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Onset and Progression of Suffusion in Non-Cohesive Soils Using a Large Co-Axial Erosion Cell

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ABSTRACT

Internal erosion is one of the major causes of the failure of water retaining structures. Suffusion is one of the mechanisms through which the internal erosion process initiates within the embankment dams and their foundations. The process of suffusion includes particle dislodgement followed by the migration of those dislodged particles with the seepage flow through the constrictions of pore network formed by the soil primary fabric. In the present paper, a novel experimental setup is used to carry suffusion experiments on the mixtures of glass beads. The setup features with a large coaxial cell which is ideal for implementing the electromagnetic measurement techniques (present study uses Spatial TDR) and also run the internal erosion test within the cell. The suffusion test was conducted under upward seepage flow by increasing the hydraulic head in multiple steps. The onset of suffusion is identified both visually and from a sudden decrease in the local hydraulic gradients. During the test, the changes in the TDR-trace measured at the cell input using STDR device. These TDR traces can be used to obtain the spatial porosities of the soil specimen during the process of suffusion which will be useful information for the validation of the computational models.

INTRODUCTION

Suffusion is one of the mechanisms through which the internal erosion process initiates within the embankment dams and their foundations. The process of suffusion involves detachment of selective fine fraction from the matrix of internally unstable soil under the action of seepage forces and migration of detached particles through the contractions of coarse fraction, leaving behind the soil skeleton formed by the coarse soil particles. The prosses of suffusion is illustratively shown in Fig. 1. Suffusion results in an increase of hydraulic conductivity, porosity, the formation of sinkholes and the potential onset of other forms of internal erosion. Suffusion can also alter the mechanical properties of soil (Scholtès *et al.*, 2010) which may threaten the stability of water retaining structures (embankment dams, levees, dykes etc.). This highlights the need for a deeper understanding of the mechanism of suffusion, it's initiation and progression on time scale under different hydraulic boundary conditions.

A large number of experimental and numerical studies are available in the literature on suffusion mechanism in sand-gravel mixtures, silt-sand-gravel mixtures and clay-silt-sand-gravel mixtures (Kenney and Lau, 1985; Wan, 2006, Nguyen et al, 2019; Yang et al., 2019). Most of the previous studies were focused on the onset of suffusion and how this onset was influenced by different parameters such as particle size distribution, particle shape, porosity, loading conditions, hydraulic boundary conditions and confining stress. The information on changes in the spatial porosity during the process of suffusion may help for better understanding of this complex phenomenon, which is interrelated to changes in hydraulic and mechanical properties. This information will also be useful to develop and validate the internal erosion prediction models.

In the literature, various methods were adopted for measuring the porosity. To name a few, (i) using the information on changes in layer heights from visual observations; (ii) using Particle Image Velocimetry (PIV) for tracking the migration of fine fraction and variations in the soil matrix and (iii) by generating the high-resolution 2D and 3D images of soil specimens using Computed Tomography (CT) scans, a source of gamma-ray and scintillation counter to measure the profiles of porosity from beginning to the end of internal erosion tests. All the aforementioned techniques have certain drawbacks (Bittner et al., 2017). The profiles of spatial porosity during the process of suffusion can also be obtained from the electromagnetic measurements made on soil specimen under test either in time or frequency domain. This approach will take advantage of the difference in the electric permittivity of different phases in the soil (Robinson et al., 2003; Scheuermann, 2016).

