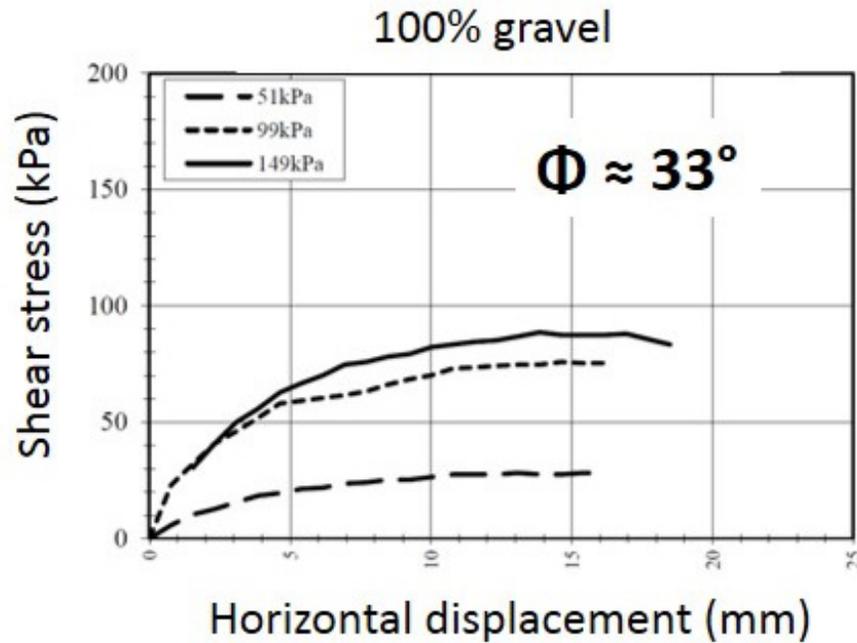
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**Fig. 5.** Horizontal displacement versus vertical displacement of gravel measured in the large direct shear box.

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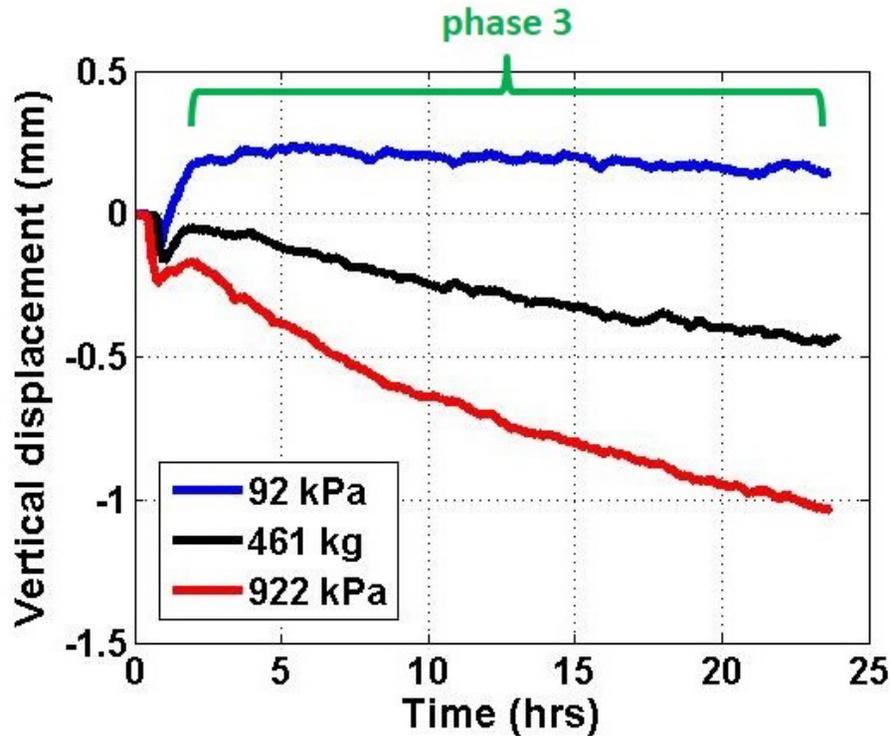
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Interactive Discussion





**Fig. 6.** Vertical displacement versus time for a sand sample measured in the ring shear apparatus. After the previously described phases 1 and 2 of vertical displacement, the specimen shows a third phase of behavior: a return to negative vertical displacement again. The magnitude is governed by the normal stress. Also, the intensity of dilation in phase 2 seemed to be restricted by the normal stress.

**Impact of particle shape on friction angle**

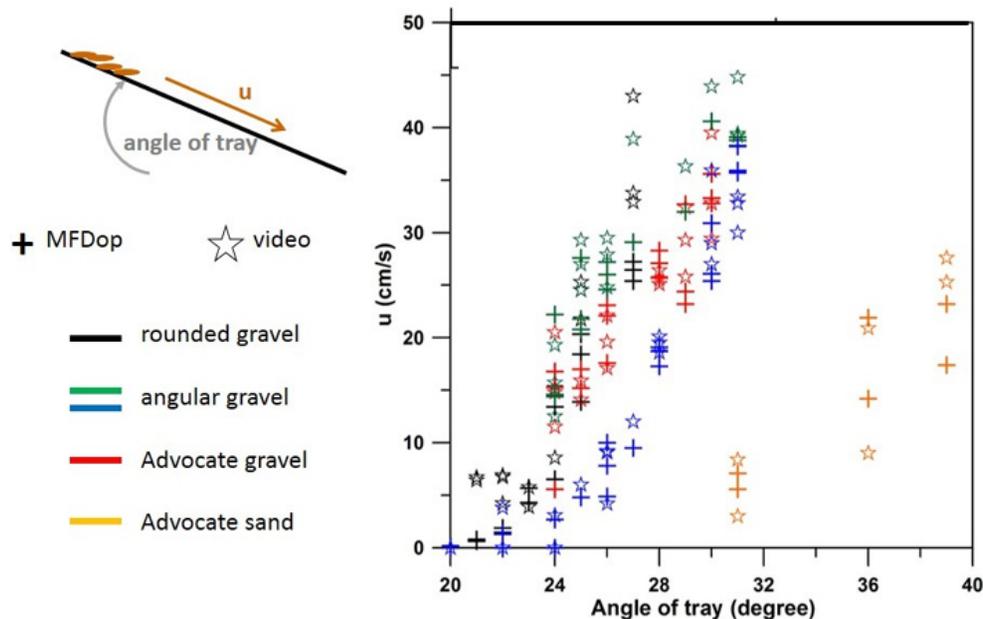
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## Impact of particle shape on friction angle

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**phase 1:**  
re-arrangement of loose surface  
particles during shearing  
=> compaction



**phase 2:**  
new orientation of particles with  
extended shearing  
=> dilation



**phase 3:**  
destruction of particles



**Fig. 8.** Conceptual sketch of particle arrangement explaining the observed time-dependence of vertical displacement during shear.