Stability of supported geomembrane tube flood barriers of novel design

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Abstract

Geomembrane tube is an alternative method for the construction of flood barriers, cofferdams and breakwaters for flood risk management. Compared to the traditional method of using sandbags to build flood barriers, geomembrane tubes could be inflated very quickly using water, folded and transported easily after the flood recedes and reused in the future. A method of inserting the L-shaped block on the downstream side of a geomembrane tube is proposed to prevent the geomembrane tubes from rolling off or slipping along the ground surface. Numerical studies using particle flow code (PFC2D) software are carried out to analyse the behaviour of the geomembrane tube supported by L-shaped blocks. Parametric studies are also conducted to identify the influences from the key factors and to provide predictive charts for practical usage. It is found that the optimum edge length of the L-shaped block is $0.12L$ and the suggested initial pumping pressure is $0.162\gamma L$ where $L$ is the cross-sectional perimeter of the geomembrane tube and $\gamma$ is the unit weight of the filling liquid. The suggested central angle of the segment of the L-shaped block is $\pi/3$. The geomembrane tube designed using the suggested parameters can sustain an external water level of $0.296L$.

KEYWORDS

flood, flood barrier, geomembrane tube, geosynthetic, PFC2D

1 | INTRODUCTION

Flood and storm disasters over the past decades have become higher in frequency and stronger in intensity. There are several types of floods such as coastal flooding, river flooding and surface water flooding. The surface water flooding often occurs due to an accumulation of rainwater or an overflow of water from water bodies, such as a river, lake or ocean. The commonly used sandbag barrier requires a huge amount of manpower and time to fill and transport which is limited during a disaster. Furthermore, the floodwater contaminated sandbags can quickly become a breeding ground for bacteria if not disposed of properly. The geomembrane tube is an alternative for constructing flood barriers, cofferdams and breakwaters (Biggar & Masala, 1998; Fowler, 1997; Kim et al., 2004; Plaut & Suherman, 1998; Shin & Oh, 2007). The geomembrane tubes are made of very low permeability materials, such as rubber, PVC and polypropylene. Compared to the traditional method of using sandbags to build flood barriers, geomembrane tubes could be inflated promptly using floodwater, folded and transported conveniently after the flood recedes and reused multiple times.

The geomembrane tube system cannot be too high because the external water pressure acting on the headwater side may make the geomembrane tube roll over or slip along the ground surface. Several methods have been proposed in...
recent years to improve the stability of the geomembrane tube system, such as attaching an apron on the headwater side of the geomembrane tube (Kim et al., 2004), stacking one tube on top of two tubes (Kim, Moler, Freeman, Filz, & Pluaut, 2005), one tube with one baffle or two baffles inside and two tubes inside of one bigger tube (Kim, 2003). One of the simplest methods is to use wedges to support the geomembrane tube on the downstream side (Huong, Plaut, & Filz, 2002; Sun, Yue, & Guo, 2017).

Analytical solutions have been proposed to analyse the geomembrane tubes resting on rigid foundations (Cantré & Saathoff, 2011; Guo, Chu, & Nie, 2014; Guo, Chu, Yan, & Nie, 2014; Leshchinsky, Leshchinsky, Ling, & Gilbert, 1996; Liu & Silvester, 1977) and on deformable foundations (Guo, Chu, & Yan, 2011; Guo, Kou, Zhou, Nie, & Chu, 2017; Plaut & Suherman, 1998). The cross sections of geomembrane tubes supported by wedges on the downstream side and acted by external hydraulic pressure have also been analysed by Plaut and Klusman (1999). Most of these solutions are based on the assumptions that the tube is long enough to be simplified into a plane strain problem, the friction between geomembrane and internal water is negligible and the tubes are resting on a rigid base. As there is no closed-form solution for the proposed theories, all the above analytical solutions require the running of computer programs.