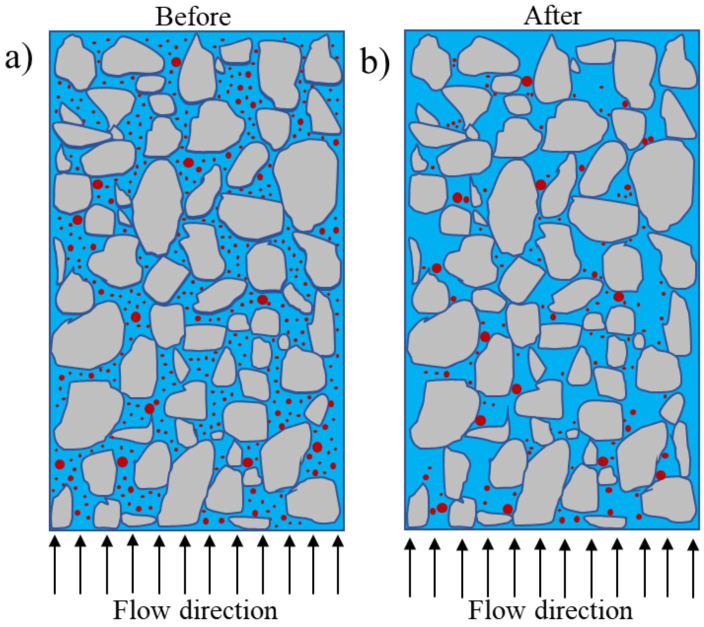

Fig. 1 Suffusion in internally unstable soils

In the present study, a novel experimental setup designed and developed at the University of Queensland is used to carry suffusion experiments on the mixtures of glass beads. The setup features a large coaxial cell, which is ideal for implementing the electromagnetic measurement techniques (present study uses Spatial TDR) and also run an internal erosion test within the cell. Besides, the changes in the local hydraulic gradients and hydraulic conductivities were monitored using 14 pressure transducers and a flowmeter in the downstream side of the cell. During the test, the changes in the TDR-signal is observed from the onset of suffusion to failure of the specimen which indicates the migration of fine particles, resulting in the change of spatial porosity.

EXPERIMENTAL SETUP AND TESTING

The test setup comprises of a large coaxial cell, a hydraulic control system, Spatial TDR and data acquisition system. The schematic diagram of the experimental setup is given in Fig. 2. The coaxial erosion cell can accommodate the soil specimens of height up to 400 mm. The commercially available coaxial rigid transmission line components are used to manufacture this cell to keep the fabrication costs minimum. The conical transition at the cell bottom connects the cylindrical core to the TDR device via coaxial cable. The TDR device feeds the electromagnetic signals to the cell and also records the reflected signals. The cylindrical core of the cell has inner and outer conductors made up of copper tubes. The outer tube has the inner diameter of 151.9 mm and the outer diameter of the inner tube is 41.3 mm.

