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# Measuring Acceptable Velocity and Shear Stress Force on Levee Reinforcement Material Based on Biopolymers

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Extreme weather events, such as torrential rainfall, are becoming increasingly frequent owing to global warming; thus, developing new technologies for levee reinforcement and maintenance is essential. Conventional reinforcement methods, often relying on artificial materials, have limitations such as hindering vegetation growth and causing environmental issues. This problem was addressed in this study by evaluating the durability of a biopolymer-based levee reinforcement technique that combines a natural biopolymer with aggregates to provide an eco-friendly solution for levee protection. A fixed steep-slope flume at the Rural Research Institute of the Korea Rural Community Corporation was used to assess the permissible flow velocity and shear stress of the biopolymer-based method. Measurements and video analysis were performed using a high-speed camera as an advanced noncontact sensing technology to accurately determine flow velocities and assess material performance under extreme conditions. The biopolymer reinforcement remained undamaged under maximum discharge conditions in the flume (flow velocity of 9.4 m/s; energy slope of 0.7908). With a shear stress resistance of 372.37 N/m²—approximately 4.1 times greater than the target requirement of 90 N/m²—the biopolymer-based material demonstrated superior durability over conventional revetment systems. This study highlights that this method has significant potential as a cost-effective, efficient, and environmentally sustainable alternative to traditional levee reinforcement methods and offers enhanced performance and durability.

## 1. Introduction

Globally, extreme hydrometeorological events that exceed the historical ranges of spatiotemporal variability—such as localized torrential rainfall accompanying the rise in average temperature caused by global warming—are occurring with increasing frequency. The magnitude, frequency, and spatial distribution of floods are deviating significantly from past patterns, causing difficulty in predicting associated damages. Levees provide reliable flood

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control under such abnormal climate conditions and are relatively economical; therefore, the development and dissemination of new technologies for levee reinforcement and maintenance are of critical importance.[1,2]

During extreme flood events, increased flow velocity and rainfall intensity often lead to slope erosion or overtopping-induced failures. Such damage is often prevented by employing slope-protection techniques, including the installation of impervious layers that block seepage and prevent failure or reinforcement using revetment blocks such as gabions and cement-concrete blocks. However, these methods typically rely on artificial materials, which hinder vegetation growth, and concrete-based materials, which may cause environmental issues owing to toxic leachate.[3] To ensure the hydraulic stability of various levee protection methods, hydraulic parameters, such as flow velocity and shear stress, must be verified through hydraulic testing.

Lee and Kim[4] and Kim[5] conducted experiments on biopolymer-mixed soils, stone mattresses, and the Flextone method using 1/70 and 13/100 slope flumes at the Andong River Experiment Center of the Korea Institute of Civil Engineering and Building Technology as per ASTM D6460,[6] D7276,[7] and D7277.[8] Cooley and Thornton[9] evaluated the stability of tufted-geosynthetic revetment systems under increasing flow velocity using full-scale experiments with a 1.2-m-wide 1:2 slope flume. Takahashi *et al.*[10] installed riprap blocks on a sloped channel after placing sand with a median particle size (D50) of 0.35 mm along a 1.4-m-long flume bed and conducted overtopping experiments, measuring block movements and pore-water pressure to propose design improvements. Okuda *et al.*[11] examined soil erosion and revetment damage by installing small-scale aluminum revetment blocks on silica sand placed in a laboratory flume with a length of 10 m and a width of 0.8 m under various channel configurations.

In this study, a fixed steep-slope flume owned by the Rural Research Institute of the Korea Rural Community Corporation was used to evaluate the permissible flow velocity and shear stress of a biopolymer-based levee reinforcement technology, an eco-friendly material system. In the biopolymer technique, a natural biopolymer adhesive extracted from castor oil was combined with aggregates to protect river and levee slopes safely. To accurately and reproducibly assess the performance of materials composed of biopolymers and aggregates, test panels ($1 \times 5$ m$^2$) were fabricated and installed in the designated test section of the steep-slope flume. A high-speed camera was installed to measure high-velocity flows and to establish a video-based flow-measurement system (Hydro-STIV).

