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A probability based model for the erosive wear of concrete by sediment bearing water

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ABSTRACT

The purposes of this work were: (i) to understand how erosive wear is affected by the random meso structure of concrete, and (ii) to develop a model for erosive wear of concrete structures due to the action of sediment bearing water loads. An aggregate generation algorithm with certain novel features is used to generate a database comprising 400,000 aggregates with varying levels of angularity and flakiness. Using these aggregates, a probabilistic model for mass loss due to aggregate erosion was formulated. A Monte Carlo simulation is used to obtain the time to failure for single aggregates; these were used to obtain an estimate of slurry erosive loss from the concrete structure, where successive layers of aggregates are assumed to satisfy the ergodicity assumption. The mass loss estimates were compared with experimental results for a sediment bearing water jet. A good qualitative match was observed, with both experimental results and probabilistic estimates exhibiting very similar dependence on meso geometry.

1. Introduction

Erosive wear in concrete is caused by friction and impact of water borne silt, sand, gravel, rocks, ice and other debris on the concrete surface [2]. Coastal structures such as sea-walls, breakwaters and groynes, as well as hydraulic structures such as spillway aprons and stilling basins are particularly susceptible to erosive wear, resulting in surface fractures, concrete peeling and corroded reinforcing bars. Previous research on mass loss due to erosion in concrete structures has mostly been experimental in nature. Researchers [7,8,16] have attempted to relate erosion in concrete to its material properties through empirical equations, with the equation parameters best fitted to the experimental data. These equations enable determination of the erosive mass loss in terms of the compressive strength of concrete. However the approach has limitations, since the wide variation in concrete properties makes it unlikely that a single set of parameter values can describe the dependence of mass loss on compressive strength. It is however well known [24,27] that the compressive strength of concrete depends on its meso structure. Hence a more detailed understanding of erosive mass loss is likely to be obtained by attempting to understand its dependence on the meso-structure.

In order to model mass loss due to erosion using meso-mechanics it is necessary to understand the processes that lead to erosion damage. Liu et al. [13] suggested that erosive wear at a concrete surface due to long term hydraulic impingement by water borne sediment takes place in three stages. Initially, peeling due to impingement of water molecules, closely related to the hydraulic pressure, occurs. Then impact due to water borne sediment causes cracking at the interfaces between sand particles and cement gel, resulting in mortar removal and exposure of the coarse aggregates. The final stage involves removal of coarse aggregates, once the interface between coarse aggregates and mortar are fully damaged. The second stage is dominated by interface failure between fine aggregates (sand) and cement gel (mortar failure). The strength of this interface depends on cement paste strength as well as the bond strength between finer particles and cement paste, which in turn depends on the water-cement ratio, curing conditions etc. The third stage is dominated by interface failure between the coarse aggregates and mortar. The above description of the erosive wear process assumes that the strength of the aggregates (both fine and coarse) is sufficiently high; consequently erosion occurs through interface failure rather than due to splitting or shearing failure of individual aggregates. This is generally true for normal-weight concretes.

Interface failure is thus critical for erosive failure of normal strength concrete. Interfacial stresses depend on the random and heterogeneous geometries of the aggregates, and on the strength and fracture properties of the bond, which are also random and heterogeneous. The meso-mechanical analysis has to account for this randomness in geometric and material properties, as well as the prevalence of multiple length scales, since the size of the

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aggregates in concrete span between 500 μm (fine aggregates) to up to 40 mm (coarse aggregates). In this paper therefore, a discontinuous, particle based approach, capable of modeling the random, heterogeneous, multi-scale nature of the meso structure of concrete is adopted. The model accounts for the randomness in the meso level geometry and material properties; however, the meso-structural mechanics of interfacial de-bonding and failure between interacting particles is treated deterministically. The outline of the paper is as follows. The random variables that are the ingredients of the model are identified, and their probability distributions described in Section 2. In Section 3 the algorithm for generating 3D particles of arbitrary size, angularity and flakiness is described, along with the procedure used to model the random loading and the random interface properties. The probabilistic model for erosive failure is discussed in Section 4. In Section 5, the experiments performed to determine erosive mass loss from concrete slabs subjected to water jet loading are described. The results of the experiments are compared to the mass loss predicted by the probabilistic model in Section 6. Section 7 summarizes the conclusions of the research.

While this paper deals with erosive wear in Portland Cement Concrete (PCC) which is still widely used in the construction industry, recent research in Polymer Concrete (PCt) has shown that in addition to other desirable properties, PCt possesses high abrasion resistance. PCt can therefore be used in the construction of pre-cast components that act as abrasion-resistant surfaces for hydraulic structures such as dams, dikes, reservoirs and piers. A comparison of the relative merits of PCC and PCt can be found in the paper by Martinez-Barrera et al. [14].