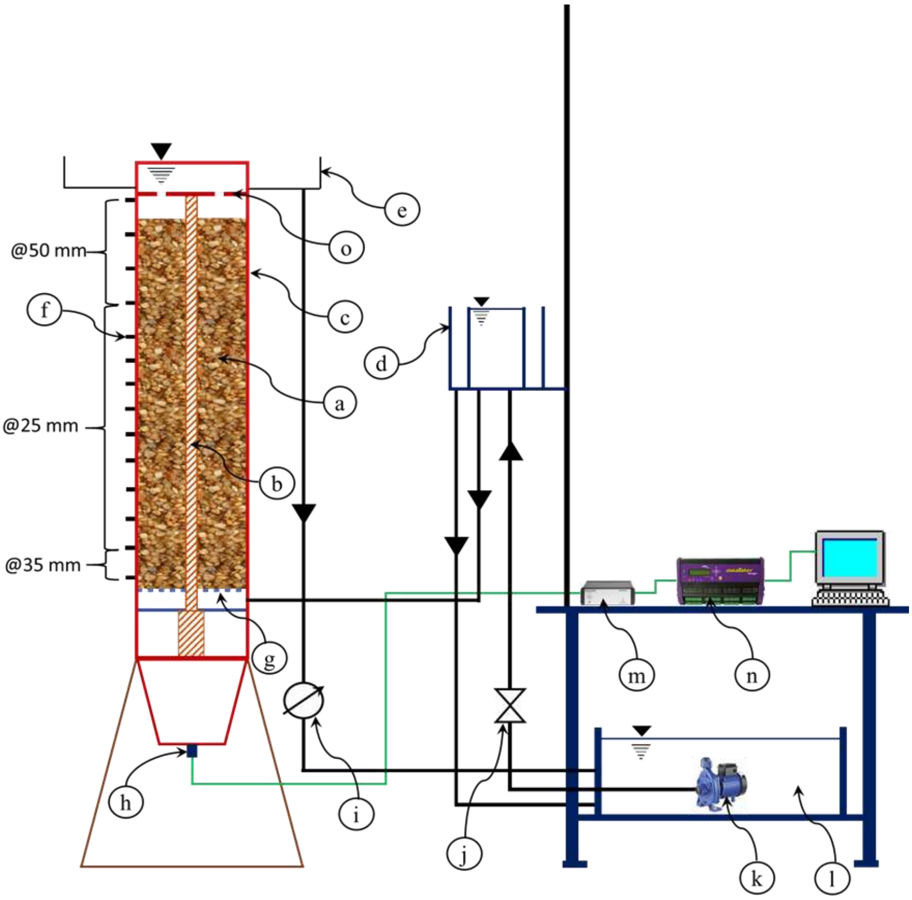

Fig. 2 Schematic view of the experimental setup used in the present study (a) test specimen (b) inner conductor (c) outer conductor (d) Upstream constant head and overflow tank (e) Downstream constant head and overflow tank (f) Pressure transducers (g) Flow homogenizer (h) Coaxial feeding line and connection to TDR device (i) Flowmeter (j) Valve (k) Pump (l) Water reservoir (m) TDR device (n) Datalogger (o) Distance piece

The hydraulic boundary conditions acting on the test specimen can be altered with the help of a moveable constant head overflow chamber on the upstream side of the test specimen. Whereas, the downstream water head is kept unchanged by a constant overflow at the cell top. For the given hydraulic potential, alterations in flow rate are not possible in the existing system. The water circulates in a closed-loop comprising of a submerged pump in a large reservoir of 100 litres capacity, a constant head overflow chamber, a control valve, coaxial erosion cell with overflow on top and a flow meter.

The pressures exerted by the pore water along the depth of the test specimen are measured using 14 pressure transducers mounted on the sidewall of cell in vertical distances between 25 mm and 50 mm. The flow rates are measured using the flowmeter connected on the downstream side of the cell. As per the data from the manufacturer, the pressure transducers and flowmeter can measure with an accuracy of 0.5% and 1.5% respectively. The measurements of pore water pressure and flowrate are recorded continuously throughout the test in the intervals of 10 seconds using a data logger. The above parameters can be used to determine the local hydraulic gradient and permeability of the soil under test. To have a uniform flow boundary condition at the inlet of the soil specimen, a distance piece and flow homogenizer is used which is made of 10 mm thick polymethyl methacrylate acrylic glass (PMMA). The PMMA has a low dielectric permittivity of about 3.7, this features a specific peak in the measured TDR-signal which marks the start of the soil column.

For a better understanding of suffusion process, it is important to have visual observations of particle movements during the onset and progression stages of suffusion. For this purpose, an inspection window of 420 mm high and 40 mm wide is arranged in the cell. At the end of the inner conductor, a metallic short circuit is fitted which causes a sudden drop in the TDR signal. The impedance mismatches at the beginning and end of the cell can be used to define the TDR signal travel time. In the present study, a Sequid Spatial Time Domain Reflectometer (STDR-65) device is used for making the electromagnetic measurements. This device generates a voltage step signal having a short rise time of 65 ps which is feeding at the cell bottom and also records the response voltage signal that reflects from the top of the cell. After performing the Short-Open-End calibration, the rise time can be optimised using the STDR-65 software (Seunis) to increase the smoothness of the signal without losing any important information. A rise time of 1000 ns is the current study.

