Research on Working Status of Impervious Geomembrane along Cracks of High Membrane-Faced Rockfill Dams

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Abstract: To address the “cramp effect” caused by displacement and sediment of impervious geomembranes in the cracks along high membrane-faced rockfill dams and the problem the declining mechanical performance of the geomembranes caused by long-time tensile stress, this study developed a set of simulation devices according to the working status of impervious geomembranes in the cracks along the dam. With PVC geomembranes as the test material, this study performed tests to identify the law of decline of membrane’s mechanical performance under different conditions of deformation with the temperature of the reservoir unchanged. It used the fractional mathematical model to process the test data and concluded the law of declining mechanical indicators of the PVC geomembrane. On the basis of the test data analysis, this study divided the decline of the geomembrane’s mechanical performance under constant large deformation into two stages, proposed structural solutions to mitigate or avoid decline of mechanical performance and lengthen the service life of impervious geomembranes.

1. Introduction

Yiming Shu and et al. [1] divided impervious membrane rockfill dams into membrane-faced rockfill dams and membrane-core rockfill dams according to the location of the geomembrane on the section of the dam; the former refers to rockfill dams in which the impervious membrane is located in the upstream of the dam; they also indicated that the impervious membrane above 150 meters of a high membrane-faced dam is smaller than 2.00mm. In western China where hydropower resources abound, to improve the gradient regulating performance of power stations and the quality of electric power, a 300m-high dam is to be built on the upstream of Jinsha River, Lancang River and Nu River, which gives rise to the Longtou Reservoir [2]. Located in an economic backwater with complicated landforms, thick riverbed covering layers and inconvenient traffic access, this region has over ten dams which can be built into 150m-high rockfill dams. Nevertheless, out of concern for environmental protection and ecological maintenance, options for anti-seepage materials are limited, so high membrane-faced dams with geomembranes as the impervious material become one of the most competitive types of dams.

Impervious membranes used in membrane-faced rockfill dams nowadays include the polyethylene/high density polyethylene (PE/HDPE) membrane and the polyvinyl chloride (PVC) membrane, but PE/HDPE membrane thicker than 1mm is usually too stiff to adapt to deformation of the bedding layer when the reservoir starts to store water [4]. Haimin Wu and et al found that when the displacement of
When a high-membrane-faced rockfill dam remained the same, the PVC membrane had better performance than the PE/HDPE membrane in adapting to the deformation, and they pointed out that the deep covering layer of the dam should be given top priority in using the PVC membrane to prevent seepage [5]. Due to such advantages as high elasticity, resilience, extensibility and good impervious performance, the PVC membrane has long been a preferred material in dam-building projects, and according to statistics issued by International Commission of Large Dams (ICOLD) in 2006, 143 high dams among the total of 216 dams around the world uses the PVC membrane to prevent seepage, accounting for a proportion of 60.3%, and there was a trend of using the PVC membrane on the surface of the dam to curb seepage [7]. For instance, the Bovilla Dam, a 91m-high membrane-faced rockfill dam built in Albania in 1996, uses the 3.0mm-thick PVC geomembrane for prevention of seepage [8], and the 87m-high Nanou six-level membrane-faced rockfill dam built in Laos in 2016 uses the 3.5mm-thick PVC membrane [9-10].

High membrane-faced rockfill dams usually have to undertake high head pressure of water. At the early stage of water storage in the reservoir, there is large vertical displacement due to the dam-filling load and water pressure; it is especially true for high-stress soft membrane-faced rockfill dams built on the ground foundation of thick covering layers, in which case the sediment of the covering layer far exceeds the vertical deformation of the anti-seepage wall [11]. Generally, the higher the rockfill dam, the smaller the deformation modulus of the dam-building materials, the larger the dam’s deformation and the larger displacement of the cracks around the dam [12]. Therefore, there is severe displacement-induced deformation at the anchoring sites along the cracks in the impervious structure of the membrane-faced rockfill dam, which usually leads to the “cramp effect” [13] (as shown in Figure 1). During the “cramp effect”, the membrane is deformed due to strong tensile stress, and when the displacement of the dam ends, the membrane will continue to stay in the status of large displacement and deformation in a given position. In this status, the stress distribution of the PVC geomembrane is quite complicated, and it is still a matter of controversy among Chinese researchers as to whether the indicators of mechanical performance change and meet the requirements after the large deformation [14].