2. Identification of the independent random variables

2.1. Particle geometry

2.1.1. Size of aggregate

The magnitude of the stresses that develop at the interface between two aggregate particles depends on the area of the interface. Interface area depends on the size and angularity of the aggregate. It is assumed that the size of the aggregate can be described by a single characteristic length parameter d: the distance between the corners of the rectangular prism that contains within it all the vertices of the aggregate, as shown in Fig. 1(a).

2.1.2. Angularity

The particle angularity (r) is a representative measure of the angularities present on the surface of the aggregate. It is calculated as the weighted average of the discontinuities in slope across all the edges of the aggregate. The discontinuity in slope (r_i) at a particular edge i, with length l_i, is the cosine inverse of the dot product of the face normals of the two adjacent faces j and k that meet at edge i (Fig. 1(b)). The particle angularity is then defined as [10]:

$$r_{\text{aggregate}} = \frac{\sum_{\text{edge}} l_i r_i}{\sum_{\text{edge}} l_i} \text{where } r_i = \cos^{-1}(n_j n_k) \qquad (1)$$

Given the definitions of particle size and angularity, for two aggregates of the same size, the interface areas may be different due to their angularities being different. Fig. 2(a) and (b) show two aggregates that have the same size but the aggregate in Fig. 2(a) has a larger interface area than the aggregate in Fig. 2(b) due to its higher angularity. The aggregate in Fig. 2(c) on the other hand has the same angularity as the aggregate in Fig. 2(a), but the size is much smaller.

2.1.3. Flakiness

Flakiness is a measure of the ratio between the maximum and minimum dimensions of an aggregate (Fig. 1(c)). Fig. 3(a) and (b) show two aggregates that have the same size (d) and angularity (r) but the aggregate in Fig. 3(a) has a lower specific surface area than the aggregate in Fig. 3(b) due to its lower value of flakiness. The flakiness measure adopted in this paper is an extension of the proposal by Wang et al. [24] for arbitrarily shaped 2D particles. Wang et al. [24] obtained the width and length (i.e. minimum and maximum dimensions) of a typical 2D particle by image analysis. The axes about which the second moment of area had a minimum or a maximum were determined by using a Ferret box and testing several different orientations of the image. The dimension of the particle, orthogonal to the axis about which the second moment of area had a minimum, was taken as the particle width. Similarly the dimension of the particle, orthogonal to the axis about which the second moment of area had a maximum, was taken as the particle length. The ratio of length to width was taken to represent the flakiness. This approach was adapted to compute the flakiness of 3D particles: the maximum and minimum principal value of the mass moment of inertia of each particle was determined from an eigen analysis; the ratio of these two values was then taken to represent the particle flakiness:

$$\text{flakiness}\,(f) = \text{Maximum principal value of } I/\text{Minimum principal value of } I \qquad (2)$$

Aggregate size, roughness and flakiness are independent variables which together give a complete measure of the interface area of a particle. As will be seen later, the interface area is the main geometrical parameter of interest, since bonds form at the interfaces and determine the particle's resistance to erosive loads.

2.2. Particle configuration

2.2.1. Exposed area of aggregate

The external load acting on an aggregate is resisted by the bonded faces of the aggregate. For distributed external loading, the magnitude of the stresses that develop at the bonded faces depends on the fraction (η) of the area of the aggregate exposed to the distributed load. The total exposed face area of the aggregate

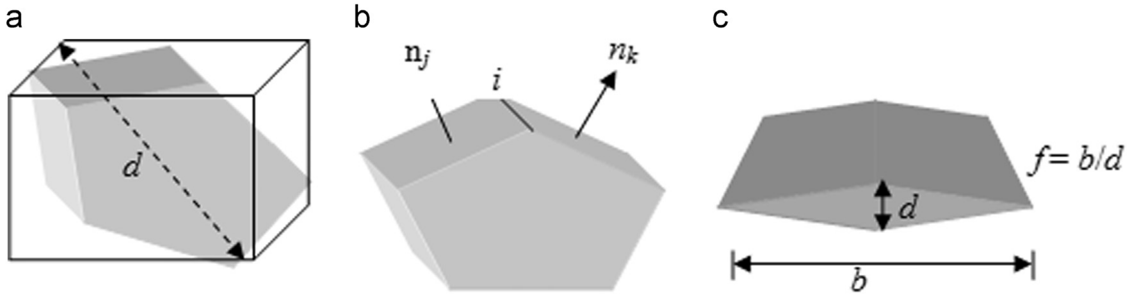

Fig. 1. (a) Aggregate size, (b) angularity, and (c) flakiness.