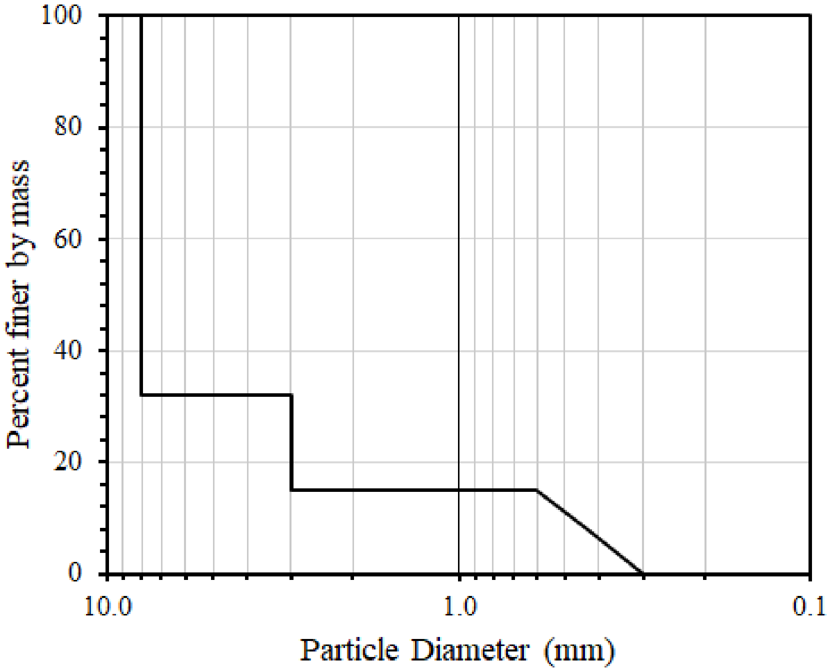

Fig. 3 Grain size distribution of the soil tested in the present study

In the present study, a mixture of glass beads is tested for internal instability in a coaxial erosion cell and its grain size distribution is shown in Fig. 3. For coarse fraction, glass beads of sizes 8 mm and 3 mm are used with the mixing ratio (8 mm/3 mm) of 4. For fine fraction, glass beads of size ranging from 0.6 mm to 0.3 mm are used. Three layers of glass beads of sizes 6 mm, 3 mm and 2 mm are used a base filter to prevent the trickling down of fine particles through the flow homogenizer. The mixture contains 15% fine fraction by mass. The mixture is prepared by thorough mixing of coarse and fine fractions for 3 minutes by adding 10% water content to dry glass beads. After mixing the specimen is placed into the erosion cell in layers of height 50 mm and then the specimen is saturated at a very low gradient. The final height of the specimen before the beginning of the test is 216 mm. During the tests, the specimen is subjected to vertical upward flow. The hydraulic gradient is increased in multiple steps and the increments are kept small enough to identify the onset of suffusion.

TEST RESULTS

The hydraulic gradient is increased gradually with increments $\Delta i_{avg} \approx 0.046$, to a maximum of $i_{avg} = 0.51$. Each stage was lasted for about 10 minutes. The tested specimen exhibited high susceptibility to suffusion. Fig. 4 shows the comparison of the specimen before and after the test. The onset and progression of the suffusion can be visually observed through the inspection window in the cell. The first dislodgment (but no migration) and local fluidization of the fine particles are observed at $i_{avg} = 0.138$. With the next increment in i_{avg}, migration of fine particles is observed. At $i_{avg} = 0.416$, the specimen was failed and the sand boiling condition is observed at the top of the specimen.

