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Physical Model Test of Leakage through Composite Cut-Off Wall with Defective Geomembrane

Zhuofu Jiang*, Soon Hoe Chew, Kai En Low, Chuanjin Tang, Jun Yuan Lee, Tse Shing Seah
National University of Singapore, Singapore, Singapore

** e1010620@u.nus.edu*

ABSTRACT: The vertical composite geomembrane-cement bentonite (CGCB) cut-off wall, which consists of a layer of geomembrane sheet installed within cement-bentonite wall, has been widely used in pollution control and the remediation of contaminated sites as an effective barrier system. Compared to cut-off materials such as bentonite or cement-bentonite (CB), which are often sensitive to environmental changes, geomembrane can maintain good stability and very low permeability even under severe environmental conditions. However, because of construction activities and advised ground conditions, defects on geomembrane may occur during construction or over the long term. Once defects, such as holes or cracks, appear, the leakage flow rate through the geomembrane barrier system can increase substantially. Hence, this study explores the use of geomembrane coupled with CB in the cut-off wall. While various analytical models have been proposed to estimate leakage through CGCB cut-off wall, very limited of them have been validated through physical modelling. This study develops a novel laboratory apparatus to physically measure the leakage behaviour of a CGCB cut-off wall with defects on the geomembrane. A preliminary test conducted after about 5 days of CGCB cut-off wall curing yielded a system permeability of 2×10^{-7} m/s, which was much higher than the permeability measured from the 14-day cured CB specimens alone. This indicates that, at the early stage of CGCB cut-off wall, the presence of a geomembrane defect may lead to a higher system permeability than expected. Though the underlying mechanisms require further investigation, the proposed laboratory apparatus is validated to be useful for such study.

1 INTRODUCTION

Developed initially for hydraulic cut-off in dam foundations, cement-bentonite (CB) walls have since been extensively utilised for limiting lateral contaminant transport at industrial and landfill sites (Garvin & Hayles, 1999). More recently, their application has expanded into reclamation works for seepage control. In Singapore, for example, CB walls are incorporated in land-reclamation projects with "empoldering" method. Different from traditional reclamation projects where the reclaimed land is above the sea water surface, the "empoldering method" enable the reclaimed land to be lower than the sea surface by using CB wall to prevent seawater intrusion driven by the higher hydraulic head on the seaward side as shown in Figure 1(a).

However, CB cut-off walls may show reduced performance when exposed to extreme chemical or environmental conditions. For example, high sulphate concentrations in coastal environment can degrade the cement matrix and create micro-fissures in CB materials. These changes increase permeability and reduce stiffness of CB materials in long term

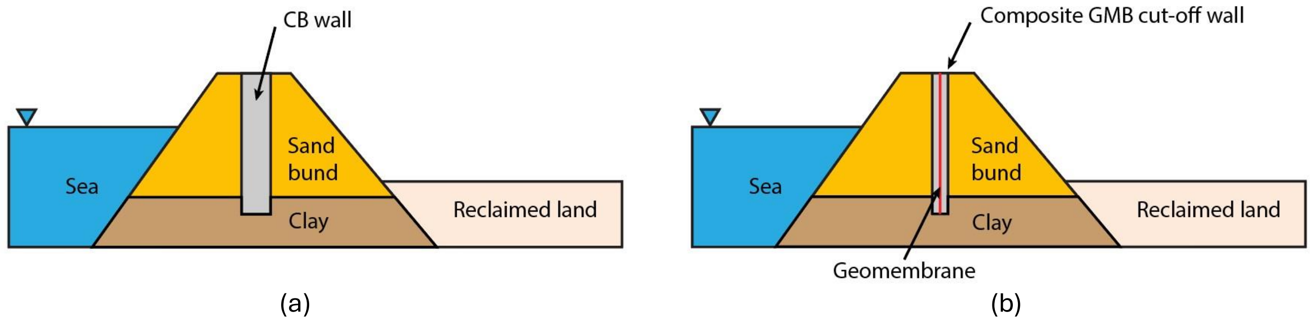

Figure 1. Schematic diagrams of empoldering reclamation method with (a) CB cut-off wall, and (b) CGCB cut-off wall.