Chinese studies on the deformation of the dam’s membrane largely focus on technical measures to avoid the cramp effect at the anchoring sites in the cracks along the membrane. Two studies by Yiming Shu[15] [16] proposed the method of avoiding concentrated deformation of the membrane at the anchoring sites to curb seepage at the anchoring sites. Yiming Shu and et al [17] explored the necessary conditions for emergence of the cramp effect of high membrane-faced rockfill dams in detail and put forward the technical solution of replacing internal deformation with effective geometric deformation to avoid the cramp effect. Xiaozhen Jiang and et al [18] made effective simulation of the characteristics of the membrane’s deformation by adding three-dimensional spring units to the surrounding anchoring sites. Though Jiang’s study found that the membrane was susceptible to tensile damages at the bottom of the dam, it didn’t reflect the changes in the status of the membrane during large deformation. To unveil the status changes of the PVC membrane at the surrounding anchoring sites under constant large deformation in the membrane-faced rockfill dams, this study employed the method of structural modelling to explore the law of changes of the working status and mechanical performance of the membrane under constant large deformation.
2. Experiment Equipment and Scheme

2.1. Experiment Material and Specimen
PVC membranes in China are generally used to prevent seepage in buildings or underground tunnels. Normally, this type of membrane is no thicker than 1.5mm, with its mechanical performance and anti-seepage indicators unable to prevent seepage under high head pressure of water. To satisfy the experiment requirement, our study team entrusted Hongxiang New Geo-Materials Co., Ltd. to prepare quality PVC geomembranes (2.0mm thick) which satisfy the requirement of preventing seepage in high membrane-faced rockfill dams.

2.2. Experiment System
The PVC geomembrane is a type of polymer with basic functions of high-molecular materials, the mechanical performance of which is dependent on the temperature [19]. The equipment for the constant large deformation experiment needs to meet the following requirements: accurate dependent variables, accuracy and long-time stability of the stress (load) measurement system, control of the constant temperature.

When the reservoir begins to store water, the temperature of water stays in a constant range 4±1℃, which is assumed to be the range of temperature in our experiment. The experiment system consists of two modules: a constant-temperature mono-directional tensile system and a constant-temperature continuous large deformation stress (load) monitoring system. In the former system, the temperature is controlled via the mechanical performance testing system for geosynthetics in extreme environments; the latter system consists of a constant-temperature testing box, a paperless recorder and a continuous large deformation displacement control device (as shown in Figure 2)

2.3. Experiment Scheme and Method
According to relevant research in China and abroad, the width-length ratio has little impact on the relation between the tensile stress and the strain of the geomembrane [20]. In this experiment, tensile specimens with a width-length ratio of 0.5 is used. The width of the specimens is 50mm, their cramp length 100mm and their rate of extension 2mm/min.

The initial deformation of the specimens is 5%, 10%, 20%, 30%, 40%, 50%, 60% and 80%, and the monitoring time for continuous large deformation under a constant temperature is 1235 hours. After the specimens are loaded into the continuous large deformation displacement control device, the initial...
deformation value is identified by the constant-temperature mono-directional tensile system, and the constant large deformation displacement control device is used to fix the scale of deformation. When the scale is fixed, the displacement control device will be removed from the constant-temperature mono-directional tensile system to the constant-temperature continuous large deformation load monitoring system to monitor the changes in the stress. Meanwhile, the paperless recorder will record the changes in the load and the data will be recorded 10 times per minute.

Fig 2. Continuous large deformation of displacement-control device

3. Fractional Model

The viscoelasticity of polymers can be expressed by conventional viscoelasticity numeric models, such as the Maxwell model, the Kalvin model, the Burger model, the fractional model and other viscoelasticity models and fractional or exponential nonlinear models. Yingying Zhang and et al [21] have made tests on the stress relaxation performance of the PVC membrane under different temperatures and found that the fractional model could achieve good fitting results for the relaxation modulus.

The fractional Maxwell model replaces the spring unit and the Newton dashpot unit with two fractional viscoelastic units \((\alpha, E_1, \tau_1)\) and \((\beta, E_2, \tau_2)\). The stress of these two fractional units is equal.

\[
\sigma(t) = E_1 \tau_1^\alpha D^\alpha \varepsilon(t) = E_2 \tau_2^\beta D^\beta \varepsilon(t)
\]

where \(\sigma\) is the stress (Mpa), \(\varepsilon\) the strain (%), \(E_i\) the strength of the modulus (MPa) and \(t\) the time (hour); \(\alpha\) and \(\beta\) refer to the attenuation index and the dimensionless parameter, respectively. The strain relation between the fractional units can be expressed in Eq. (2) and (3):

\[
\varepsilon_1(t) = E_1^{-1} \tau_1^\alpha D^{-\alpha} \sigma(t)
\]

\[
\varepsilon_2(t) = E_2^{-1} \tau_2^\beta D^{-\beta} \sigma(t)
\]