The numerical method which can provide in detail the cross section and tensile force of the geomembrane tube is another way to analyse the geomembrane tube system. The finite difference program fast lagrangian analysis of continua (FLAC) (Itasca, 2000) was used to analyse the geomembrane tubes (Huong, 2001; Kim, 2003; Kim et al., 2004; Kim, Filz, & Pluaut, 2005). As the geomembrane was simulated using beam elements in the FLAC software, the influence from its bending moments is the limitation of this method. An alternative method for simulating the geomembrane tube is using particle flow code (PFC2D) developed by Itasca (2008). The PFC2D is a well-used discrete element method which can simulate the interaction behaviour between geosynthetics and soil (Bhandari & Han, 2010; Ferellec & McDowell, 2012; Wang, Jacobs, & Ziegler, 2014). Compared to the numerical method of using FLAC to simulate the flexible geomembrane tube, there is no bending effect between PFC2D balls (Sun et al., 2017).

**FIGURE 1** Numerical model of the geomembrane tube supported by the L-shaped block. (a) Definition of the parameters. (b) Initial state of the balls and walls of the system. (c) Method of transforming hydraulic pressures to point loads
A method of inserting the L-shaped block on the downstream side of a geomembrane tube is proposed to prevent the geomembrane tubes from rolling off or slipping along the ground surface. Numerical analyses using PFC\textsuperscript{2D} are conducted to investigate the performance of the proposed method. Parametric studies are also conducted to identify the influences of the key factors and to provide design charts for practical applications.

2 | NUMERICAL MODELLING

Nondimensional parameters are adopted in this study. The height $H$, the contact width with ground surface $b$, the width $B$ of a geomembrane tube, and the height of the external water level $H_w$ (see Figure 1a) are normalised by the perimeter of cross section, $L$. The tensile force of the geomembrane tube $T$ is normalised by $\gamma L^2$ where $\gamma$ is the unit weight of the filling water. The cross-sectional area $A$ and the initial pumping pressure $p_0$ are normalised by $L^2$ and $\gamma L$, respectively. The cross section of the L-shape block is shown in Figure 1a with equal height and width of $L_b$. The central angle of the segment is denoted as $\alpha$. To prevent the destruction of the geomembrane tube from the sharp end of the L-shaped block, the two ends of the L-shaped block are filleted as shown in Figure 1a.

The outline of the numerical model in PFC\textsuperscript{2D} (Itasca, 2008) is shown in Figure 1b. As all the parameters are non-dimensional, the unit weight of filling water $\gamma$ and the perimeter of geomembrane tube $L$ in the numerical studies are set to be 1.0. The geomembrane tubes are modelled by 500 rigid balls with diameter $d$ of 0.002 and unit weight of 1.4. As no bending moment occurs among the geomembrane materials, the balls are bonded via contact bonds which can only transmit forces. The L-shaped block and the rigid ground are simulated using rigid walls and fixed displacements in all

| Table 1 | Parameters used in PFC\textsuperscript{2D} simulation |
|---------|-----------------|
| Name    | Values          |
| Unit weight of filling material | 1.0 |
| Solid density of ball | 1.4 |
| Ball diameter | 0.002 |
| Ball normal stiffness | 6.45E6 |
| Ball shear stiffness | 6.45E6 |
| Ball normal stiffness for wedge | 1.08E10 |
| Ball shear stiffness for wedge | 1.08E10 |
| Contact bond normal strength | 1.0E6 |
| Contact bond shear strength | 1.0E6 |
| Contact normal stiffness | 5.0E9 |
| Contact shear stiffness | 5.0E9 |
| Friction coefficient between ball and wall | 0.00 |
| Friction coefficient between balls | 0.00 |

Figure 2 Validation of the current study. (a) Normalised height versus pumping pressure curve. (b) Normalised width versus pumping pressure curve.

Figure 3 Comparison of the results from current study and Huong et al. (2002). (a) $H_w/L = 0.1494$ and $L_b/L = 0.041$. (b) $H_w/L = 0.180$ and $L_b/L = 0.082$.
The frictions between the balls and that between walls and balls are not considered. Details of the parameters used in the PFC2D are summarised in Table 1.

