
Data Repository 1: X-ray computed tomography reveals that grain protrusion controls critical entrainment shear stress in fluvial gravels
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Section 1: Flume Morphology
The morphology of the flume bed is shown in Fig. DR1.

Figure DR1: Flume set up, showing the riffle-pool topography. Flow is from top to bottom of the image. Circles show the approximate locations of the baskets in the riffle (R), pool tail (T), deep pool (D), and shallow pool (S). Flume dimensions are 60 x 2.1 x 0.7 m.
Section 2: X-ray computed tomography (XCT) images of the baskets

Images of different stages of the XCT processing methods are shown in Fig. DR2.

Figure DR2: a and b) photo and scan of basket surface; c to e) cross-sections through XCT scan showing entire basket, grains only and matrix only respectively. The different components were segmented using a semi-automated classification; f) 3D image of a set of grains, with a surface grain and three supporting grains shown.
as translucent. For these four grains grain-grain contacts (red patches) and particle-to-contact vectors (green) are shown.

Section 3: Methods for comparison with bedload models:
We use the XCT results to calculate the number of grains that would be entrained at different values of $\tau^*$, and compare these numbers to the number of grains that are predicted to be entrained using both the Meyer-Peter Muller (1948) and Wilcock and Crowe (2003) bedload transport models.

For the XCT data, we assume that the total area, $A$, of all 20 baskets is arranged as a single area with downstream length, $L$, which is a grain step length, and width $w = A/L$. Values of $\tau_c$ for each grain are converted to $\tau^*$ using the $D_{50}$ for all baskets (23 mm). For each applied $\tau^*$, all grains with $\tau^*_{c,g} < \tau^*$ will leave $A$ in a time step with duration $t$.

One approach to calculating $t$ is to use grain saltation velocity ($v$): $t = v/L$, which gives the time for all grains to leave area $A$. However, this assumes that grains are instantaneously entrained and move at velocity $v$. However, their actual velocity will be a virtual velocity that incorporates rest periods and so is a fraction of $v$. We therefore add a transport rate reduction factor ($F$) such that $t = Fv/L$; when $F = 1$, grains are travelling at their saltation velocity with no rest periods.

For the bedload transport model we use both Meyer-Peter and Muller (1948) and Wilcock and Crowe (2003), which give bedload transport rates ($q_b$) in $m^3 m^{-1} s^{-1}$. These are converted to number of grains using $V$, the volume of a spherical $D_{50}$ grain. For both bedload models we use a uniform grain size of $D_{50}$. Although we could implement Wilcock and Crowe (2003) with a full grain size distribution, the uncertainties around other components of this comparison mean that this level of sophistication is unnecessary. Furthermore, our data suggest that $\tau_c$ is not a significant function of grain size (Fig. 2L). To compare the model bedload transport rates to the XCT scan results, we calculate the number of grains ($N$) as $N = (q_b w t)/V$, which is equal to $N = (q_b (A F v/L))/V$.

Implementing this calculation requires estimates of $v, L, F$ and $\tau^*_{c,m}$, where the latter is the critical shear stress implemented in the bedload models. For $v$ and $L$ we use equations fitted by Sklar and Dietrich (2004) to a selection of data from saltating grains in which $v$ and $L$ are power functions of $(\tau^*/\tau^*_{c,m})^{0.56}$ and $\tau^*_{c,m}$, with exponents of 0.56 and 0.88 respectively. We also require a value of $F$. Schmidt and Ergenzinger (1992) report mean step lengths and rest periods for radio-tracked particles of 19 m and 1380 s respectively, with travel velocities between 0.01 and 0.5 m s$^{-1}$ giving $F = 0.02$ to 0.6. Habersack (2001) shows for a radio-tracked particle in a small flood $F = 0.03$, whereas in larger event $F = 0.25$. To account for the uncertainty in both $\tau^*_{c,m}$ and $F$, we calculate relationships between $\tau^*$ and $N$ for both bedload models using $\tau^*_{c,m}$ ranging from 0.03 to 0.06, and $F$ from 0.02 to 0.2. The up-kick at small values of $\tau^*$ for the Wilcock and Crowe (2003) model is because as $\tau^*$ decreases, the timestep increases faster than the decrease in the bedload transport rate.

References

**Supplementary Table**

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