The objective of this experiment was to present an innovative sensing-based evaluation methodology for analyzing the stability of biopolymer-based levee reinforcement techniques through full-scale hydraulic testing. We aimed to contribute to the development of objective testing standards and to support future pilot applications of this technology in reservoirs managed by the Korea Rural Community Corporation. Ultimately, we sought to derive practical outcomes that will help prevent flood damage while addressing environmental issues such as carbon neutrality.

## 2. Hydraulic Experiment

### 2.1 Biopolymer-based reinforcement method

The biopolymer-based reinforcement method is developed by mixing biopolymers with aggregates and coating aggregate surfaces during mixing. The resulting binder forms a multi-point adhesive structure with the surrounding aggregates, creating an irregular and continuous pore network. This technique is a new hybrid levee reinforcement method that combines the advantages of conventional rigid and flexible reinforcement systems. It can be applied directly on-site through a relatively simple process in which the mixture is blended and spread without causing damage to the existing levee. Its rapid curing time also reduces construction costs and shortens construction periods (Fig. 1).

Because the method involves covering the entire inner and outer slopes of the levee, it provides enhanced protection against erosion even when flood levels exceed the original design height owing to increased extreme rainfall and flash floods. Moreover, it delays structural failure, thereby ensuring adequate emergency response time. Importantly, this technology is environmentally friendly; unlike traditional cement-concrete materials, it does not release harmful substances into the river environment. It uses nontoxic materials that do not affect aquatic ecosystems or organisms, and it supports early vegetation establishment and growth, thereby contributing to ecological health.[12]

### 2.2 Apparatus and analysis method

The fundamental hydraulic characteristics that determine the hydraulic stability of revetments included the discharge, average flow velocity, water depth, energy slope, roughness coefficient, and shear stress. Because this experiment was conducted under shallow-water conditions with high flow velocity, even small measurement errors can lead to significant inaccuracies in calculating parameters such as energy slope and shear stress. Therefore, potential sources of error during velocity and water-level measurements must be minimized.

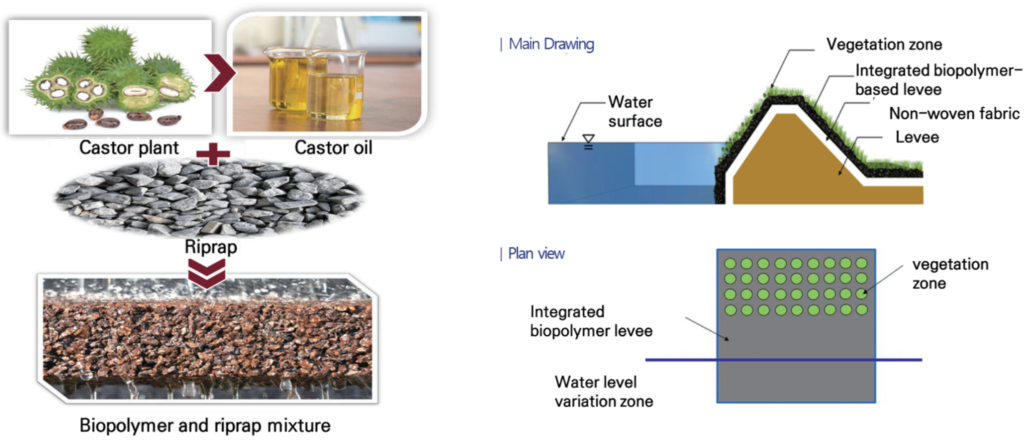


Fig. 1. (Color online) Components of the developed technology.

### 2.2.1 Velocity measurement

Precise velocity measurement within the experimental flume is essential for determining the permissible flow velocity and shear stress of the levee reinforcement method. The flume used in this study is characterized by steep slopes and high flow velocities, and the flow characteristics become irregular owing to the porosity and roughness of the reinforcement surface. In general, velocity meters are classified into contact-type instruments, which insert sensors directly into the flow, and noncontact-type instruments, which utilize external measurement techniques such as imaging, optical methods, or ultrasound. Among these, image-based velocity measurement techniques are known as space-time image velocimetry (STIV), which calculates flow velocity by generating a space-time image (STI) from video frames. An STI is constructed by stacking pixel values along a predefined velocity transect across successive video frames. In an STI, the flow motion appears as streaked patterns, and the slope of these streaks is used to estimate the flow velocity.