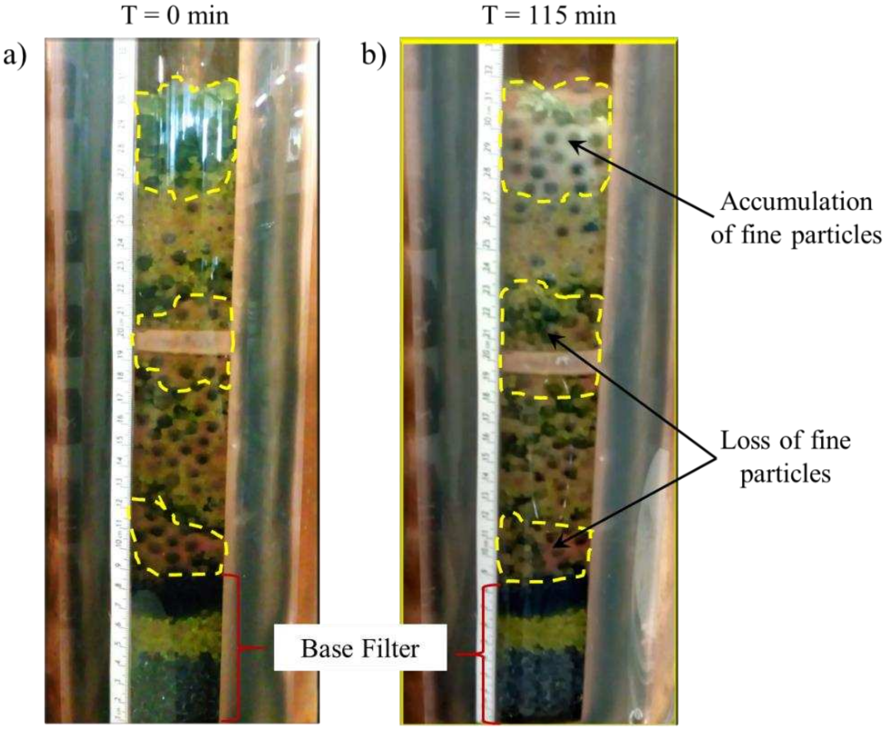

Fig. 4 Specimen a) before (time, T = 0) b) after (time, T = 115 min) the test

Fig. 5 shows the temporal changes in the head distribution measured within the test specimen during the experiment. Initially, water head along the specimen is linearly disturbed which confirms the homogeneity of the specimen. The gradient was increased gradually in stages of 0.046, to a total of 0.51 and then it was decreased as the top overflow tank reached its maximum capacity. The head distribution is almost linear at the i_{avg} of 0.046 and 0.093. Thereafter, the increase in the gradient resulted in non-linear water head distribution within the specimen which indicates that the specimen is no longer homogeneous. When the gradient is increased to 0.138, a significant head loss is observed and this can be attributed to the dislodgment of fine particles (onset of suffusion) at multiple locations within the specimen which was evidenced visually through the inspection window. At higher gradients of 0.51, there is a huge loss in the head in the uppermost portion of the specimen which indicates the accumulation of fine particles that are migrated from the bottom portion of the specimen (refer Fig. 5). The temporal variation of local hydraulic gradient during the whole test is shown in Fig. 6. The sudden drop in the local hydraulic gradient in the layer 7-8 indicated the onset of suffusion.

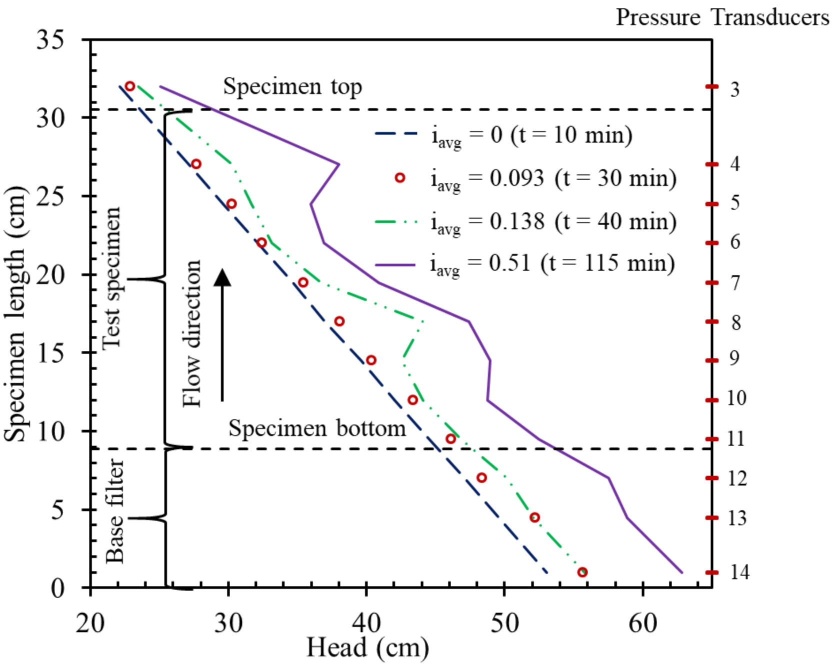

Fig. 5 Temporal variation in the water head profiles

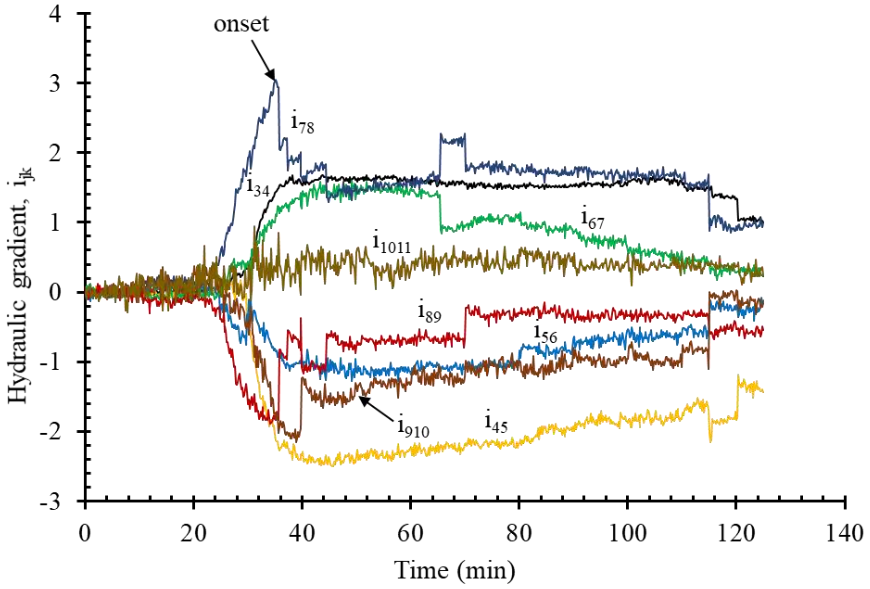

Fig. 6 Temporal variation in the local hydraulic gradients

Fig. 7 illustrates the comparison of the reflection coefficient measured using the STDR device before the start and end of the test. From Fig. 7, it can be observed that there is a measurable change in the reflection coefficient which resulted from the changes occurred in the soil pore structure (i.e., due to the migration of fine particles during the test). The local changes in the pore structure of saturated glass beads alter the local dielectric permittivity which in turn affects the travel time of electromagnetic wave that propagates through the cell. Subsequently, it modifies the reflection coefficient measured at the cell input. The measured reflected TDR signal can be analysed to determine the spatial profile of state variables (for example, density, moisture content and porosity) of the soil under test. This can be achieved by applying a suitable inversion model to the reflected TDR trace. A conventional TDR does not provide this profile information as it can only give the mean value. The development of an efficient inversion algorithm to obtain the permittivity profile and then the porosity profile is under the future scope of work.

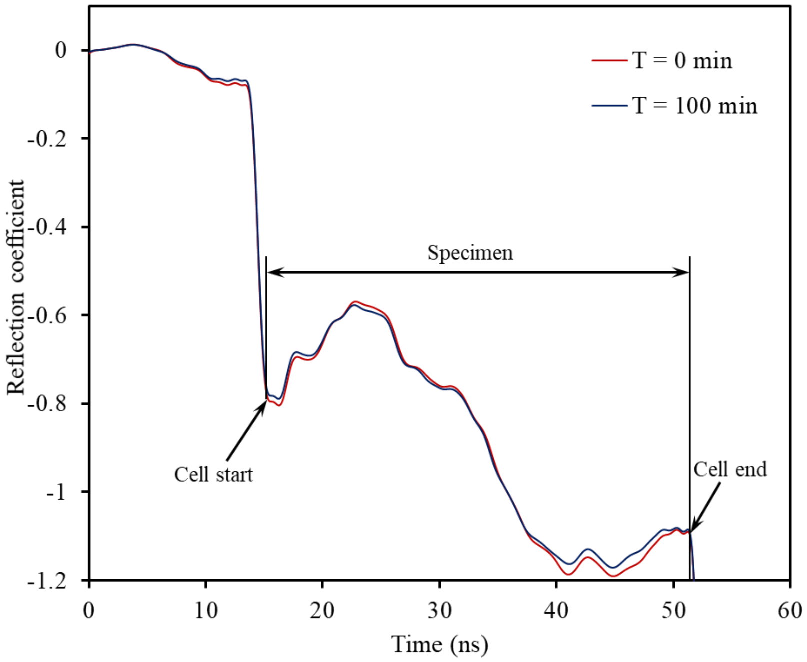

Fig. 7 Modification in the TDR trace because of suffusion

CONCLUSIONS

In the present study, a mixture of glass beads was tested for internal instability under upward seepage flow using the large coaxial cell with spatial Time Domain Reflectometer (STDR). The coaxial cell is ideal for implementing electromagnetic measurement techniques and running the erosion tests within the cell. The pore-water pressures within the specimen were monitored with the help of 14 pressure transducers mounted on the outer wall of the cell. The tested specimen exhibited high susceptibility to suffusion. The onset of suffusion is characterised from the sudden change in the local hydraulic gradient and companion visual observations. The change in the TDR trace is successfully measured using the STDR device. In future, a suitable inversion model will be developed to obtain the profile of spatial porosity and also to measure the change in local porosity. This information will be useful to verify the reliability of erosion prediction models.

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