As no hydraulic pressure can be applied directly onto the balls in PFC2D, a converted point load method is adopted during the calculation. As shown in Figure 1c, \( P_x \) and \( P_y \) denote the horizontal and vertical forces acting on the centre of the ball due to horizontal and vertical hydraulic pressure \( p_{n1} \) and \( p_{n2} \), respectively. The hydraulic pressures \( p_{n1} \) and \( p_{n2} \) are calculated by

\[
P_{n1} = P_0 + \gamma \left[ H - \left( \frac{y_n - y_{n-1}}{4} \right) \right]
\]

\[
P_{n2} = P_0 + \gamma \left[ H - \left( \frac{y_n + y_{n+1} - y_n}{4} \right) \right]
\]

where \( \gamma \) is the unit weight of filling water, \( H \) is the height of geomembrane tube, and \( P_0 \) is the initial pumping pressure.

The equivalent horizontal and vertical point forces \( P_x \) and \( P_y \) due to the hydraulic pressures \( p_{n1} \) and \( p_{n2} \) are calculated as

\[
P_x = P_{n2} \left( \frac{y_{n+1} - y_n}{2} \right) + P_{n1} \left( \frac{y_n - y_{n-1}}{2} \right)
\]

\[
P_y = P_{n2} \left( \frac{x_{n+1} - x_n}{2} \right) + P_{n1} \left( \frac{x_n - x_{n-1}}{2} \right)
\]

The numerical analysis is divided into the following two steps: (a) build the initial equilibrium state between the gravity and internal hydraulic pressures acting the geomembrane tube; and (b) apply the point forces calculated from the
lateral hydraulic pressure onto the balls until the whole system is balanced. The equilibrium of the system is controlled by the criterion that the height of geomembrane tube in the calculation cycle varies with less than a tolerance of $10^{-6}$.

### 3 | VERIFICATION OF THE MODEL

To verify the accuracy of the numerical model, the numerical results are compared to the solutions given by other analytical and experimental methods. The first comparison is made on the basis of the analytical solution proposed by Leshchinsky et al. (1996). The theory was calibrated against a geomembrane tube with $L = 9$ m, $\gamma = 12$ kN/m$^3$, and inflated by different pumping pressures $p_0$. The numerical analysis in this study was conducted using nondimensional parameters. The same models of wall and balls are used as those discussed in Section 2. No friction was considered between balls and wall. For comparison between the two sets of results, the height $H$, width $B$ and pumping pressure $p_0$ of the geomembrane tube from the analytical results conducted by Leshchinsky et al. (1996) are normalised using $H/L$, $B/L$ and $p_0/\gamma L$, respectively. The normalised initial pumping pressure $p_0/\gamma L$ versus height $H/L$ and width $B/L$ of the geomembrane tube is plotted in Figure 2a and b.

![Figure 6](image1.png) **Figure 6** Relationship between ultimate lateral water level and the radian of the L-shaped block. (a) $p_0/\gamma L = 0.050$. (b) $p_0/\gamma L = 0.204$

![Figure 7](image2.png) **Figure 7** Distribution of the normalised tensile force $T\gamma L^2$ along the geomembrane tube inflated by $p_0/\gamma L = 0.087$ and supported by L-shaped block with edge length $L_b/L = 0.12$. (a) $\alpha = 0$ and $H_c/L = 0.242$. (b) $\alpha = \pi/6$ and $H_c/L = 0.242$. (c) $\alpha = \pi/3$ and $H_c/L = 0.242$. (d) $\alpha = \pi/2$ and $H_c/L = 0.242
respectively, which show very good agreement between the two results.