In this experiment, installing submerged instruments inside the flume was not feasible. Therefore, a video-based flow measurement technique—STIV—was applied, enabling the stable measurement of flow velocity and discharge solely from surface video images without requiring tracer particles or laser illumination. Although conventional STI analysis relies on a trained operator to adjust parameters and correct interpretation results, recent advances using AI deep learning have enabled more automated and reliable STI analysis. In this study, a pretrained model (Hydro-STIV), developed using approximately 200000 image datasets—including real river footage—was utilized to ensure robust performance (Fig. 2). This model allows accurate and stable velocity estimation across a wide range of conditions, including flow-shadow regions

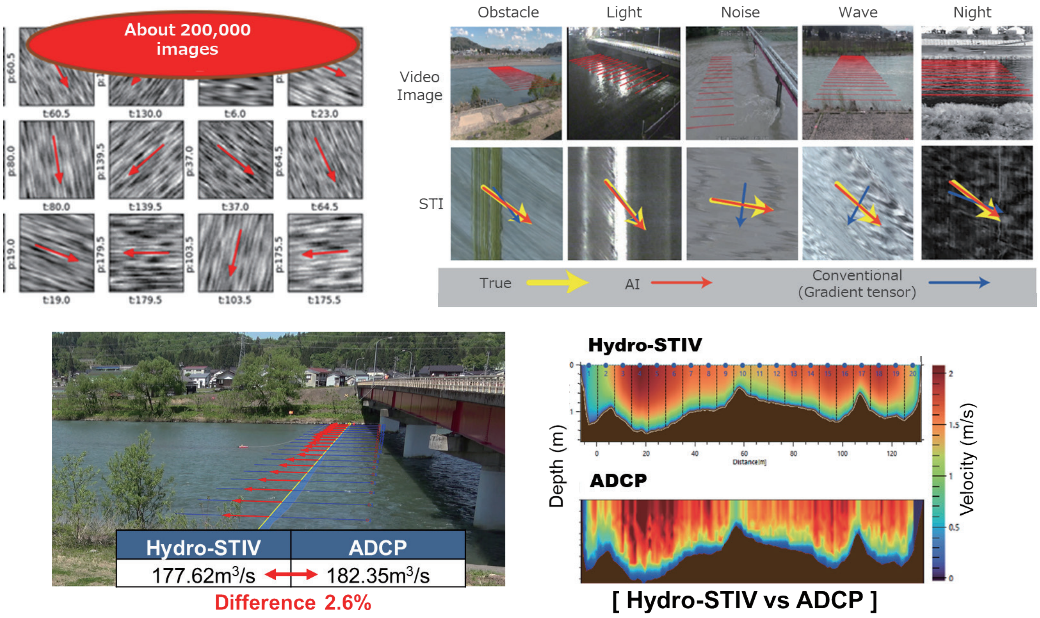


Fig. 2. (Color online) AI analysis and accuracy of STIV measurement.

near obstacles, highly turbulent flows during floods, rainfall conditions, and even when using far-infrared cameras, without the need for operator intervention.

To verify the accuracy of flow velocity and discharge measurements obtained using Hydro-STIV, its results were compared with those from field measurements conducted at the River Experiment Center of the Korea Institute of Civil Engineering and Building Technology, where an acoustic doppler current profiler (ADCP), a contact-type measurement device, was used. The comparison showed that the transverse velocity distribution matched well, and the difference in calculated discharge was within 3%, demonstrating that Hydro-STIV can accurately measure flow characteristics and variations in discharge.

### 2.2.2 Experimental conditions and measurement of water level at the side line

The discharge conditions and experimental settings for this study were controlled using the automatic flow control system at the Hydraulic Research Center of the Rural Research Institute. The inflow discharge from the overhead water tank into the steep-slope flume was regulated by adjusting the valve opening rate to 20% (0.19 $m^3/s$), 30% (0.51 $m^3/s$), and 40% (0.75 $m^3/s$), thereby establishing three discharge conditions for evaluating the permissible flow velocity and calculating the permissible shear stress of the biopolymer reinforcement method. In addition, water levels were measured using ultrasonic water-level sensors and visual observation at five side-line locations (Side Line Nos. 1–5) along the upstream and downstream sections of the flume.

