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The impact of ellipsoidal particle shape on pebble breakage in gravel

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ABSTRACT

We have studied the influence of particle shape and consequently loading configuration on the breakage load of fluvial pebbles. Unfortunately, physical strength tests on pebbles, i.e., point-load tests, can only be conducted under one specific stable loading configuration. Therefore, the physical uniaxial strength tests performed in this study were extended by a two-dimensional finite-element stress analysis, which is capable of investigating those scenarios that are not possible in physical tests. Breakage load, equivalent to that measured in unidirectional physical tests, was determined from the results of the stress analysis by a maximum tensile stress-based failure criterion. Using this assumption, allows the determination of breakage load for a range of different kind of synthetic loading configurations and its comparison with the natural breakage load distribution of the physical strength tests. The results of numerical modelling indicated that the configuration that required the least breakage load corresponded with the minor principal axis of the ellipsoidal pebbles. In addition, most of the simulated gravel-hosted loading configurations exceeded the natural breakage load distribution of fluvial pebbles obtained from the physical strength tests.

1. Introduction

The study of sediment deformation is of great interest for disciplines concerned with near-surface geological processes such as soil mechanics, engineering geology and hydrogeology. Moreover, sediments affected by natural deformation processes, such as sand and gravel, are important commodities, extensively used in the construction industry and a common geological feature. Pebble breakage in gravel results in a change of pebble properties and microstructure and may therefore lead to several phenomena including (i) a decrease in permeability in both natural aquifers and industrial drainage-and filter systems, (ii) an increase in subsidence of buildings and constructions built on gravel foundations and (iii) a change of the mechanical bulk properties of gravel such as shear strength or stiffness [1].

Fluvial gravel deposits are mainly comprised of pebble sized aggregates (4–64 mm). The predominantly fluvial sediment transportation leads to a rounded ellipsoidal shape of the pebbles [2] and may also lead to preferred orientation of the longest axis of the pebbles. The specific shape of fluvial pebbles distinguishes them from many other more spherical and/or angular sedimentary particles in terms of their micro-mechanical response to bulk load, which is distributed and transferred over its particle contacts. The particle-shape may affect pebble rotation and translation in deformation bands [3], the packing density [4] or the contact force network and/or bulk strength [5,6]. The ellipsoidal pebble shape and its control on the stress distribution of potential loading configurations may also have a significant effect on the breakage tendency of pebbles and the investigation of this effect is the aim of this study.

Fractures are reported in imbricated pebbles of a natural fluvial gravel deposit [7]. Fig. 1 shows a section of a gravel layer from this outcrop that exhibits several pebbles with one or more fractures sub-parallel to the minor principal axes of the ellipsoidal pebbles. The fractures are Mode I, which indicates that the maximum tensile stress must have been perpendicular to the fracture plane and in this case also to the minor principal axis of the ellipsoidal pebbles. Hence, a preferred load transmission sub-parallel to the minor principal axes seems most likely.

This assumption is supported by two dimensional numerical studies of ellipse-shaped particle assemblies in biaxial compression [5]. Fig. 2b shows results of those studies indicating that force chains tend to be unidirectional and more localised in comparison to assemblies of spherical particles (Fig. 2a). Additionally, force chains in the assembly of ellipse-shaped particles are often oriented sub-parallel to the semi-minor axes of the ellipses. The numerical results show a clear link between the shape-controlled contact force network and the natural occurrence of fractures in imbricated fluvial pebbles. However, it is not clear if and to which extent the applied load that is necessary for breakage of an individual pebble varies with the position and orientation of the loading axis between two opposing contacts.

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The breakage load varies because the stress distribution inside irregular bodies is varying as a function of the loading geometry [8]. For the imbricated fluvial pebbles this could mean that they break more or less easily in the preferred loading direction relative to any other potential loading configuration. For example non-oriented pebble deposits may have no specific or a different preferred pebble loading orientation. This effect could influence the breakage rate of single pebbles in conjunction with the partitioning effect of the contact force network (Fig. 2) depending on the degree of pebble imbrication, but detailed investigations of this effect on ellipsoidal bodies, such as pebbles, have not yet been carried out.

The effect of shape on the internal stress distribution of bodies under non-uniform load is well known and reflected by the persistent standardisation of specimen shape for rock testing standards [9]. Remarkably, there are only two rock strength tests that allow testing of irregular shaped specimen, namely the point-load test (PLT) [10] and the Protodyakonov Impact Test [11], but both tests are greatly affected by scattering of the test results [12]. However, the point-load test is widely applied in science and industry, due to the small, simple and portable test equipment and rapid testing. The test yields the uncorrected point-load strength index (*Is*), which must be corrected to account for the specimen size to obtain the point-load strength index (e.g., Is_{50}) [13]. This index can then be used to estimate other rock strength parameters such as the unconfined compressive strength (*UCS*) or uniaxial tensile strength (*UTS*).

