Earth Surf. Dynam. Discuss., 1, C738–C748, 2014
www.earth-surf-dynam-discuss.net/1/C738/2014/

Interactive comment on "The impact of particle shape on friction angle and resulting critical shear stress: an example from a coarse-grained, steep, megatidal beach" *by* N. Stark et al.

N. Stark et al.

ninas@vt.edu

Received and published: 29 April 2014

We thank Dr. Kleinhans and anonymous referee #2 for the detailed comments and suggestions which will certainly lead to an improvement of the article. In the following, we reply and discuss the respective comments and suggest changes and additions to the manuscript, respectively.

Comment 1: "There is a large body of literature in the fluvial sedimentological community and in the Powders and Grains community on the angle of repose including mixture effects and particles with shapes other than spherical. This literature is not referred to but is useful. See for instance http://proceedings.aip.org/resource/2/apcpcs/1542/1

and also the review in http://dx.doi.org/10.1029/2011JE003865. Also there have been a number of papers in WRR (Water Resources Research) and JGR on the beginning of motion of particle size mixtures such as recent work of Wu, work by John Buffington and Montgomery, Peter Wilcock, Stephan Vollmer and others. These works analytically derive threshold of motion curves (Shields curves) where angle of repose is explicitly incorporated and particle size sometimes as well. There is also a lot older work including Paul Komar and Li 1986 in Sedimentology that is of interest. Finally there is some work on the dilation of water-worked beds (maybe a paper by Lynne Frostick and perhaps some work by John Wooster et al on infiltration of fines into a gravel bed)."

We agree with Dr. Kleinhans. Although geotechnical laboratory results have rarely been presented in the framework of subaqueous sediment dynamics, there is more relevant literature available than has been used for the manuscript. For the revision of this manuscript, particularly the following articles have been reviewed and will be considered in the revision: R.P. Behringer et al. (2013); J.M. Buffington et al. (1992) N. Estrada et al. (2013) D.L. Foster et al. (2006); W.K. Illenberger (1991); P.D. Komar and Z. Li (1986); J.R. Metcalf (1966); A.A. Pena et al. (2013); G.S. Riley and G.R. Mann (1972); B. SaintCyr et al. (2013); P.R. Wilcock (1993); F.-C. Wu and Y.-J. Chou (2003).

Comments 2: "There is something that I don't understand but appears relevant for this paper: the friction angle derived from the direct shear test occurs under a normal stress of up to 64 kPa. Now in the natural situation of transported sediment the submerged sediment is actually at the bed surface. A normal stress of about 50 kPa means that a sample with unit surface area is subjected to a weight of 5000 kg. With a typical sediment + pores density of about 1500 kg/m3 this translates to a sliding sediment layer of more than 3 m thick, which is a considerable avalanche. How is this comparable to the friction or, rather, pivot angle of moving sediment particles ON a bed surface? Perhaps the material properties in these very different conditions can be compared and indeed I think so, but it is not yet well explained and argued here and I don't know why it would be comparable and I don't know references where this is discussed."

One of the main objectives of the manuscript is to test the hypothesis if the flat and elliptic particle shape impacts the friction angle and shearing behavior of the sand-sized particles. If so, how this possibly contributes to the stability of the beach (l. 41-43). This hypothesis can be supported by findings by e.g. Riley and Mann (1972) who documented that the tendency of "flake" shape particles to settle on their plane of greatest stability increased the angle of repose of glass particles significantly, and by studies by Kirchner et al. (1990) and Buffington et al. (1992) who highlighted the importance of grain shape on the friction angle of coarse sediments in river beds. Geotechnical laboratory tests have been chosen to investigate the shearing behavior, as those direct shear box and ring shear tests are well established techniques to test the shearing behavior of sediments including maximum shear stresses and dilatory behavior under controlled normal stresses (Craig, 1974; Das, 1990). Furthermore, the availability of different box sizes and the ring shear allowed testing of different sediment mixtures and long-term shearing of the finer fractions to investigate changes in shearing behavior dependent of gravel-sand mixture, as found to be variable at the Advocate Beach surface. We agree with Dr. Kleinhans that there are significant differences between the shear apparatus procedure and shearing in the framework of sediment mobilization and transport at the beach surface. Particularly, the apparent normal stresses differ as correctly pointed out by Dr. Kleinhans. Nevertheless, the following arguments justify the use of the presented geotechnical laboratory techniques in this study.