To determine the maximum flow velocity and shear stress within the specimen zone, three measurement lines were established: the central measurement line at the specimen (Side Line No. 4), an upstream line 0.6 m upstream (Side Line No. 3), and a downstream line 0.6 m downstream (Side Line No. 5). High-speed video recordings (150 frames per second) were captured for 5 s at each measurement line to analyze flow conditions (Fig. 3).

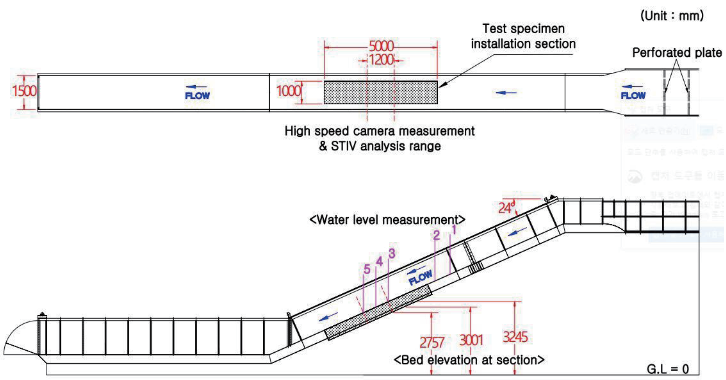


Fig. 3. (Color online) Hydraulic test flume and analysis range.

#### 2.2.3 Manufacturing and installation of test specimens

A specially fabricated mold made of H-beams was set in place, and the biopolymer binder mixed with aggregates using a mechanical mixer was placed inside the mold. During placement, compaction was repeatedly performed to ensure that the aggregates were uniformly distributed between the mold sections, thereby producing the test specimen (Fig. 4). The completed specimen was then lifted with a hoist and installed within the steep-slope flume at the designated $1 \times 5$ m$^2$ test section, where final leveling was carried out (Fig. 5).

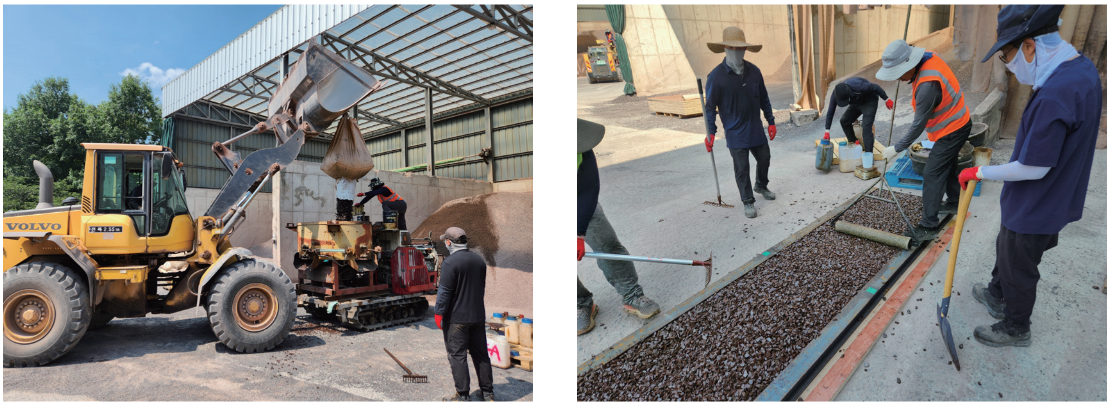


Fig. 4. (Color online) Process of producing the test specimen.