(Verástegui-Flores et al., 2013). In addition, cation exchange with marine salts may alter the montmorillonite fabric and reduces the workability of CB material. It also changes the strength and permeability of bentonite-based systems (Li et al., 2024). Besides, repeated wetting–drying cycles will cause shrinkage cracking in conventional CB materials. Subsequently, more preferential flow paths will be created and result in a compromised field performance of CB walls (Cao et al., 2020). These findings indicate that CB walls may not always maintain a stable long-term performance under severe and complex conditions.

Due to the potential long-term degradation of CB walls under aggressive environmental conditions, composite geomembrane-cement bentonite (CGCB) cut-off walls are increasingly regarded as a safer option (Figure 1(b)). CGCB cut-off wall incorporates a layer of geomembrane inside the traditional CB in the trench. The composite system thus has a secondary hydraulic barrier (i.e. geomembrane) with very low permeability and better chemical and environmental resistance. As a result, even if the CB material degrades, the overall cut-off performance can still be maintained by the contribution from the geomembrane.

The concept of using geomembrane together with a layer of low permeability soil (i.e. bentonite) to form a composite liner is not new, and which has been widely used in containment facilities such as landfills or tailing storage facilities (Giroud and Bonaparte, 1989; Rowe and Abdelatty, 2012; Rowe and Fan, 2024). However, for such containment applications, geomembranes and the soil are normally horizontally placed. While for the CGCB cut-off wall, here geomembrane sheets are vertically placed and sandwiched by low permeability CB soil on both sides. In practice, vertical geomembrane barriers are typically installed as prefabricated HDPE panels with mechanical interlocks along the panel edges, which allow adjacent panels to be connected laterally to form a continuous barrier.

Nevertheless, local damage to the geomembrane may still occur during transportation, installation, or long-term service. Once defects are present, a key question is how to quantify the permeability of the entire CGCB cut-off wall system. While the leakage rate through defective geomembrane liners have been extensively studied (Giroud et al., 1992; Touze-Foltz et al., 1999; Chai et al., 2005), the study of the leakage rate through CGCB cut-off wall with defective geomembrane remains largely theoretical (Lin et al., 2023; Xie et al., 2025) without validation by physical modelling. Therefore, this research aims to bridge this gap by developing a new laboratory testing apparatus to experimentally measure the leakage rate through the CGCB cut-off wall with defective geomembrane.

2 METHODOLOGIES

2.1 Material preparation

Sodium-activated bentonite with an API yield of 90 bbl and blast furnace cement (CEM III/B 42.5N) were used to prepare the CB slurry. In addition, a 1 mm thick high-density polyethylene (HDPE) geomembrane with a central circular defect of 10 mm in diameter was used to represent a defect in geomembrane in the CGCB cut-off wall.

2.2 Experiment apparatus

A new laboratory testing apparatus was designed and fabricated to measure the leakage through a defective CGCB cut-off wall. The steel box consisted of three chambers (left side, middle, and right side), as shown in Figure 2. The middle chamber had an internal width of 200 mm, and the left side and right side chambers each had an internal width of 100 mm. The internal cross-sectional dimension of the apparatus was 500 mm × 500 mm.

The middle chamber was used to model the CGCB cut-off wall and filled with CB slurry. The defective geomembrane sheet was installed at the center of the middle chamber section. The left and right chambers were filled with water. During testing, the left chamber was pressurised to create a hydraulic head difference across the middle chamber, and the outflow (seepage) was collected from the right chamber.

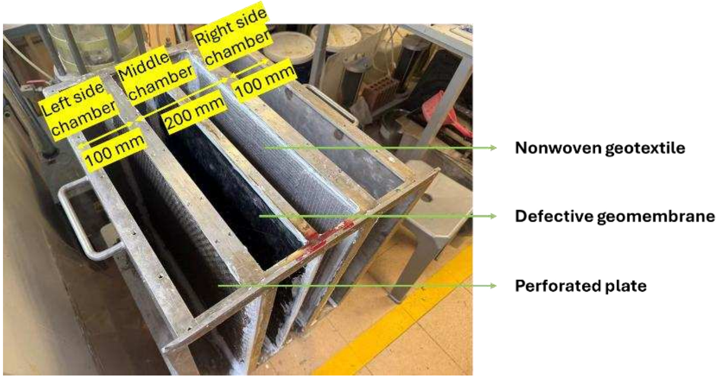

Figure 2. Internal layout of the steel-box apparatus.