- The purpose of the shear tests was to determine "the behavior of Advocate sand and sand-gravel mixtures during shearing" (l.44-46). Motivated by the observations at the beach, the objective was to investigate and possibly identify a behavior during shearing that might contribute to explaining the stability and limited entrainment of sand-sized particles during energetic conditions. We agree that the direct and quantitative comparison of the angle of internal friction as determined in the laboratory shear tests to the angle of repose on the beachface is a matter for discussion. The difference in normal stress is only one of the differing issues (e.g., packing state and sample preparation, beach slope, etc.). However, it can be argued that a qualitative comparison is justified.

The angle of internal friction is clearly dependent on sample density and packing as has been documented by numerous authors. It is well known since the mid 20th century (e.g., Taylor, 1946) the friction angle will decrease with looser packing. Furthermore, it has been argued that the angle of repose approximates the angle of internal friction at the loosest condition of packing (e.g., Metcalf, 1966). Thus, the observation of the exceptionally high angles of internal friction would still favor the conclusion that this impacts the mobilization of sediment at the beach and likely contributes to a higher stability of the beach sands, as it might even represent the most conservative estimate of the angle of repose. However, Metcalf (1966) specifies that the angle of repose actually does not equal the angle of internal friction at the loosest packing state, but at the first state of consolidation caused by initial shearing. This was particularly true for quartz sand and crushed sandstone in his study.

- The shear tests allowed a high resolution measurement of dilatory processes which contribute centrally to the conceptual sketch of the shearing process. Observations at such high resolution would have hardly been possible in the field, and would also have been difficult in other laboratory tests. Particularly, the dilatory behavior should have rather suffered from the higher normal stresses. Furthermore, the repeatable behavior under different loads and even long-term shearing highly supported the conclusion: i.e. that the specific particle rearrangement and dilatory behavior of the elliptic sediment particles under shearing led to an increase in shearing resistance that likely contributes to the limited entrainment of sandy particles under hydrodynamic forcing. Following that, we argue that the geotechnical shear tests serve the objectives and support the conclusions in this manuscript, despite the "unrealistic" normal stresses with respect to the beachface scenario. However, we agree that this should be discussed in more detail and clarified.

We suggest the following changes of the manuscript in accord with this discussion:

- Change of title to: "The impact of particle shape on the angle of internal friction and the implications for sediment dynamics at a steep, mixed sand-gravel beach".

- Add section to Introduction giving more background on shearing behavior, testing and parameters, and the resulting choice of methods. Add section on attractiveness of including geotech lab methods to the investigation of sediment dynamics.

- Expand section in Methods describing the procedures.

- Add section in Discussion on the impact of normal stress and the relation of angle of internal friction to angle of repose and applicability of the results on the beach sediment mobilization scenario. We agree that this is certainly a shortcoming in the current manuscript.

Comment 3: "A table with the different mixtures, friction angles and observed behaviour would be very convenient to have as a summary of sections such as 3.1.1."

Agreed, such a table will be included.

Comment 4: "Some systematic data analyses are lacking. The angularity of the sediments are clearly known, so why is this not plotted against the friction angle? Shape is easily parameterized by some sort of shape characterisation (see Folk 1966 in Sedimentology and I think there also was an extensive review in 2012 or 2013 in Sedimentology on particle shape description classifications)."

Agreed, we will determine the Corey Shape Index and include it in the table mentioned under comment 3.

Comment 5: "Furthermore, figure 3 has the time series with horizontal displacement and the shear stress. Usually, in such tests, the peak shear strength just before 'failure' is plotted against the different normal stresses. A linear fit to these points results in an apparent cohesion (intercept) and the angle of internal friction (the slope of the line). This simple analysis has not been done but the data presented in the paper allows the authors to do this for the different sediments. Given the main objective of the paper, a direct comparison of these values for the different sediments would be most useful. We found, by the way, in a similar setup of the same size that for low normal stresses

this analysis is rather inaccurate and the data is rather sensitive to sample preparation and sample inhomogeneity including larger particles being dragged along the shear plane, and, as the authors here report, even particles being destroyed. However, with least squares linear regression the effective uncertainty of the angle of repose should be straightforward to quantify."