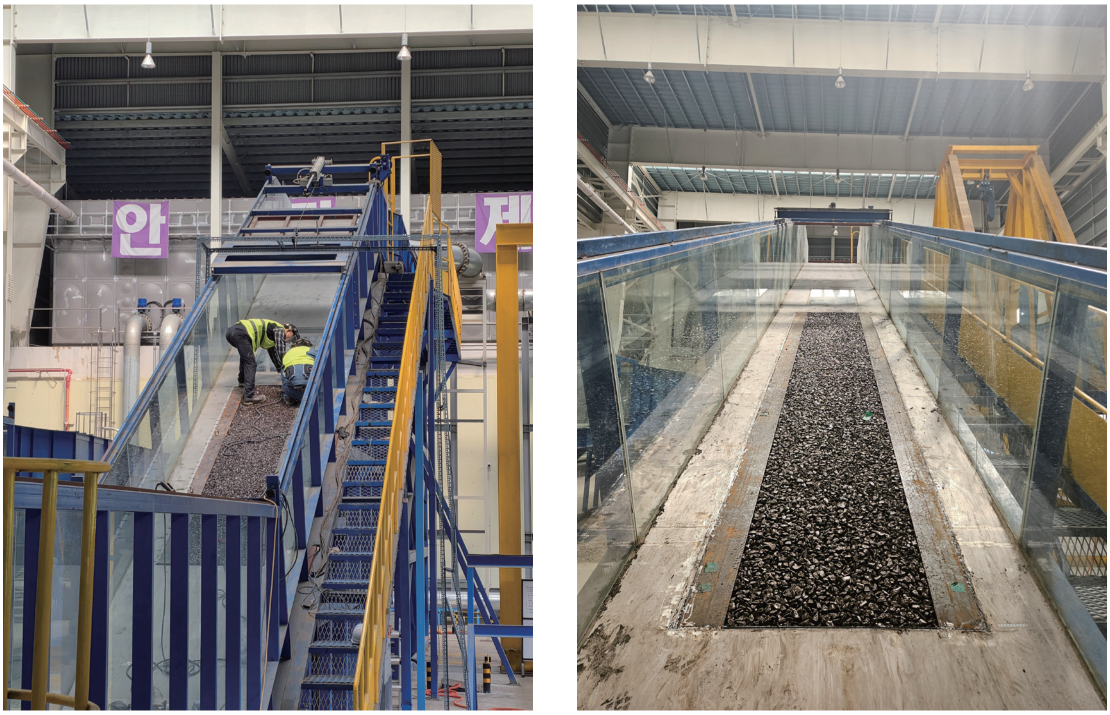


Fig. 5. (Color online) Installation of the test specimen.

## 3. Results

Once the target discharge condition was reached, the flow was maintained in a steady state for release, and the flow velocity was measured using the one-point method in accordance with KS B ISO 748. During the discharge, observations were made to identify any changes in water level or flow velocity caused by the loss or displacement of the specimen installed on the channel bed. After each discharge, the bed elevation was measured, and the condition of the specimen was visually inspected. Experiments were conducted under three discharge conditions, and the entire testing process was documented through photographs and video recordings.

### 3.1 Results of image-based velocity measurement

To ensure repeatability and consistency in the results of video analysis and velocity measurement for each side-line section, the 5 s video recordings were divided into five segments at 0.3 s intervals (Nos. 1–5), and the analysis results for each segment are presented. For velocity analysis, 15 velocity transects were assigned to each side line, and the deep-learning-based automated measurement method produced highly stable and accurate velocity estimates without manual correction (Fig. 6). A slight decrease in average flow velocity from the upstream toward the downstream direction was observed, confirming that the presence of the test specimen increased hydraulic resistance and reduced flow velocity.

The velocity-analysis sections located outside the specimen zone represented the general flow characteristics of the steep-slope flume. In these sections, the maximum velocity was observed, and nearly identical velocity values were recorded across the three measurement lines (Fig. 7). Under the given experimental conditions, steady flow was maintained for more than 1 h, during which the maximum flow velocity in the flume reached approximately 9.4 m/s (Tables 1–3).

A visual inspection conducted before and after the experiment confirmed that no physical changes—such as settlement or displacement—occurred in the specimen. This indicates that the

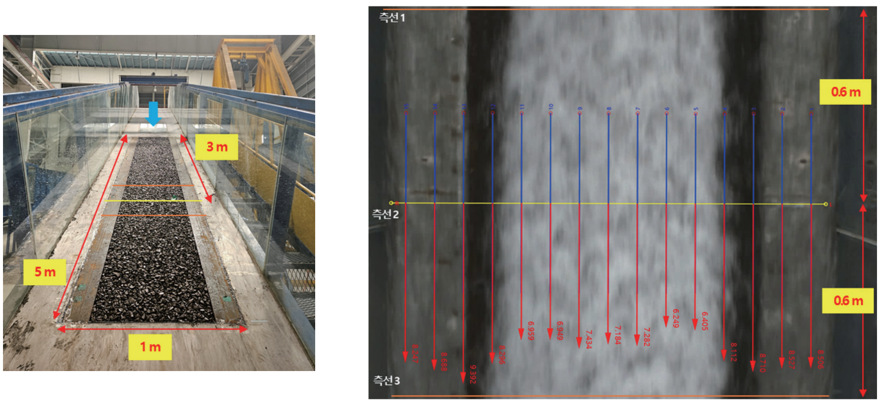


Fig. 6. (Color online) Side line in the test specimen and measurement range.

