AE ANALYSIS OF PARTICLE CRUSHING: TOWARDS 3D ANALYSIS OF SOILS

Sha Luo

UNIVERSITY OF BRISTOL

Abstract:

Particle breakage plays an essential role in the life-circle of practical geotechnical applications. The crushing process of particle induces changes in the soil's particle size distribution (PSD) and alters the stiffness and strength of granular soil, while significant volumetric contraction is associated. However, the real-time monitoring of the PSD is still problematic due to the non-accessible character of geotechnical structures. Therefore, the non-destructive method, Acoustic Emission (AE) technique, can provide a reasonable solution. Based on our previous crushing studies involving single soil particles and 2D soil samples under the 1D compression loading tests, it was shown the possibility to use AE method to detect and characterise the soil particle mechanical behaviour. With these analyses, a concept process is defined to present the real-time particle size distribution of the sample during the loading by using AE technique, which is an essential progress to the real-time PSD monitoring of 3D soil sample.

1. Introduction

When the stresses imposed on soil particles exceed their strength, the particles will break, [1]. Particle breakage plays a significant role in geotechnical engineering analysis. As a consequence, the crushed fragmentation directly leads to changes in the volume and stress-strain behaviour of soils [2]. The crushing behaviour also significantly affects both shear strength and compressibility of soils [3]. What is more, the amount of particle crushing directly influences changes of the soil’s particle size distribution, which in turn leads to variance in permeability [1]. A realistic investigation of both stress level and stress path dependence in the crushable sand was provided by Bolton [4]. Therefore, the physical understanding of soil crushing will directly affect the application of the mathematical theory to represent soil particle behaviour [5] adequately. In the research on the rockfill behaviour in embankment dams [6], the influence of particle breakage on the assessment of the displacement is also considered crucial. Without considering the crushability of sand, the stress-stress response of the soil cannot be accurately captured [7]. Therefore, it is essential to have a full understanding of particle crushing.

As the result of the soil particle crushing, the particle size distribution (PDS), percentage of the total mass of soil occupied by a given size fraction, shifts. While the distinctive deformation and strength properties of a granular soil come from its particulate nature, in geotechnical design the soil has to be treated as a continuous material. However, the link between the crushing of particles and standard granular soil mechanics parameters through adequate continuum constitutive models has not yet been modelled satisfactorily. In the establishing of a continuum based constitutive model for granular materials that soundly incorporates the
concept of particle crushing, the model's main feature will be the characterisation of the particle crushing through the effect of the grain size distribution changes: grain size distribution becomes part of soil state group variables like the stress and density. There remains an unsolved issue: How does PSD evolve with mechanical loading history? The qualitative assessment of the evolving particle size distribution (PSD) requires, in principle, many tests on identical samples, stopped at different points on their stress path in order to discover the current grading. However, no experimental programme can cover the required range of stress and stress paths as well as soil densities.

In these conditions, the Acoustic Emission (AE) appears as a viable technology for soil breakage characterization. The AE is a non-destructive detection (NDT) method to check the degree of damage to a solid or structure according to the stress wave generated from the inside of the solid or structure when there are sudden damaging processes, such as deformation caused by loading. Compared with other non-destructive detection methods like ultrasound or X-ray, AE can continually monitor the whole damage process inside the structure. Therefore, it is called a dynamic non-destructive measurement. When the elements or particles are under loading, the plastic deformation caused by the concentration of stress and part of the potential energy is released in the spreading of elastic stress waves. This phenomenon is called acoustic emission. If a crack inside the structure is static without growing or changing, the acoustic emission will not appear and cannot be measured. This is a typical property of AE, which is entirely different from other NDT methods. If there were two samples of the same size and with the same type of defects in different positions and under different stresses, the released AE from them would be different due to the different degrees of damage made to the structure. This makes AE useful to monitor the safety of a structure. In geotechnical engineering, AE techniques appear suitable to provide such real-time data [8]. Since 1960’s, many publications treated the study of soils by AE techniques and concerned: small-scale laboratory tests [9], large-scale laboratory tests, slope stability monitoring in dams [10, 11] and embankments, soil movements which raised from horizontal and vertical deformations, seepage monitoring, and grout/hydrofracture monitoring.

