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Validation of a stochastic digital packing algorithm for porosity prediction in fluvial gravel deposits

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ABSTRACT

Porosity as one of the key properties of sediment mixtures is poorly understood. Most of the existing porosity predictors based upon grain size characteristics have been unable to produce satisfying results for fluvial sediment porosity, due to the lack of consideration of other porosity-controlling factors like grain shape and depositional condition. Considering this, a stochastic digital packing algorithm was applied in this work, which provides an innovative way to pack particles of arbitrary shapes and sizes based on digitization of both particles and packing space. The purpose was to test the applicability of this packing algorithm in predicting fluvial sediment porosity by comparing its predictions with outcomes obtained from laboratory measurements. Laboratory samples examined were two natural fluvial sediments from the Rhine River and Kall River (Germany), and commercial glass beads (spheres). All samples were artificially combined into seven grain size distributions: four unimodal distributions and three bimodal distributions. Our study demonstrates that apart from grain size, grain shape also has a clear impact on porosity. The stochastic digital packing algorithm successfully reproduced the measured variations in porosity for the three different particle sources. However, the packing algorithm systematically overpredicted the porosity measured in random dense packing conditions, mainly because the random motion of particles during settling introduced unwanted kinematic sorting and shape effects. The results suggest that the packing algorithm produces loose packing structures, and is useful for trend analysis of packing porosity.

1. Introduction

Porosity prediction of sedimentary deposits is of interest in a fluvial environment. Previous studies have shown that porosity, as a key structural property, plays an important role in the morphological, ecological and geological characteristics of fluvial systems. Morphologically, porosity governs the initiation of sediment motion and bank collapse (e.g., Wilcock, 1998; Vollmer and Kleinhans, 2007). Ecologically, porosity determines the interstitial space of the hyporheic zone for aquatic habitats (e.g., Boulton et al., 1998). Geologically, porosity dominates the exploitable reserve of oil, gas, and groundwater stored in the voids of fluvial deposits (e.g., Athy, 1930). To date, existing porosity predictors can generally be classified into two types: (1) empirical predictors; and (2) theoretical predictors. Most efforts to predict porosity have been empirically driven, to a large extent based upon median grain size D_{50} (e.g., Carling and Reader, 1982; Wu and Wang, 2006), sorting coefficient σ (e.g., Wooster et al., 2008), or a combination of different grain size characteristics (e.g., Frings et al., 2011; Desmond and Weeks, 2014). Theoretical predictors such as geometrical models (e.g., Ouchiyama and Tanaka, 1984; Suzuki and Oshima, 1985) or analytical models (e.g., Yu and Standish, 1991; Koltermann and Gorelick, 1995; Esselburn et al., 2011) relate porosity to the full grain size distribution of perfect spheres. The performance of these predictors has been investigated by comparing porosity values measured in situ with those computed by the predictors (e.g., Frings et al., 2008, 2011). Unfortunately, these predictors produced unsatisfying results in predicting fluvial sediment porosity (Frings et al., 2011), probably because such predictors mainly focused on grain size characteristics, ignoring other porosity-controlling factors such as depositional environment and grain shape.

Effects of grain shape on porosity have received less attention, due to the complexity of arbitrary shapes of natural particles. Over the past decade, the application of computer simulations for the study of granular particle packings has become more popular, supported by developments in the computer hardware industry. However, most of the computer simulations have been limited to simple analytical geometries such as cylinders (Zhang et al., 2006), disks (Desmond and Weeks, 2009), ellipsoids (Donev et al., 2007; Zhou et al., 2011) and spherocylinders (Abreu et al., 2003; Williams and Philipse, 2003; Zhao et al., 2012). The major reason is the practical difficulty of representing and handling irregular shapes using vector-based approaches. Traditional ways to construct an irregular particle require the user to place spherical elements within a meshed polyhedral body (e.g., Wang et al., 2007; Matsushima et al., 2009; Ferellec and McDowell, 2010;

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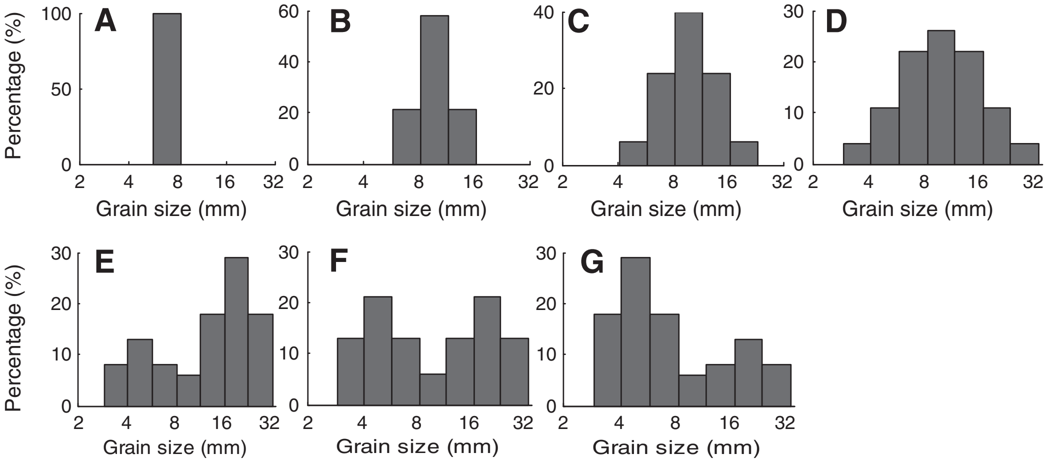