The middle chamber was separated from the left and right side chambers by perforated steel plates on both sides. A layer of non-woven geotextile was attached to the inner face of each perforated plate. The perforated plates provided lateral confinement for the CB slurry in the middle chamber, while the geotextile sheet acted as a filter to prevent bentonite slurry intrusion into the side chambers and to allow the water pressure in the side chambers to be transferred uniformly to the middle chamber.

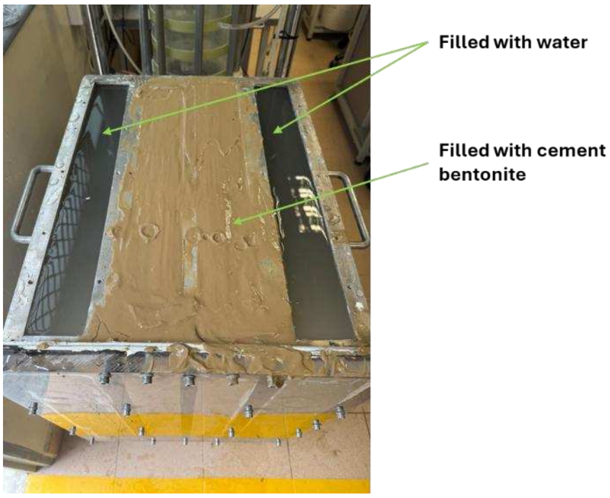

Figure 3. Steel-box apparatus after filling the middle chamber with CB slurry.

To minimize unintended leakage through the gaps between chambers (which could affect the measured seepage), silicone gel was applied to seal the gaps at the interfaces between chambers. After the box was filled (Figure 3), it was capped and connected to an external pressure-control system.

Two pressure controllers were connected to the left side chamber: (i) a coarse controller, consisting of a water tank connected to a compressed-air supply, and (ii) a fine controller (GDS Standard Pressure/Volume Controller V2). The coarse controller was used to fill the chamber with water and to remove entrapped air bubbles. After the chamber was fully filled and air-free, the fine controller took over to maintain a constant pressure in the left chamber. Throughout the tests, the right chamber was open to the atmosphere. The fine controller also recorded the change in water volume, which was used to determine the seepage volume through the system.

2.3 Experimental program

Before testing the permeability of the composite GMB cut-off wall, the basic properties of the CB slurry were first assessed.

Bentonite was soaked in water for 24 hours to allow full hydration. The bentonite slurry was then thoroughly mixed using a Hobart mixer for 10 min, after which calculated amount cement was added. The CB slurry was further mixed for another 10 min to achieve a uniform mixture. The prepared CB slurry was poured into cylindrical moulds (50 mm in diameter and 100 mm in height) to cast specimens for unconfined compressive strength (UCS) tests and permeability tests. All specimens were cured at room temperature in water.

Meanwhile, the same CB slurry was prepared and filled into the steel box apparatus. During filling, a concrete vibrator was used to minimise air voids in the slurry. The three chambers were filled in a coordinated manner, with CB slurry in the middle chamber first and followed by adding water in the side chambers. After filling, the entire system was left to cure for 5 days before conducting the system permeability test.

3 RESULTS AND DISCUSSION

3.1 Unconfined compressive strength

The UCS results of the CB mix after 7 days and 14 days of curing are summarised in Figure 4. The 7-day specimens showed a relatively low UCS, which is consistent with the early stage of cement hydration. After 14 days of curing, the UCS increased to more than twice the 7-day UCS value. Therefore, only the 14-day specimens were considered sufficiently strong for the subsequent permeability tests.

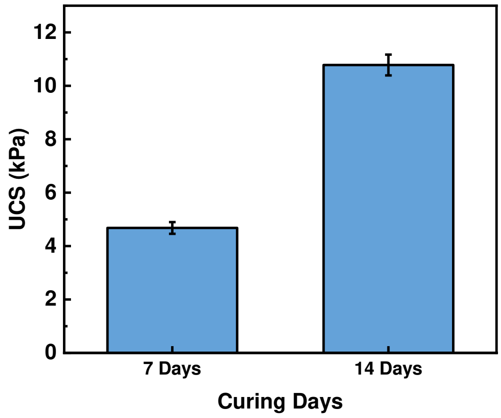

Figure 4. UCS of the CB mix after 7 and 14 days of curing.