Based on the analysis and conclusions resulted from the previous works employing AE method for single particle characterisation, this paper sets the principles of the experimental testing for the analysis of 3D particle systems. The discussion remains at a conceptual stage, and further validation is necessary. In the initial research stage, the AE detection of the individual particle crushing under the uniaxial compression was mainly explored. Different material types from rigid to soft and brittle to ductile (glass, silica, chalk and salt) were used to explore the AE capabilities. The AE capabilities to identify and characterise particle crushing of particle soil assemblies were explored using 2D analogue soil systems composed of cylindrical rods under 1D compression. The analysis focused on both general AE parameters but also on individual AE signals corresponding to main crushing events. Alongside AE passive measurements and global parameters like force and displacement, video recordings of both particle and 2D assembly systems were systematically conducted, thus linking mechanical response and crushing events to the AE emissions. According to the previous initial research, there are seven key findings as following:

1. Does the AE technique work in the detection of the particle crushing of the single particle under uniaxial compression?

In the single particle crushing test, the AE system is able to identify the particle crushing events. The particle crushing events do not refer only to the final crushing but also to
the intermediate crushing mechanisms like for example the chipping of the chalk particles.

2. What are the critical relevant AE parameters for particle crushing characterisation?

A series of AE ‘reference parameters’ – the key relevant AE parameters used to detect the particle crushing events’ were found, able to detect the relevant particle crushing events in this type of test. These AE ‘reference parameters’ include AE Amplitude, AE Average Signal Level (ASL), AE Energy, AE Root Mean Square (RMS), AE Signal Strength and AE Absolute Energy. Moreover, an indication of the particle crushing extent can be made if the cumulated values on the AE ‘reference parameters’ are monitored.

3. Can the response of the AE system be linked with the mechanical parameters?

In the single particle crushing test, the AE system can detect the particle crushing, and this matches well with the mechanical behaviour, like the sudden changing of the force-displacement response. This methodology has shown its potential for all the four different material types, which vary from brittle to ductile. The results have also been analysed based on the Principal Component Analysis method. Moreover, there is a possible relation between mechanical behaviour and the AE ‘reference parameters’. This offers a possibility for AE system to estimate the value of the relevant mechanical parameters in future research.

4. How can the AE technique respond to a range of different materials?

The mechanical behaviour and the AE system records across the four materials showed an extensive range of responses. The AE ‘reference parameters’ have a different response to the different material. For example, the AE RMS is more sensitive to the chalk particle crushing events, especially the chalk particle chipping. The Cumulated AE Absolute Energy is more sensitive to the salt particle crushing growing process. In the results of the frequency domain analysis of the critical crushing hits, the particles made of different materials have different typical frequencies in the critical crushing AE signal. The AE signal appears to represent a signature of the material type.

5. Is AE sensitive to particle size change and shape?

The particle size directly affects the mechanical parameters during a crushing test and AE ‘reference parameters’. The relation between the particle size and the mechanical parameters and AE ‘reference parameters’ in the four materials are similar, although some slight differences exist. However, the particle shape (Irregularity) affects the mechanical behaviour and the frequency distribution of the AE signals which respond to the particle crushing.

6. Can AE data on single particle be used for particle crushing identification in a large particle assembly of soils?

In the 2D sample in the one-dimensional compression test, the noise (energy) released from the individual particle crushing can propagate through the sample and is recorded by the AE system. This could be matched with several loading drops recorded on general force-displacement responses and could be used to refer to the occurrence of
the cracks. The AE ‘reference parameters’ found in single particle test are also useful. Due to the material property of the chalk cylinder, three key AE “reference parameters” to detect the cracks in the 2D sample tests are useful for the cracking detections, and they are AE Amplitude, AE RMS and AE Signal Strength.