The numerical model was also compared to large-scale laboratory model tests conducted by Guo, Chu, Yan, and Nie (2014). In the model tests, three geomembrane tubes with dimensions of 1 m wide by 2 m long (Model T1), 1.5 m wide by 3 m long (Model T2) and 2 m wide by 4 m long (Model T3) were inflated by tap water. Different initial pumping pressures were used to inflate the geomembrane tube. For comparison of the two sets of the results, the same normalisation method was adopted such as $H/L$, $B/L$ and $p_0/\gamma L$ where $\gamma$ is the unit weight of tap water and $\gamma = 10 \text{kN/m}^3$. The normalised height $H/L$ and width $B/L$ versus initial pumping pressure $p_0/\gamma L$ curves are shown in Figure 2a and b, respectively. Good agreements verified the accuracy of the proposed method.

The third comparison is made between the current numerical model and the numerical analysis conducted by Huong et al. (2002) using FLAC. The geomembrane tube with a thickness of 0.508 mm and perimeter of 1.473 m was modelled by beam elements. The elastic modulus of the beam element was $1 \text{MPa}$ and its unit weight was zero. The wedge is isosceles triangular with its top angle of $\pi/2$ and unit weight of 4.5 $\text{kN/m}$. The boundaries of the wedge are fixed in all directions. The subgrade was simulated as stiff soil with no deformation considered. The geomembrane tube was inflated with water ($\gamma = 10 \text{kN/m}^3$) to an internal head of 46.5 cm, which leads to a tube height of 33.4 cm. The friction coefficients between the wall and balls and those between the wedge and balls are 0.53 and 0.267, respectively. In the current numerical model, the normalised pumping pressure is calculated as $(46.5-33.4)/1.473/100 = 0.0889$. Two cases selected from Huong et al. (2002) with normalised wedge height of $6/1.473/100 = 0.04073$ and $12/1.473/100 = 0.08147$, and the normalised external water height of $22/1.473/100 = 0.14936$ and $26.5/1.473/100 = 0.1799$, respectively, are selected for comparisons. To compare the two sets of results using non-dimensional parameters, the $x$ and $y$ coordinates of the cross-sectional geometry are normalised using $x/L$ and $y/L$, respectively. The cross sections from the two methods are plotted together in Figure 3 which shows fair agreement between the two sets of results.

### 4 PARAMETRIC STUDIES

Parametric studies were conducted to investigate the key parameters that influence the performance of the geomembrane tube supported by L-shaped block. The cross sections of the geomembrane tubes initially inflated by the pumping pressure of $p_0/\gamma L = 0.050$, supported by the L-shaped block with $L_0/L = 0.06$ and $\alpha = \pi/3$, and acted on by different external water levels are shown in Figure 4a. It can be seen that the geomembrane tube is stable when the external water level is 0.166 but starts to roll over the block when the external water level is 0.175. A similar phenomenon also happens for the geomembrane tube inflated by $p_0/\gamma L$ of 0.162 and supported by the same L-shaped block with $L_0/L$ of 0.06 (see Figure 4b), where the geomembrane tube is stable at an external water height of 0.214 but rolling off at 0.230. Comparing Figure 4a and b shows that the ultimate external water level increases from 0.175 to 0.214 when the initial pumping pressure $p_0/\gamma L$ increases from 0.05 to 0.162. Similarly, it is also observed from Figure 4a and c that the higher L-shaped block makes the system sustain higher
external water. However, the height of the L-shaped block has its turning point. As shown in Figure 4d, the ultimate external water level is the same as the height of the geomembrane tube which means that an L-shaped block is high enough to support the geomembrane tube. The ultimate external water level that the system could sustain is influenced by the edge length of the L-shaped block $L_b$, the central angle of the segment $\alpha$ and the initial pumping pressure $p_0$.

