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Internal erosion of chemically reinforced granular materials: A granulometric approach

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SUMMARY

Internal erosion (IE) of chemically reinforced granular materials results in dislodgement of particles from their rigid skeleton due to seepage stresses. Whether or not these particles can be dislodged and flushed out by seepage depends on (i) the amount of binding agent used to reinforce the granular matrix, (ii) the structure of pore network and (iii) severity of seepage stresses. Results of IE tests are presented for compacted-sand reinforced with increasing amounts of silica gel. The silica gel is a binding agent that permits low-permeability materials reinforcement. IE tests provided information about eroded particles, macro/micro-structural changes and indicators of ongoing IE mechanisms. For instance, data highlighted the existence of up to three IE stages. This includes flushing of movable particles, binder removal and subsequent releases then self-filtering of fine particles within the rigid skeleton. From the careful monitorings of effluent particles (in terms of concentrations and sizes), it was possible to gauge the dynamics of binder removal. Besides, it was also possible to follow changes in dimensions of the smallest constriction that drives travel distances of dislodged particles.

1. Introduction

Erosion is ubiquitous in the natural and urban environments. Surface soils of the earth have been continuously changing as erosion sculpts the landscape. It reduces mountains to a fraction of their original size and carves out valleys and canyons between cliffs. Man-made infrastructures that support society, like dams or levees as well as agricultural lands also experience the processes of erosion and transport of detached material. For instance, in 2005 during Hurricane Katrina, the levee failures in New Orleans, USA, submerged 80% of the city causing death of >1100 inhabitants (Jonkman et al., 2009). The Federal studies that were initiated to provide answers about structures vulnerability stated that most levees sections that performed well were made of less erodible materials (Andersen et al., 2007; IPET, 2007).

Among all the erosion forms, internal erosion (IE) is especially dangerous since it is one of the most common causes of failure of embankment dams (Sherard et al., 1972a, 1972b; Arulanandan and Perry, 1983; Foster et al., 2000a, 2000b; Foster and Fell, 2001; Wan and Fell, 2002, 2004; Ronnqvist, 2005; Fell and Fry, 2007; Reiffsteck, 2007; Fox and Wilson, 2010). Four types of mechanisms have been identified in this context (Bonelli and Brivois, 2008): (i) development of defects in the primary fabric of large particles that support imposed stresses (like grain removal inducing stacks faults or dislocations), (ii) suffusion, which is the process whereby the fines fraction is entrained internally through the primary fabric of large particles, (iii) elongated cavities or channels that are eroded backward toward the reservoir, and (iv) contact erosion, which occurs at the interface between two solid domains of distinct granulometric distributions provided the coarse layer is not appropriate filter for finer layer. Actually, there may be no apparent geomorphic evidence, or only subtle evidence (such as minor cracks, slides, and depressions), that one or several IE processes are taking place. Moreover, a dam may breach within a few hours after evidence of the IE becomes obvious: as a spring discharging at the downstream toe of an embankment. Therefore, it is relevant to monitor changes in physical characteristics of the solid structure at an early stage of erosion. Variations of pore conditions (e.g. like the water content and permeability) and dynamics of particles fluidization (i.e. dislodgement then transport) are expected to trace the processes that control IE.

So far, research on the IE mainly focused on low cohesion or cohesionless granular materials like sand, gravels and diverse non-cohesive soils (US Army Corps of Engineers, 1953; Loebotsjkov, 1969; Arulanandan et al., 1980; Kovacs, 1981; Kenney and Lau, 1985; Burenkova, 1993; Reddi et al., 2000; Bendahmane et al., 2008). The data from the literature showed that the potential for instability of low cohesion/cohesionless materials depends on the ability of their small particles to be flushed throughout the

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constrictions of their pore network. However, unlike cohesionless granular materials, the reinforced granular materials are expected to endure seepage stresses even though their primary fabrics of particles prove to be unstable and/or their small particles in pores partially flushed out (Tam, 1996). Hence, granular material reinforcement has brought about a plethora of engineering applications: e.g. soil stabilization, slope protection, tunnels and underground excavations (Pitt et al., 2007). In this study, we performed IE tests on reinforced compacted-sand columns (CSCs) to probe the mechanisms inherent to IE in these particular granular materials. This paper, which is restricted to chemically reinforced CSCs, has three objectives. First, probing IE stages within CSCs reinforced with increasing amounts of stabilization agent. Second, the monitoring of particles released into the effluent with respect to their granulometry. Third, investigating the microstructural changes induced by seepage.

2. Material and methods

2.1. Internal erosion experiments

Three IE tests were performed at a constant inflow rate ($0.1\ \mathrm{L\,min^{-1}}$, fluid velocities around $10^{-3}\ \mathrm{m\,s^{-1}}$) from the bottom to the top of a transparent tube of height 0.1 m and 0.1 m in diameter filled with reinforced compacted Fontainebleau sand (Fig. 1). IE tests are different according to the reinforcement of the CSCs (i.e. amounts of binding agent). During every IE test, the weight of the CSC, the injection pressure (P_{inj}) and the granulometric distribution of eroded particles (from 0.01 to 100 μm) were measured at different time intervals. The experimental program also included a series of scanning electron microscope (SEM) micrographs.