This analysis has actually been done. The peak shear stress (that in this study in most cases also resembles the residual shear stress, highlighting the loose state of packing of the samples) has been plotted against the different normal stresses to determine the angle of internal friction presented in this manuscript. Tests were repeated with material from the same samples, and similar results were derived. This has not been highlighted in the manuscript, and we agree that this should be added. Furthermore, we agree with the idea of applying a least squares linear regression to determine the uncertainty when normal stresses are very low and the angle of internal friction approximates the angle of repose. Suggested changes:

- Add peak shear stresses in table (see comment 3)

- Add comment on test duplicates

- Add statistical analysis of uncertainty at low normal stresses.

Comment 6: "Also, figure 7 is a dimensional plot with interesting trends. I think the experimental data of the direct shear tests and the angle of the tray allow you to do without much effort some very interesting analyses. In the first place, how does the angle of internal friction derived from the shear tests compare to the intercept of a curve fitted to the date in fig 7 (where intercept is a minimum angle)? And, if the angle on the horizontal axis is normalised by that intercept, does the data collapse? Would it be possible to collapse the data if the velocity on the vertical axis is normalised by settling velocity in water? Was this velocity in fig 7 in each experiment constant in time anyway? I would expect not. There probably is a static friction angle at which the material starts moving, but once in movement only a lower angle is required to keep it moving: the dynamic friction angle. When the material is placed on a tray with a larger angle, wouldn't you expect ongoing acceleration? In Pouliquen's work there is interesting discussion on this effect (Phys Rev E and other granular community literature). So perhaps the intercept in this plot is the most interesting information: the static friction angle determined in a different way independent of the direct shear box test."

The intercept here is significantly lower, being a consequence of the smooth tray surface (see l. 196-199). Most of the sediment was fed from a hopper, but the impact of the smooth tray still has to be considered and clearly led to the smaller tray tilt angles at low velocities when compared to the angle of internal friction. Nevertheless, it was striking that the sand was mobilized significantly later. Normalization of the horizontal axis by the respective intercept of each material does not lead to a collapse. Settling velocities in water were not determined, but represent an interesting avenue for further research. The measured particle velocities during the tilting tray experiment varied over time. Different phases of motion were observed, depending on tray tilt angle and sediment. For example, at intermediate tray tilt angles, motion started with only small numbers of particles slipping, before larger groups moved as sheet motion, etc. However, during all runs a "major phase of motion" could be identified, being the phase when most of the particle motion occurred. A time-average over this phase was used to determine characteristic transport velocities for the respective runs and tray tilt angles. These values are presented in Figure 7. Details on the different velocity measurements over time, including discussion of the different phases of motion, are given in Stark et al. (2014) in the Journal of Atmospheric and Oceanic Technology and would exceed the scope of this manuscript.

Suggested changes:

- Add more detailed discussion about boundary effects that interfere with a direct comparison of the intercept and the shear box results.

- Add some more detail on how velocities in Figure 7 were determined, and refer to Stark et al. (2014) for more details.

Comment 7: "Was porosity measured? This would be a proxy for the number of particle-particle contacts: the more poorly sorted a mixture, the lower the porosity (Frings et al. in Sedimentology and WRR) and the more contacts. This could contribute to material strength and I would expect that poorly sorted sediment is more difficult to dilate, because dilation immediately leads to kinematic sorting with the smaller particles percolating down into the mixture. Porosity can be estimated directly from particle size distributions, which would be good to have in this paper anyway. From this reasoning, an increase of friction angle for mixtures is expected, and the behaviour of mixtures reported elsewhere and discussed in this paper on page 1195 are therefore unexpected and intriguing."

Porosity was not measured. In the case of the sand samples (unimodal), we also expect that the porosity changed with the particle arrangement and likely in response to the dilatory behavior. Thus, we suspect that an estimate of porosity based on particle size alone might be misleading. We agree that the observed friction angle of the sand-gravel mixtures was very surprising, being one of the main arguments supporting the importance of the sand particles regarding shearing resistance at this beach. We also agree that this aspect could and should be discussed in more detail, particularly with its importance for the beach dynamics.

Suggested changes:

- Detailed discussion of the surprising shear results of sand vs. sand-gravel vs. gravel

Comment 8: "Are the mixtures in the experiments bimodal or unimodal? Bimodal experiments show very different behaviour (see work of Peter Wilcock et al. in J. of Hydraul. Engineering and elsewhere)."

All experiments in the small direct shear box, the ring shear and in the tank used unimodal sediments, while in the large shear box bimodal mixtures of gravel-sand were tested at two different mixtures.