4.1 | Central angle of the segment

The central angle of the segment of the L-shaped block is studied to investigate its effect on the ultimate external water level that the system could sustain. The solutions are given for different $p_0/\gamma L$ and $\alpha$. The unit weight of fill water is 1.0. The parametric studies are conducted using $L_b$ of 0.08$L$ and 0.15$L$, respectively. The calculated $H_{cr}/L$ versus $\alpha$ curves are shown in Figure 5a. It can be seen that $H_{cr}/L$ increases with respect to $\alpha$. The $\alpha = \pi/3$ separates the curves into two sections with small slopes before this magnitude and large slopes afterwards. The phenomenon indicates that the designed central angle of the segment of the L-shaped block should be larger than this value. The higher L-shaped block sustains higher external water levels. This is the reason why the ultimate external water level in Figure 5b is larger than that in Figure 5a under the same other conditions. Take the case of $p_0/\gamma L = 0.087$, $\alpha = \pi/3$ for example, the ultimate external water levels that the geomembrane tube supported by a L-shaped block with edge length of 0.08$L$ and 0.15$L$ could sustain are 0.207$L$ and 0.258$L$, respectively. Another obvious phenomenon that can be observed from Figure 5a and b is that the higher the initial pumping pressure $p_0/\gamma L$, the higher the ultimate external water level that the system could sustain. However, a higher initial pumping pressure $p_0/\gamma L$ could also induce higher tensile stress generating along the geomembrane tube. This will be discussed later in this paper. Figure 6a and b present $H_{cr}/L$ versus $\alpha$ curves for the geomembrane tube supported by different L-shaped blocks with various $L_b$ and inflated by $p_0/\gamma L$ of 0.050 and 0.204, respectively. Similar to the phenomenon observed in Figure 5a and b, $H_{cr}/L$ increases with respect to $\alpha$. The central angle with a magnitude of $\pi/3$ separates the curves into two sections with small slopes before this value and large slopes afterwards.

The tensile force distribution along the geomembrane tube inflated by initial pumping pressure $p_0/\gamma L$ of 0.087 and supported by L-shaped block with $L_b$ of 0.12 is shown in Figure 7. The $\alpha$ values of 0, $\pi/6$, $\pi/3$ and $\pi/2$ are used to investigate their influence on the tensile force distributions.
along the geomembrane tube. It can be seen that the tensile forces are not uniform along the cross section of the geomembrane tube. However, there are little differences in the magnitudes as shown in Figure 7a–d. It is worth noting that the tensile force along the geomembrane tube should be constant because the contact frictions between the geomembrane tube and rigid foundation or those between the geomembrane tube and filling water are not considered in the study. This mismatch is due to the limitations of the numerical model.

4.2 Height of the L-shaped block

The edge length of the L-shaped block is studied to investigate its effects on the ultimate external water level that the system can sustain. The parametric studies are conducted using \( \alpha \) of 0, \( \pi/6 \), \( \pi/3 \) and \( \pi/2 \). The solutions are given for different \( p_0/\gamma L \) and \( L_b \). The calculated results of the ultimate lateral water versus the edge length of the L-shape block curves are shown in Figure 8. It can be seen that the ultimate external water level increases nonlinearly with respect to the edge length of the L-shaped block. The ultimate lateral water level versus the edge length of the L-shape block curves are in a bilinear relationship. For all the calculated cases, the turning points locate at \( L_b/L = 0.12 \). When the heights of the L-shaped block are smaller than 0.12\( L \), the edge lengths of the L-shaped block have great impact on improving the water-retaining performance of the geomembrane tube. When the heights of the L-shaped block are larger than 0.12\( L \), the maximum height of the geomembrane tube becomes constant. It can be concluded that the optimum edge length of the L-shaped block is 0.12\( L \). The tensile force distribution along the geomembrane tube inflated by initial pumping pressure \( p_0/\gamma L \) of 0.050 and supported by L-shaped block with \( \alpha \) of \( \pi/3 \) is shown in Figure 9. The edge lengths of the L-shaped blocks \( L_b/L \) are in the range of 0.06 to 0.12. Similar to the phenomenon observed in Figure 7, the tensile forces along the geomembrane tube are nonuniform but with little differences in magnitudes.