7. The mechanical parameters (decreasing percentage and compression stress) show a clear link with the AE Amplitude and AE Absolute Energy; the Fracture Energy connected well with the Cumulative AE Signal Strength at the critical cracking moment. In the frequency domain analysis, the finding that the frequency of the AE signal recorded at the crushing moment is dependent on the material is further proved. The frequency composition of the signals corresponding to various individual particle breakages in the same sample type is very similar.

2. Conception & Methodology

With the conclusions from previous research of 1D and 2D soil samples, the estimation of Particle Size Distribution (PSD) curve of the 3D test during the whole test could finally be achieved with the AE technology. The main concept idea of the estimation process is presented in the flowchart shown in Figure 1. In there, the input data has two parts, one part is collected before the test, and the other part is collected during the test. Before the test, the primary sample information should be identified, which include the size, material and original PSD. This is because from the previous finding, the frequency distribution of the crushing AE signal is more relative to the particle material. Moreover, the sample size will affect the spread of the AE signal, which will directly affect the frequency distribution and amplitude of the AE signal. During the test, the AE signal released during the test will be recorded and will be firstly analyzed under frequency domain, from where the crack could be identified. Then, the identified AE crack signal will be an in-depth analysis with the relevant essential reference to estimate the crushed material, the crushing event type and the size of the crushed surface. Finally, this result will be counted into the final PSD estimation calculation system to offer the real-time PSD curve.
Based on the research results of the studies of 1D and 2D soil sample systems made by the silica, glass, chalk and salt particles (Figure 2), the 3D soil sample test system will be kept in the similar way. In each case, the sample is compressed between two rigid steel plates, of which one is fixed to the loading ram that incorporates an LVDT for vertical displacement.
measurements and load cell. The lower platen moves upwards at a constant speed until the crushing of particles occurs or extensive damage takes place in the sample. During the test, two piezoelectric sensors with a bandwidth of 10 kHz and 1 MHz record the acoustic emissions. The channel one sensor is fixed to the steel base platen, just below the sample at a depth of about 1 cm, using a mechanical system that ensures a constant holding force. The channel two sensor is placed in the same position on the platen in each of test. For both AE sensors, silicon grease is also used to make sure the sensors contact well with the platens. Before the tests, the relevant sensor tests and lab environment tests are also applied.

Figure 2. The photos of tested particles (glass, silica, chalk and salt)

Figure 3. Diagrams of loading system for the uniaxial compression tests

At this stage, only four soil materials have been analysed deeply from the single particles to 2D sample. The relevant information, like typical frequency distribution and the relevant AE reference parameters, are already been analysed and identified. The input material information of the four type particles for the PSD curve monitoring of the 3D sample is ready to process. However, regarding the sample with other material, the estimation of the PSD curve could also be archived by firstly analyzing the single particle to 2D sample.
3. Applications & Future Work

As one of the most fundamental physical properties of soil, particle-size distribution strongly affects many physical and chemical soil properties. There are many classical techniques to determine PSD in soils including sieving, procedures based on sedimentation, such as the pipette and hydrometer methods and numerous techniques like laser light scattering. However, these methods suffer from either numerous disadvantages or limited measurement size. Comparing with them, the AE estimation of the PSD system is free of these disadvantages. Moreover, it could estimate or measure the PSD even without interrupting the test or destruct the structured sample.

In the future, after the uniaxial compression test, more complex soil mechanics tests can be conducted, starting for example with the direct shear box. Tests could also be employed in triaxial apparatus and hollow cylindrical torsional apparatus. Then, the adequate assumption for the construction of the constitutive model based on the experimental results could be developed. The most challenge of the calculation PSD system will be to convert the complex experimental results of the AE technique into a simple output to describe the material state.

References:


