ABSTRACT

Internal erosion in dams is viewed by engineers as being of particular concern with regard to safety, as there is a danger that there may be no external evidence, or only subtle evidence, that the erosion is taking place. A dam may breach within just a few hours of internal erosion becoming apparent. In order to assist in finding a solution to the lack of external evidence, a series of experimental tests was developed. The tests consisted of applying hydraulic stresses to reconstructed consolidated cohesive soils to evaluate different types of internal erosion (i.e. suffusion and backward erosion). Different parameters such as hydraulic gradient, confining pressure and clay content were examined. When the hydraulic gradient was small, it was concluded that the erosion of the structure’s clay fraction was due to suffusion. When the hydraulic gradient increased, it was concluded that the sand fraction erosion commencement was due to backward erosion. Moreover, the clay content was found to be an important parameter leading directly to internal erosion. The effects of confinement on internal erosion, unlike suffusion, increased backward erosion.

KEYWORDS: Backward, Suffusion, Triaxial Cell

INTRODUCTION

Internal erosion of dam soil particles, caused by water that seeps through the dam, is one of the most common reasons for levee and earth dam failures. Internal erosion is particularly dangerous as there may be no external evidence, or only subtle evidence, that it is actually taking place and a dam may breach within a few hours. It is quite common in these cases for a sand boil to be found, however, the boil may be concealed under water.

Different approaches can be applied to the investigation of internal erosion. Skempton and Brogan (1994) explained the piping of fine grains by the presence of a coarse grain framework that carried the greater part of the overburden load, whereas Monnet (1998) defined a critical piping gradient for the whole of the soil.
Backward erosion and suffusion are the two major phenomena responsible for the erosion of particles in soils. With backward erosion, the particles are detached from the downstream surface of the structure by the seepage forces in the soil. In suffusion, the process is similar, but the coarse particles form a matrix and erosion occurs in only the finer particles in the pore space between the larger particles. (Wan and Fell, 2004)

In the literature on this subject, different criteria are proposed to assess the initiation and development of internal erosion. These different approaches mostly rest on the analysis of the material’s particle size or on the estimation of the critical erosion hydraulic gradient.

**Experimental Setup**

The same procedure as that employed by Bendahmane et al. (2012) was used to run the tests.

The principle of this type of test is to allow a flow through the specimens within the cells. The cell was modified so that the head losses were limited, with fine particle discharge washed away by the process without clogging the drainage system (Fig. 1). In order for the water to be uniformly spread into the top of the sample, a thick layered glass pad was used. In addition, the funnel-shaped draining system was designed to prevent any formation of soil layers at the bottom of the sample. For the suffusion and backward erosion tests on sandy-clay samples, a 4 mm pore opening grid was used to survey the migration of all the particles (sand and clay). The cell outlet was linked to an effluent tank through a transparent drainage pipe.

The test device has unique features which have pressure and suction elements which can operate on the triaxial cell. The device also comprises some pressure regulators connected to air/water interface cells, which are used to create and preserve constant pressures. In order to carry out measurements throughout the test system, two pressure gauges and a vacuum gauge were coupled. Fig.2 shows the setup of the test.

Bendahmane et al. (2008), in studying the very beginnings of internal erosion, proposed the use of a photo sensor to detect the possible erosion initiation point, and to carry out real-time measurements.

![Figure 1: Triaxial Cell and sample setup](image-url)
The sensor was positioned on the pipe linking the triaxial cell to the effluent tank, in order to measure the clearness of the fluid coming through the pipe.

The instantaneous kaolinite content determined by the optical sensor is expressed in the form:

$$S_{\text{opt}}(t) = \frac{\Delta m_{k,\text{out}}}{\Delta m_{w,\text{out}}}$$

(1)

with $\Delta m_{k,\text{out}}$ = kaolinite mass within the effluent; and $\Delta m_{w,\text{out}}$ = water mass within the effluent.

The injection rate $q_w$ is defined by:

$$q_w(t) = \frac{\Delta m_{w,\text{inj}}(t)}{\Delta t} = \frac{\Delta m_{w,\text{out}}(t)}{\Delta t} - \frac{\Delta m_{w,\text{sam}}(t)}{\Delta t}$$

(2)

with $\Delta m_{w,\text{inj}}(t)$ = injected water mass; and $\Delta m_{w,\text{sam}}(t)$ = water mass within the sample.

For clay erosion, as the water mass changes inside the sample ($\Delta m_{w,\text{sam}}$) can be ignored in comparison with the injected water mass change. We then obtain the erosive mass rate per unit surface as:

$$q_s(t) = \frac{S_{\text{opt}}(t) \times q_w(t)}{A}$$

(3)

with $A$ = sample cross-sectional area ($m^2$).

Unlike the measurement of clay erosion, mass measurement is possible due to high quantities of eroded material. The automation in tests is useful for cohesive soil testing as it takes considerable time, thereby saving the user’s own time/manual testing and allows easier data acquisition and monitoring of the tests by the user.
Test Procedure

The material used was a Western Australian sand (grain density: 24 kN/m3) with the grain size distribution shown in Fig. 3. The clay consisted of kaolinite, the geotechnical properties of the clay can be seen in Table 1. The preparation phase was divided into three steps: installation of the sample, saturation, and consolidation. The duplication of the procedure can be achieved by the following procedure.

The sand is first mixed with a moisture content of 12%. While mixing continues, powder clay is then progressively added and mixing is then carried on for 1 additional hour. This method has been validated through confirmation of the size distribution homogeneity, achieved after mixing in Curtin University laboratory. This method differed to that of Bendahmane et al. 2008.

![Figure 3: Grain size distribution of sand and clay](image)

**Table 1: Clay index properties**

<table>
<thead>
<tr>
<th>No.</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Soil type</td>
<td>Clay</td>
</tr>
<tr>
<td>2</td>
<td>Liquid Limit</td>
<td>49</td>
</tr>
<tr>
<td>3</td>
<td>Plastic Limit</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>Pl. Index</td>
<td>26</td>
</tr>
</tbody>
</table>

As a starting point in the saturation phase, 30 kPa confinement pressure was applied to avoid any leakage between the sample and the diaphragm as recommended by Bendahmane et al. 2008. In such sand clay mixtures, saturation with de-aired water only is not effective and carbon dioxide must also be used. The confining pressure was increased in stages in conformity with Australian standard procedures. In order to control the quality of the sample consolidation, fluid volume output measurements were executed until consistency was achieved, and excess pore pressure dissipation was checked.

Details of Tests and Analyses of Results

Hydraulic gradient, clay content, and confining pressure with the following characteristics were examined during the test:

- Clay content: 10, 15, 20 and 30 %
- Hydraulic gradient variations from 10 to 180 m/m; and
• Isotropic confining pressure $\sigma_3$ ($\sigma_1 = \sigma_3$): 100, 150, 200 and 300 kPa.

As Bendahmane et al. 2008 recommended, the range of hydraulic gradients was selected to be fairly wide in order to facilitate the possible reduction of the flow path in the earth’s structure by backward erosion phenomena. In this case, it is possible for the local gradient to be much greater than the global one.

In order to increase the understanding of erosion phenomena, a distinction was made between the tests where only clay particle migration was initiated and the tests during which the transport of both clay particles and sand grains was observed.

**Clay Erosion**

To investigate clay erosion, two hydraulic gradients (i.e. 10 m/m, 60 m/m) were applied. Fig. 4 shows that internal erosion occurs when a 60 m/m hydraulic gradient is applied, but not with a 10 m/m hydraulic gradient. Due to the small quantity of fine material to be weighed, the optical sensor, calibrated for kaolinite, was used for the clay erosion tests. The results of this test proved the pattern suggested by Bendahmane et al. 2008. This showed that from the beginning of the test, the mass flow given by the optical sensor increased until reaching a maximum value, $q_{\text{max}}$. It then reduced abruptly, to finally end with an asymptotic behaviour toward zero.

![Figure 4: Typical time-mass flow curve (15%, $\sigma_3=200$ kPa)](image)

The permeability remained constant while erosion was absent. When erosion commenced, the permeability of the soil sample decreased significantly. Thus, according to the previously defined terminology, this phenomenon, characterised by some diffuse mass losses, may be termed suffusion (Bendahmane et al. (2008). In the tests carried out, suffusion induced an obstruction in the soil specimen. The tests showed that the greater the hydraulic gradient, the bigger the mass of eroded clay.

This section focuses on the effect of clay content on the erosion rate. Fig. 5 represents the maximum erosion rate versus the gradient curve (for a soil with 15% kaolinite content and 200 kPa confining pressure).
Figure 5: Influence of the hydraulic gradient on clay erosion

(15% clay content, $\sigma_3=200$ kPa)

For duplication purposes with regard to results, one of the tests, i.e. $i = 40$ m/m, 15% clay content, $\sigma_3 = 200$ kPa, was conducted four times. The results were positive regarding future test duplication.

The significant variation of the maximum erosion rate observed here can be represented using the following power law:

$$Q_{s \text{ max}} = 14e^{0.0461i}$$

where the number of tests $N = 9$; and the correlation coefficient $R = 0.998$.

Clay Content Effect on Erosion Rate

As the type of material affects the internal erosion of the soil, the effects of clay content were also evaluated and the results documented. In Fig. 6, the maximum erosion rate as a function of the clay content is shown. The results in Fig. 6 reflect a consolidated pressure of 150 kPa.
This series of tests showed that depending on the hydraulic gradient, the erosion rate of the soils studied decreased as a function of the clay content. Generally, the erosion rate doubles when the clay content decreases from 20% to 10%.

**Effect of confining pressure on clay erosion**

This section focuses on the effects of confining pressure on clay erosion. Fig. 7 shows that with an increase in the confining pressure at a constant hydraulic gradient, the clay erosion rate decreases. For the sake of duplication, the results were checked with two hydraulic gradients, with both of them showing the same trend.
Effect of confining pressure on maximum erosion rate on sand and clay (Backward erosion)

Fig. 8 shows the effects of the confining pressure on the maximum erosion rate (determined by weighing for sand erosion).

This section focuses on an investigation of backward phenomenon. This part confirms that by increasing the confining pressure, the erosion of sand within the samples tends to increase. These outcomes prove the significance of confining pressure effects on sample performances. More importantly, they confirm the existence of a secondary critical gradient, from which both clay and sand migration is initiated. This gradient depends on the confining pressure, on the clay content, and on the material. These results confirm the approach of Bendahmane et al. (2008), where a critical hydraulic gradient is necessary for backward erosion.

If the hydraulic gradient value is less than the critical backward erosion gradient value, suffusion would be the most probable scenario. On the other hand, higher values would initiate backward erosion. This confirms the results of Bendahmane et al. (2008) in terms of a critical backward erosion gradient.

Confining pressure also found to play an important role. The outcome of tests at Curtin laboratory proved that backward erosion increases as a function of confining pressure. This confirms the findings of Papamichos et al. (2001) regarding sand only, and Bendahmane et al. (2008) regarding clay and sand mixtures.

![Figure 8: Influence of confining pressure on clay and sand erosion (15% clay content)](image-url)
CONCLUSIONS AND SUMMARY

The experimental setups that were developed can be used to model both saturated and consolidated samples made of sand and clay. Both static and dynamic flows were able to pass through the triaxial cells. The critical internal erosion gradient was assessed from the instantaneous optical analysis of the effluent. In order to address the development of internal erosion, injection volume flow rates and obtained mass flow measurements were compared.

A typical mass flow curve, depending on the different hydraulic gradients evaluated, provides further understanding around the mechanism of erosion. The rate of suffusion increases according to the hydraulic gradient. The initial clay content significantly affects the suffusion mechanisms; the maximum erosion rate doubles when the clay content decreases from 20% to 10%.

Backward critical erosion gradient values are very high, and like suffusion, depend on both clay content and confinement stress. For clay content higher than 10%, no backward erosion effect was observed, whereas with a 10% clay content, the backward erosion critical gradient was:

- 100 m/m with $\sigma_3=250$ kPa;
- 120 m/m with $\sigma_3=200$ kPa; and
- 180 m/m with $\sigma_3=150$ kPa.

These values confirm the complexity of confinement effects on internal erosion. Unlike suffusion, as observed during the tests, confinement increases backward erosion.

ACKNOWLEDGEMENT

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NOTATION

- $i =$ hydraulic gradient;
- $mk_{\text{out}} =$ kaolinite mass within the effluent;
- $mw_{\text{inj}} =$ injected water mass;
- $mw_{\text{out}} =$ water mass within the effluent;
- $mw_{\text{sam}} =$ water mass within the sample;
- $N =$ number of tests;
- $qs =$ erosive mass rate per unit surface;
- $qs_{\text{max}} =$ maximum erosion rate per unit area;
- $qw =$ injection flow;
- $r =$ correlation coefficient;
- $S_{\text{opt}} =$ kaolinite content determined by the optical sensor;
- $A =$ sample cross-sectional area;
REFERENCES


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