The total strain is the sum of the two fractional units, and by adding Eq. (2) and Eq. (3), the constructive equation of the model can be achieved:

\[
\sigma(t) + \tau^\alpha \beta D^{\alpha-\beta} \sigma(t) = E \tau^\alpha D^\alpha \varepsilon(t)
\]

where \(\tau = \left( E_1 \tau_1^\alpha / E_2 \tau_2^\beta \right)^{1/(\alpha-\beta)} \quad E = E_1 \left( \tau_1 / \tau \right)^\alpha \)
By processing Eq. (4) via Fourier transformation and Mellin inverse transformation, the equation for the relaxation modulus of the fractional Maxwell model can be achieved:

When \( 0 < \beta < \alpha < 1 \), the relaxation modulus approximates:

\[
G(t) = \frac{E}{\Gamma(1-\beta)} \left( \frac{t}{\tau} \right)^{-\beta} (t \leq \tau) \tag{5}
\]

\[
G(t) = \frac{E}{\Gamma(1-\alpha)} \left( \frac{t}{\tau} \right)^{-\alpha} (t > \tau) \tag{6}
\]

where \( G(x) \) refers to the relaxation modulus (MPa), \( \tau \) the time for attenuation of characteristics (hour), \( \Gamma(x) \) the complete Gamma function.

Taking the logarithm of both sides of the equations, we will obtain the following equations:

\[
\lg G(t) = \lg k_1 - \beta \lg t \quad (t \leq \tau) \tag{7}
\]

\[
\lg G(t) = \lg k_2 - \alpha \lg t \quad (t > \tau) \tag{8}
\]

where \( k_1 = \frac{E \tau^\beta}{\Gamma(1-\beta)} \) and \( k_2 = \frac{E \tau^\alpha}{\Gamma(1-\alpha)} \)

4. Experiment Result and Analysis

4.1. Analysis of Tensile Relaxation Process and Status of the Specimen

The data monitored in the experiment are the changes in the stress and time. As the value of deformation caused by axial tensile stress and the thickness of the PVC membrane varies, this experiment measured the thickness of the specimen after deformation and transformed the data into changes in stress and time. After the transformation, the trend of changes of the specimen’s strain over time was shown in Figure 4 and Figure 5. As the figures show, changes in the post-relaxation strain of the specimen under different deformation conditions follow a similar trend over time: the rate of relaxation is fast in the early stage and the scale of relaxation reaches 50% several hours later; then the rate of relaxation slows and the strain tends to remain stable. Meanwhile, the larger the initial value of deformation, the slower the strain reaches stability and the higher the value at the stable stage.

The initial values of deformation 40%, 50%, 60% and 80% are expressed by the fractional stress-relaxation model, as is shown in Fig. 4, which shows the fitting curve of the distribution trend of the stress-relaxation modulus of the PVC membrane over time with the Maxwell model. As it shows, the relaxation modulus presents two linear distribution trends over time (early-stage relaxation and late-stage relaxation), which represents the respective impact of the spring unit and the dashpot unit. The early-stage relaxation is mainly due to the spring unit and hence takes the form of elastic relaxation; the late-stage relaxation is mainly due to the dashpot unit and hence takes the form of viscous relaxation. And there is a transition period between these two relaxation periods.
a) The initial values of deformation 30%, 40%, 50%, 60%, 80%  

b) The initial values of deformation 5%, 10%, 20%

Fig. 4: Distribution of stress and time under different strain at constant temperature.

The charts of distribution trend of four sets of specimens show that the larger the initial value of deformation, the larger the changes in the relaxation of the specimen and the faster the rate of early-stage relaxation, but the late-stage changes in the relaxation modulus follow a similar trend and the rates of relaxation do not show much difference. Table 1 displays the fitting result of the attenuation parameters of the four sets of specimens with different initial values of deformation. As Table 1 shows, the accuracy of phased fitting is high, the early-stage attenuation index $\beta$ is correlated to the initial value of deformation, and the larger the initial value of deformation, the smaller the attenuation index; it also shows that the attenuation indices of the specimens in late-stage relaxation do not show much difference, which means that the tensile relaxation caused by the dashpot unit at the late stage is not correlated to the initial value of deformation.