4.3 Initial pumping pressure

The effects of the initial pumping pressure are analysed to investigate their influence on the ultimate external water level that the system can sustain. The parametric studies are conducted using \( \alpha \) of 0, \( \pi/6 \), \( \pi/3 \) and \( \pi/2 \). The solutions are given for different \( p_0/\gamma L \) and \( L_b \). The ultimate lateral water level versus the initial pumping pressure curves are shown in Figure 10. It can be seen that the ultimate external water levels increase nonlinearly with respect to the increasing of \( p_0/\gamma L \). The turning point locates at \( p_0/\gamma L = 0.162 \). For \( p_0/\gamma L < 0.162 \), the \( H_{cr}/L \) quickly increases with respect to \( p_0/\gamma L \). For \( p_0/\gamma L > 0.162 \), the effects of \( p_0/\gamma L \) on \( H_{cr}/L \) are not obvious. This is because the system is strong enough to sustain the external water and the ultimate external water level is equal to the height of the geomembrane tube. The external water flows over the top surface of the geomembrane tube.

To investigate the effect of the initial pumping pressures on the tensile force distribution along the geomembrane tube, initial pumping pressures of 0.087, 0.162, 0.204 and

\[ \gamma L. \text{ For } p_0/\gamma L > 0.162, \text{ the effects of } p_0/\gamma L \text{ on } H_{cr}/L \text{ are not obvious. This is because the system is strong enough to sustain the external water and the ultimate external water level is equal to the height of the geomembrane tube. The external water flows over the top surface of the geomembrane tube.} \]

FIGURE 10 Relationship between ultimate lateral water level and pumping pressure. (a) \( \alpha = 0 \), (b) \( \alpha = \pi/6 \), (c) \( \alpha = \pi/3 \), (d) \( \alpha = \pi/2 \)
0.244 are used in this study. The tensile force distributions along the geomembrane tube supported by L-shaped block with edge length \( L_b \) and the central angle of \( \alpha = \pi/3 \) at the ultimate state are shown in Figure 11. It can be seen that the tensile forces are heavily influenced by the initial pumping pressure. The higher the initial pumping pressure, the higher the tensile force generated along the geomembrane tube and the higher the external water the system could sustain.

5 | CONCLUSIONS

Geomembrane tubes made of very low permeability materials can be used for the construction of flood barriers and cofferdams for flood risk management. The geomembrane tube system cannot be too high because the external water on the headwater side may make the geomembrane tube roll off or slip along the ground surface. Numerical studies using PFC\(^{2D}\) have been conducted to investigate the behaviour of the geomembrane tube supported by L-shaped blocks. Parametric studies were conducted to investigate the effects of the key parameters that influence the ultimate external water level that the system could sustain. The key parameters include the initial pumping pressure \( p_0 \), the edge length \( L_b \), and the central angle of the segment \( \alpha \) of the L-shaped block.

It is found in this study that the ultimate external water level increases with the increase of \( \alpha \) when \( L_b \) and \( p_0 \) remain constant. The designed \( \alpha \) should be larger than \( \pi/3 \). The
higher L-shaped block could sustain higher ultimate external water. The optimum edge length of the L-shaped block is \( L_b = 0.12L \). The ultimate external water levels increase nonlinearly with respect to \( p_0/\gamma L \). However, the higher initial pumping pressure also induces higher tensile force along the geomembrane tube. The optimum initial pumping pressure is \( p_0/\gamma L = 0.162\gamma L \). The geomembrane tube designed using the suggested parameters \( (p_0/\gamma L = 0.162\gamma L, L_b = 0.12L, \alpha = \pi/3) \) could sustain an external water level of 0.296\( \gamma L \). It should be pointed out that these conclusions are conducted from an L-shaped block supported geomembrane tube resting on flat rigid ground. The calculated tensile forces along a cross section of a geomembrane tube are scatter but with little difference in the magnitude. This is another limitation of the proposed numerical model.

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DATA AVAILABILITY STATEMENT

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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