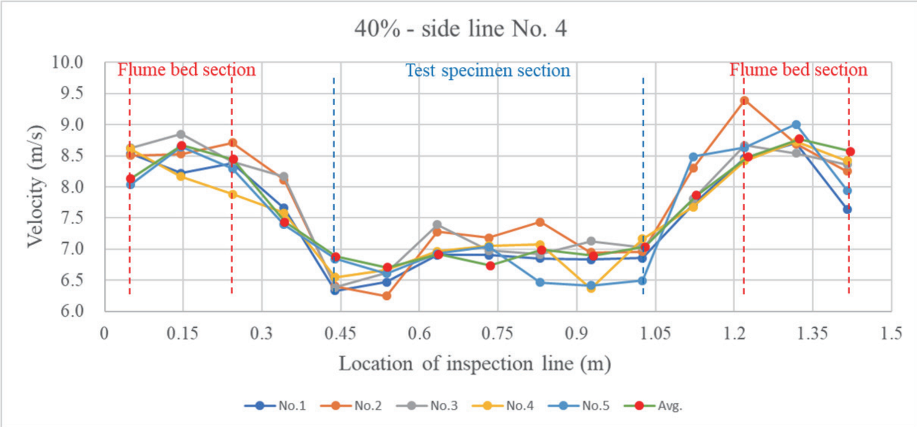


Fig. 7. (Color online) Flow velocity distribution for 40% discharge rate at side line No. 4.

Table 1
Results of STIV analysis for 20% of discharge rate at side line No. 4.

| Location of inspection line (m) | No. 1 | No. 2 | No. 3 | No. 4 | No. 5 |
|---|---|---|---|---|---|
| 0.049 | 5.392 | 5.732 | 5.515 | 5.804 | 5.574 |
| 0.146 | 5.382 | 5.536 | 5.360 | 5.577 | 5.828 |
| 0.244 | 5.613 | 5.490 | 5.823 | 5.686 | 6.064 |
| 0.342 | 5.371 | 5.330 | 5.375 | 5.416 | 5.426 |
| 0.439 | 4.479 | 4.295 | 4.659 | 4.881 | 4.602 |
| 0.537 | 4.256 | 4.574 | 4.529 | 4.226 | 4.700 |
| 0.634 | 4.322 | 4.212 | 4.596 | 4.604 | 4.955 |
| 0.732 | 4.364 | 4.204 | 4.205 | 4.310 | 4.520 |
| 0.83 | 4.161 | 4.599 | 4.362 | 3.624 | 4.336 |
| 0.927 | 4.157 | 3.993 | 4.273 | 4.367 | 3.698 |
| 1.025 | 4.256 | 4.110 | 4.303 | 4.339 | 4.336 |
| 1.122 | 5.921 | 5.501 | 5.629 | 5.702 | 5.585 |
| 1.22 | 6.214 | 6.201 | 5.701 | 6.070 | 6.025 |
| 1.318 | 5.876 | 5.887 | 6.200 | 5.971 | 5.891 |
| 1.415 | 5.677 | 5.603 | 5.678 | 5.935 | 5.595 |
| Avg. velocity in the test specimen | 4.285 | 4.284 | 4.418 | 4.336 | 4.450 |
| Max. velocity in the flume | 6.214 | 6.201 | 6.200 | 6.070 | 6.064 |

biopolymer-based levee reinforcement method exceeded the target permissible velocity of 7 m/s established for this study, demonstrating sufficient durability and functional stability under external hydraulic loading.