Fig. 1. Four unimodal (A, B, C, D) and three bimodal (E, F, G) grain size distributions used for the porosity measurements and simulations.

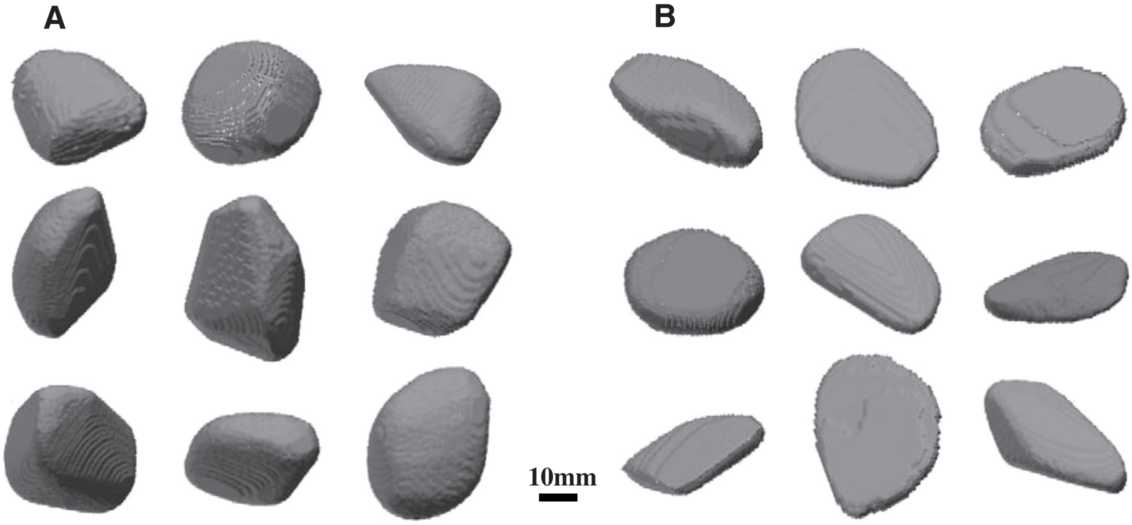

Fig. 2. Nine representative digitized particles in the 22.4–31.5 mm fraction of (A) Rhine sediments, and (B) Kall sediments, represented at a resolution of 0.5 mm/voxel.

Fukuoka et al., 2013), which consumes high computational costs with large numbers of components (spheres) involved (Hubbard, 1996; Song et al., 2006). Although techniques using 3D polyhedral (Latham et al., 2001) or continuous superquadric functions (Williams and Pentland, 1992; Lu et al., 2012) provide a straightforward way to generate irregular particle shapes, complex contact-detection algorithms are needed, leading to deterioration in simulation speed as particle complexity increases (Johnson et al., 2004).

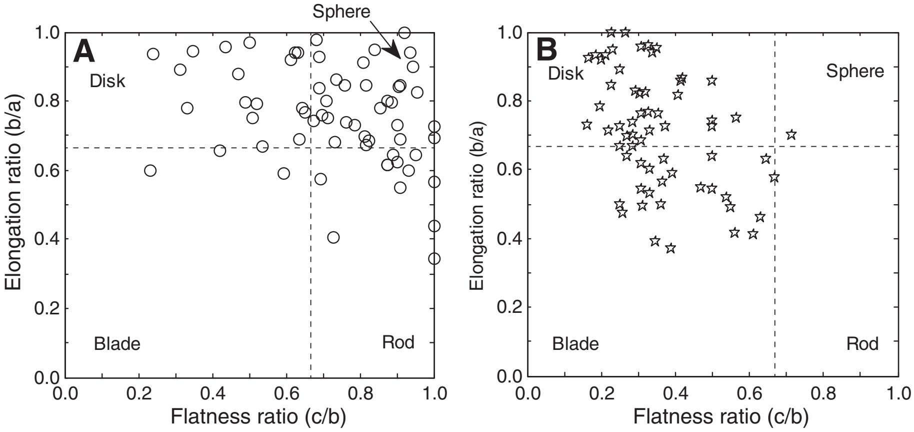

Fig. 3. Shape properties of (A) Rhine sediments, and (B) Kall sediments in the Zingg classification. ($n = 9 \times 7 = 63$).