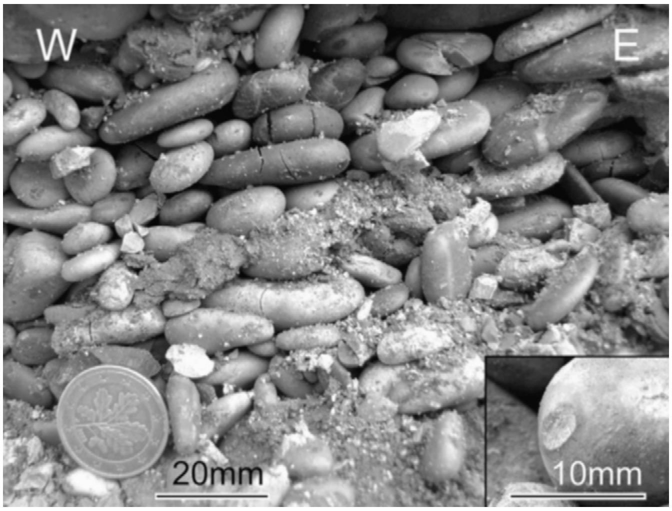

Fig. 1. Gravel layer at the outcrop from where samples were taken. Note a series of sub-parallel fractures in some pebbles, which are perpendicular to the longest principal axis of the pebbles. The inset shows a pebble with a solution pit at one of its former contacts.

In this study, fluvial pebble samples from a Miocene fluvial gravel deposit [14] were tested in the point-load test configuration for irregular specimens [12]. The resulting uncorrected point-load strength index, which is the force applied on the point load cones at catastrophic failure, of a large number of pebbles was statistically analysed. The non-standardized data was chosen for two principal reasons: First, the size of the pebbles was below the minimum size value recommended by the standard method for point-load testing [10,15]. On small samples, the contacts between the sample and the cones cannot be considered as theoretical points as in the case of standard point-load tests. Second, the point-load test configuration in this study is intended to mimic the contact geometry and loading configuration between pebbles in gravel, under central loading parallel to the minor principal pebble axis, and not to estimate rock strength properties such as *UCS* or *UTS*. The resulting distribution of breakage force values of the point-load tests, termed breakage load in this study, can be seen as a loading configuration specific test value that incorporates material and size variations of pebbles from a specific gravel sample.

Unfortunately, the ellipsoidal pebbles can only be tested in a centred position sub-parallel to the minor principal pebble axes, since this is the only stable test configuration. This problem was already recognised and described by Moss [16] for non-spherical quartz grains from fluvial sediments. In order to address this problem, finite element stress analyses were carried out in this study that allowed the investigation of different kinds of synthetic loading configurations, which are present in natural gravel deposits but difficult to achieve with standard point-load test devices. The numerically investigated loading configurations are: (i) translation of the loading axis parallel to the minor principal pebble axis, (ii) rotation of the loading axis around the centre and

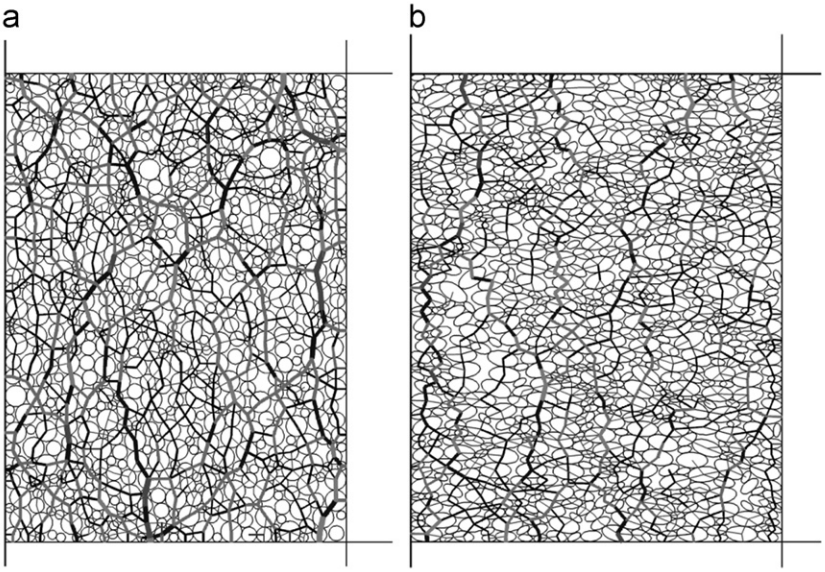

Fig. 2. Sphere- and ellipse-based discrete element method simulations of biaxial compression (after 10% shortening). The ellipsoidal particles in (b) have an aspect ratio of 2:1. Lines joining particle centres are normal forces; their thickness is proportional to force magnitude. (modified after [5]).