2.2. Sample preparation

The Fontainebleau sand is a reference granular material that consists of sub-rounded grains with intermediate sphericity and a grain size range of 50–400 μm. Its particle and bulk densities are $\sim$2600 kg m^{-3} and 1500–1600 kg m^{-3}, respectively, with an internal friction angle of 40–45° and a cohesion of 70 Pa (van Mechelen, 2004). A colloidal dispersion of high molecular polysilicic acids was used to reinforce the sand matrix. Indeed, preliminary IE tests done on unreinforced Fontainebleau sand columns highlighted the prompt destabilization of their granular structure (see below). Due to its colloidal nature and its high water content ($\sim$70%), the dispersion allows the reinforcement of low permeability materials ($<10^{-10}$ m^2). The colloids size lies between 5 and 75 nm and the transformation of the colloidal silica dispersion into insoluble silica gel (i.e. the binder; $\sim$1300 kg m^{-3} particle density), upon addition of a saline solution, is irreversible. The gelation time was set to $\sim$1 h. Once impregnated with the dispersion, and prior to gelation, sand compaction was achieved at the centimetric scale by using a dynamic impact method (load of 2.5 N; height of 0.1 m). Finally, prepared samples were kept at 20 °C and 50% relative humidity for 1 week to gain strength and harden fully until IE tests. In the experiments, the amounts of colloidal silica dispersion were set for the silica gel to occupy 33%, 50% and 66% of the porosity of the compacted Fontainebleau sand ($n = 0.38$). We thus referred to the prepared CSCs as N_{33}, N_{50} and N_{66}, respectively. The obtained (n; k) (as determined from the added amount of binder and water permeability measurements) for N_{33}, N_{50} and N_{66} equalled (0.25; 10^{-13} m^2), (0.19; 5×10^{-14} m^2) and (0.13; 5×10^{-15} m^2), respectively. The bulk density of the sand matrix was kept constant (close to 1600 kg m^{-3}).

2.3. Probing IE intensity

To investigate the IE intensities, we monitored the evolutions of P_{inj}, mass changes of CSCs during erosion tests and granulometric distributions of particles from the effluents (Fig. 1). P_{inj} measuring system included a pressure transducer (Model 14 from AEP), which was used together with an automated data acquisition and processing software (WinATS 6.0 from Sysma®). The interval of measurable relative pressure values was between 50 kPa and 2000 kPa, and the accuracy of the measurements equalled 0.10%. The pressure at the top of the CSCs was set equal to the standard atmosphere. The volumetric water content (i.e. θ) was determined by monitoring the CSCs weights at a 0.1 g scale. θ accounts for two mechanisms: (i) the spreading of injected water within capillaries (i.e. this results in CSCs weights increase in the absence of notable particle releases) and (ii) the filling of newly formed pores (i.e. the evolution of CSCs weights is the net result of injected water and eroded material amounts). Hence, to adequately appraise the θ increases, volumes (resp. amounts) of 1–100 μm eroded particles were repeatedly assessed using the granulometric distributions of effluent particles. Finally, coarse eroded particles were collected using a certified 100 μm sieve placed above the lower effluent reservoir. Their mass was measured after drying at 90 °C for 24 h: the >100 μm particles primarily consisted of highly insoluble (silica gel coated) sand grains that exhibit limited wetting. This permitted to lower the drying temperature while keeping the data comparable. As a matter of fact, further drying at 110 °C for 24 h did not result in significantly lower dry weights (<0.5%).

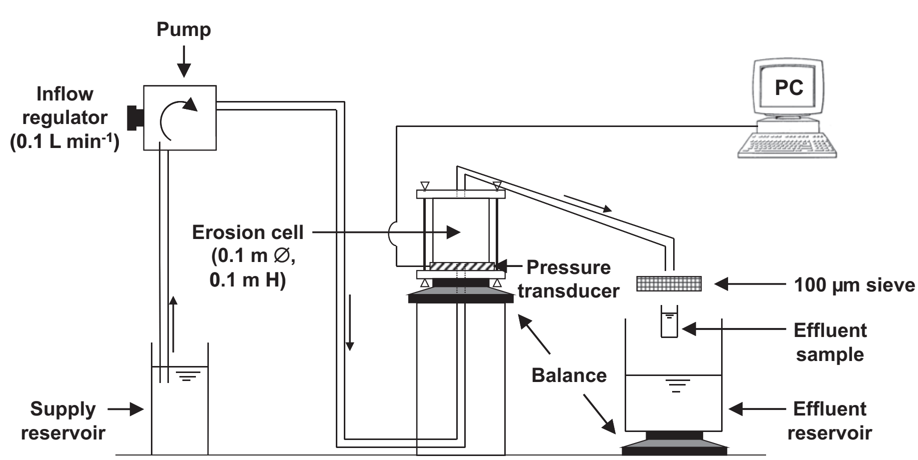

Fig. 1. Experimental set-up for internal erosion tests.