3.2 CB sample permeability test

The permeability of the specimens was measured using a triaxial permeameter by applying a 20 kPa pressure difference between the top and bottom surfaces of the specimen. Based on the measured flow rate, the permeability of the 14-day specimens was calculated as 9.1×10^{-9} m/s.

3.3 System permeability test

After 5 days of curing, the permeability test of the whole system was conducted. Ideally, the system test should be performed after the same curing period as the CB specimens (i.e., 14 days) to allow direct comparison. However, due to time constraints, the system test was carried out earlier.

After the left chamber was filled using the coarse controller, the water inlet was switched to the fine pressure controller to pressurise the system and record the leakage. A pressure difference of 20 kPa was initially considered for consistency with the CB specimen permeability test. However, at 20 kPa, the flow velocity was too high for the GDS pressure controller to maintain the target water pressure. Therefore, the inlet pressure was set to 10 kPa during the system permeability test (Figure 5). Based on the measured seepage volume over time, the system permeability of the CGCB cut-off wall with defective geomembrane was calculated using Darcy's law:

$$k = \frac{Q}{A \times i \times t} \approx 2 \times 10^{-7}\ m/s \qquad (1)$$

where Q is the cumulative seepage volume, k is the system permeability, i is the hydraulic gradient, A is the effective flow area, and t is the test duration.

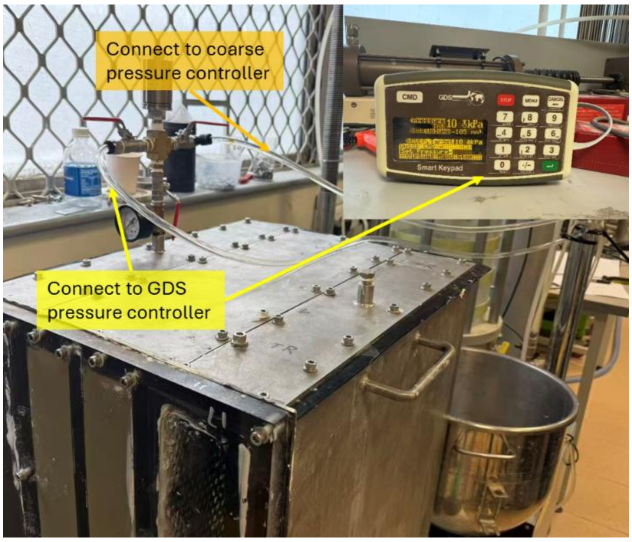

Figure 5. GDS pressure controller during the system permeability test.

The measured system permeability was much higher than the permeability obtained from the 14-day CB specimens. Several factors may have contributed, including: (i) the shorter curing period of the CB slurry in the middle chamber (5 days), which likely resulted in a higher CB permeability than that of the 14-day specimens; (ii) imperfect interface contact between the CB slurry and geomembrane, and between the CB slurry and the steel box boundary, which may have formed preferential flow paths; and (iii) possible additional leakage from welding defects within the apparatus. Therefore, the present result should be regarded as a preliminary system-level measurement, and the effect of curing time on the measured system permeability cannot be isolated from other possible factors which contribute to the high system permeability of CGCB cut-off wall (e.g., interface leakage and apparatus-related leakage).

4 CONCLUSIONS

In this study, a new laboratory apparatus was developed to measure leakage through a CGCB cut-off wall with defective geomembrane. The 14-day CB specimens showed sufficient strength and had a permeability of 9.1×10^{-9} m/s, whereas the CGCB system permeability with defective geomembrane measured after 5 days of curing was 2×10^{-7} m/s under a constant pressure difference of 10 kPa. This preliminary result indicates that the overall permeability of a defective CGCB system can remain relatively high at an early curing stage and/or under possible boundary-related effect. At this stage, the test does not allow the individual contributions of CB curing condition, interface leakage, and apparatus-related leakage to be separated. Nevertheless, the study demonstrates the feasibility of the proposed apparatus for system-level leakage measurement of CGCB cut-off walls with defective geomembranes. Future work will focus on further verifying and minimizing the influence of boundary conditions on the test results, so as to obtain a more accurate measurement of the permeability of CGCB systems with defective geomembrane.

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