Table 1  Fractional Maxwell fitting parameter value and standard deviation

| Initial deformation | Fitting parameters | Fitting parameters |
|---------------------|--------------------|--------------------|
|                     | $\beta$            | standard deviation $S$ | $\alpha$ | standard deviation $S$ |
| 80%                 | 0.096              | 0.0025              | 0.065    | 0.0006               |
| 60%                 | 0.097              | 0.0025              | 0.065    | 0.0006               |
| 50%                 | 0.119              | 0.0034              | 0.064    | 0.0006               |
| 40%                 | 0.128              | 0.0043              | 0.061    | 0.0005               |

Fig. 5: Distribution of logarithm of stress relaxation modulus with time logarithm and its fractional

Fig. 6: Diagram of breaking elongation and strength with initial deformation
4.2. Analysis of Decline of Mechanical Performance

After being processed under constant large deformation for 1235 hours, the specimen is then placed in an environment in the temperature range 4±1℃ for 240 hours. When the specimen regains the stress-strain balance, the average width, length and breadth of each specimen within the standard distance is measured, and the mono-directional tensile test is performed on the 8 sets of specimens under the temperature range of 4±1℃. Fig. 6 shows the correlation between the strength and elongation at break of the 8 sets of specimens which have different values of initial deformation and the value of initial deformation.

As Fig. 6 shows, the elongation and strength at break of the 8 sets of specimens have declined compared with the original specimens. Comparison shows that the strength at break shows little change, but the elongation at break shows large difference, and the larger the value of initial deformation, the slower the decline of the elongation at break.

The relaxation decline rate is defined by the elongation at break of the pre-processed specimen and the that of the original specimen, as is shown in Eq. (9):

$$\kappa = \left( \frac{\zeta_s - \zeta_m}{\zeta_m} \right) \times 100$$  \hspace{1cm} (9)

where $\zeta_s$ refers to the elongation at break of the pre-processed relaxation specimen (%), $\zeta_m$ the elongation at break of the original specimen (%), $\kappa$ the rate of decline of the elongation at break (%).

The rate of decline of the elongation at break of specimens with different values of initial deformation is shown in Table 2. It can be seen that when the temperature stays within the range 4±1℃, the stress relaxation has impact on both the strength and elongation at break of the PVC geomembrane under mono-directional tensile stress; the value of initial deformation has large impact on the elongation at break: the larger the value of initial deformation, the higher the rate of decline of elongation at break.

| Value of initial deformation | 5%  | 10% | 20% | 30% | 40% | 50% | 60% | 80% |
|-----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| $\kappa$                    | 15.8| 21.2| 27.4| 30.0| 31.0| 32.7| 41.4| 45.9|

As the experiment result shows, constant large deformation causes decline of mechanical performance of the PVC geomembrane; when the value of initial deformation reaches 80%, the rate of decline of elongation at break under mono-directional tensile stress reaches 45.9%, which undermines safety of the impervious structure.

5. Conclusion

According to the experiments and the results, the following conclusions are reached: 1) the status of the PVC geomembrane in high membrane-faced rockfill dams under constant large deformation can be presented as relaxation of the membrane, which can be divided into two stages: the early-stage relaxation and late-stage relaxation. In the early stage, the rate of relaxation is large and is mainly presented as elastic relaxation; in the late stage, the rate of relaxation is relatively smaller and is mainly presented as viscous relaxation. 2) for PVC geomembranes with different values of initial deformation, their rates of early-stage elastic relaxation are different, but their rates of late-stage viscous relaxation remain similar, so the rate of late-stage relaxation bears little connection with the initial deformation value and the viscosity of the membrane determines the rate of decline of its mechanical performance. 3) constant large deformation will reduce the strength and elongation at break of the PVC membrane under mono-directional tensile tests; the larger the value of initial deformation at the anchoring sites of the membrane, the larger the decline of its mechanical performance, so technical measures should be taken to avoid deformation at the anchoring sites of the membrane. 4) when designing high membrane-faced rockfill dams with PVC geomembranes, the PVC geomembrane geometric deformation should be used to replace the internal structural deformation of
the materials at sites of large displacements, such as the anchoring sites, to lengthen the service life of the dam.

Acknowledgements
This research is supported by the National Natural Science Foundation of China (research grant: 51379069). The authors would like to acknowledge Professor Yiming Shu of Hohai University for improving the quality of the writing. The authors would also like to thank the editor and the reviewers for their valuable comments and suggestions that have led to an improved manuscript.

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