Suggested changes:

- Add details on grain size distribution

- Add this information in table suggested in comment 3

Comment 9: “Beginning of discussion: friction angles of 42-46 degrees are indeed high but have been reported in the literature for other angular and irregular sediments. Carrigy (1970 in Sedimentology) and JRL Allen in his large 1984 book (reports on highly elliptic rice and spaghetti included in there) for instance. The rest of the discussion is highly interesting in pointing out that mixtures reporting elsewhere have reducing friction angles.”

Agreed.

Suggested changes:

- Add references and findings by Carrigy (1970) and Allen (1984) in respective part of discussion.

Comment 10: “The phases in the conceptual sketch (fig 8) are interesting, but what happens on the seabed during the events of interest? The paper starts of by describing the general situation but the discussion does not come back to this. However, it is of great interest. There has been a lot of work on sand-gravel mixtures in rivers, including the peculiar bedforms and sorting trends and imbrication, all of which may be highly relevant in this environment. Either remove the environment altogether or say more about it later (if you can - perhaps not enough is known to say anything).”

Agreed. It will be difficult to draw final conclusions for the beach environment, or possibly other environments such as rivers, solely from this data set. However, we are confident the stated hypothesis is supported by the data, and can be correlated to the

findings from the beach experiment. Furthermore, a wider outlook regarding follow-up research opportunities could be given. Figure 8 depicts a concept of particle rearrangement that is in accordance with the observed shearing behavior during the geotechnical shear tests. Loosely and randomly distributed particles at the sediment surface rearrange when shearing is initiated. This has also been observed for surface sediments on sloped surfaces (Metcalf, 1966), and in particular flat, elliptic particles are expected to position on their face of largest support (Riley and Mann, 1972). At this stage a compaction and a negligible shearing resistance has been recorded, expressing the settlement due to rearrangement and the easy gliding of particle face over particle face. At the beach, this behavior would already favor low particle entrainment. Particles can slide easily over each other, allowing some bedload transport, but tilting, rolling and lifting of the particles is hampered by this arrangement. With continuing shearing defects, e.g. caused by a broken particle with angular edges as observed in the samples, particles of different size, or gaps, as well as increased sediment density as a consequence of compaction during shearing, disturbs the sliding over the particle face. A rapid increase in shear stress and dilation has been observed in the shear box, and the arrangement appeared resistant until destruction of particles in the long-term tests (Fig. 8). With regard to the beach environment, possibly the defect, but certainly the dilation can be associated with the protrusion of particles which would generally suggest an easier entrainment of particles (Kirchner et al., 1990). In this case however, the shear box tests suggest that the interlocking of particles forms a particularly strong network that likely contributes to limited entrainment of the sand-sized particles. Overall this suggests that these particles would favor a sliding bedload transport than entrainment. In the field such a particle network might even be strengthened by the trapping and filling of pores with finer particles, or broken particle pieces. The described behavior appears also to be in accordance with geomorphologic observations during the same beach experiment documented by Hay et al. (submitted to ESurf). During a storm event, ripples were formed and destroyed by the passing swash and surf zone of the flood and ebb tide, respectively. The crests consisted of sandy sediment fractions, and were likely build and washed out by sand mobilized as bedload transport. Hay et al. (submitted) pointed out that processes of crest formation and destruction involved predominantly local sediments, and not sediments transported in suspension. Progressing waves at higher tidal levels were not sufficient to initiate significant sediment transport, and only very limited movement of the ripples was observed using a side scan sonar when the water depth equaled $\geq$ 0.5 m. During calmer hydrodynamic conditions, no formation of ripples was observed. Different tests in the field and in the laboratory could be conducted to investigate the above described behavior in more detail. In the laboratory, geotechnical tests could be extended and correlated with the detailed analysis of particle motion in a flume or tank. In the framework of more laboratory analyses, also tilting tray tests with rough surface trays, or similar investigations of the angle of repose (e.g., Metcalf, 1966) should be conducted. In the field, video recordings of the formation of the ripples with the passing swash and surf zone would confirm the processes involved in the formation and destruction of the ripples. Measurements of suspended sediment concentration would give further information about the amount of sediment and type of sediment that can be entrained under different hydrokinetic forcing.

Suggested changes:

- Add a more detailed discussion about the implication of the findings on the beach environment (see also comment 2).

- Add outlook on further research opportunities.

Interactive comment on Earth Surf. Dynam. Discuss., 1, 1187, 2013.