### 3.2 Results of calculating the shear stress force

To calculate the shear stress ($\tau$) acting on the revetment under the discharge conditions, the required hydraulic parameters included discharge $Q$, average flow velocity $V$, water depth $y_i$,

Table 2
Results of STIV analysis for 30% of discharge rate at Side Line No. 4.

| Location of inspection line (m) | No. 1 | No. 2 | No. 3 | No. 4 | No. 5 |
|---|---|---|---|---|---|
| 0.049 | 7.355 | 8.25 | 8.224 | 7.973 | 7.952 |
| 0.146 | 7.746 | 8.068 | 7.614 | 7.986 | 7.867 |
| 0.244 | 6.971 | 6.878 | 7.501 | 7.48 | 7.391 |
| 0.342 | 7.052 | 6.912 | 7.04 | 7.105 | 7.099 |
| 0.439 | 5.974 | 6.229 | 5.819 | 6.212 | 6.215 |
| 0.537 | 5.534 | 5.356 | 5.572 | 5.959 | 5.883 |
| 0.634 | 6.051 | 5.723 | 6.273 | 6.246 | 5.735 |
| 0.732 | 6.23 | 6.29 | 5.856 | 5.682 | 6.251 |
| 0.83 | 6.101 | 6.239 | 6.172 | 5.872 | 5.632 |
| 0.927 | 5.619 | 5.603 | 5.519 | 5.538 | 5.666 |
| 1.025 | 6.07 | 6.127 | 6.252 | 6.181 | 6.236 |
| 1.122 | 6.979 | 7.089 | 7.097 | 7.341 | 7.005 |
| 1.22 | 7.692 | 7.984 | 7.715 | 7.728 | 8.224 |
| 1.318 | 8.352 | 8.184 | 7.869 | 8.075 | 8.302 |
| 1.415 | 7.939 | 7.435 | 7.387 | 7.339 | 7.483 |
| Avg. velocity in test specimen | 5.94 | 5.938 | 5.923 | 5.956 | 5.945 |
| Max. velocity in flume | 8.352 | 8.25 | 8.224 | 8.075 | 8.302 |

Table 3
Results of STIV analysis for 40% of discharge rate at Side Line No. 4

| Location of inspection line (m) | No. 1 | No. 2 | No. 3 | No. 4 | No. 5 |
|---|---|---|---|---|---|
| 0.049 | 8.534 | 8.506 | 8.624 | 8.613 | 8.036 |
| 0.146 | 8.22 | 8.527 | 8.845 | 8.168 | 8.64 |
| 0.244 | 8.382 | 8.71 | 8.403 | 7.88 | 8.292 |
| 0.342 | 7.658 | 8.112 | 8.165 | 7.583 | 7.395 |
| 0.439 | 6.336 | 6.405 | 6.389 | 6.552 | 6.847 |
| 0.537 | 6.471 | 6.249 | 6.615 | 6.673 | 6.608 |
| 0.634 | 6.907 | 7.282 | 7.393 | 6.964 | 6.932 |
| 0.732 | 6.904 | 7.184 | 6.977 | 7.054 | 7.039 |
| 0.83 | 6.85 | 7.434 | 6.92 | 7.075 | 6.465 |
| 0.927 | 6.833 | 6.949 | 7.127 | 6.372 | 6.42 |
| 1.025 | 6.859 | 6.959 | 7.035 | 7.167 | 6.498 |
| 1.122 | 7.717 | 8.296 | 7.806 | 7.675 | 8.483 |
| 1.22 | 8.462 | 9.392 | 8.663 | 8.42 | 8.632 |
| 1.318 | 8.701 | 8.688 | 8.542 | 8.729 | 9.005 |
| 1.415 | 7.643 | 8.247 | 8.361 | 8.418 | 7.943 |
| Avg. velocity in test specimen | 6.737 | 6.923 | 6.922 | 6.837 | 6.687 |
| Max. velocity in flume | 8.701 | 9.392 | 8.845 | 8.729 | 9.005 |

and energy slope $S_i$ (Fig. 8). For each side line, the representative water depth was determined as the average of the measured depths at that line. The water depth was obtained by correcting the difference between the water level and the bed elevation using the bed slope:

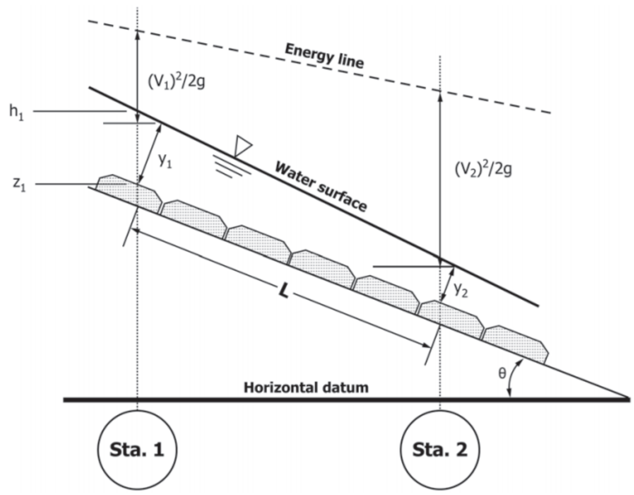


Fig. 8. Hydraulic analysis and control volume variable definition.[7]

$$y_i = \left(h_i - z_i\right)\cos\theta, \tag{1}$$

where $y_i$ is the water depth at point $i$ (m), $h_i$ is the water level (m), $z_i$ is the bed elevation (m), and $\theta$ is the bed slope.

Here, bed elevation refers to the height from the datum to the specimen surface, water level is the height from the reference point to the water surface, and water depth is the vertical difference between the water surface and the specimen surface.

The shear stress acting on the channel bed is calculated as

$$\tau = \gamma y_i S_i\,, \tag{2}$$

where $\tau$ is the shear stress force (N/m$^2$), $\gamma$ is the unit weight of water (9810 N/m$^3$), $y_i$ is the water depth at point $i$ (m), and $S_i$ is the energy slope at point $i$.

On the basis of the STIV analysis results for each discharge condition, hydraulic quantities such as the water depth at each measurement point, the distance between measurement points, and the energy slope were derived, and shear stress values were subsequently computed. The shear stress for the test specimen was verified up to the maximum allowable discharge of the steep-slope flume. Under the 40% valve-opening condition, the specimen demonstrated hydraulic stability up to 372.37 N/m² (Table 4). This performance exceeded the target permissible shear stress of 90 N/m² established for the project.

Although the critical shear stress at failure could not be determined—because the biopolymer-based reinforcement did not reach a failure state within the experimental conditions—the experimental process and results indicate that the material exhibited durability well beyond the shear stress levels observed in this study.

Table 4
Results of STIV analysis for 40% of discharge rate at Side Line No. 4.

| Valve open rate | 20% | 30% | 40% |
|---|---|---|---|
| STIV data at Side Line No. 3 (m/s) | 6.0708 | 8.5320 | 8.9146 |
| STIV data at Side Line No. 4 (m/s) | 6.1498 | 8.2406 | 8.9344 |
| STIV data at Side Line No. 5 (m/s) | 6.0896 | 8.3876 | 8.3904 |
| Distance between measurement points (m) | 1.2 | 1.2 | 1.2 |
| Discharge ($m^3$/s) | 0.18594 | 0.5080725 | 0.746295 |
| Energy line | 0.3933 | 0.5075 | 0.7908 |
| Shear stress force (N/$m^2$) | 82.31 | 185.87 | 372.37 |
| Potential head (m) | Line No. 3 | Line No. 4 | Line No. 5 |
| | 3.245 | 3.001 | 2.757 |
| Velocity head (m) | | | |
| Line No. 3 | 1.880 | 3.714 | 4.055 |
| Line No. 4 | 1.930 | 3.465 | 4.073 |
| Line No. 5 | 1.892 | 3.589 | 3.592 |
| Total head (m) | | | |
| Line No. 3 | 5.144 | 6.994 | 7.347 |
| Line No. 4 | 4.953 | 6.504 | 7.122 |
| Line No. 5 | 4.672 | 6.385 | 6.398 |

## 4. Discussion and Conclusions

The objective of this study was to evaluate the durability of a biopolymer-based levee reinforcement method—that involved mixing an eco-friendly biopolymer with aggregates—using the fixed steep-slope flume at the Hydraulic Research Center of the Rural Research Institute, Korea Rural Community Corporation.

STIV-based video analysis was performed to determine flow velocities at each measurement line, and the permissible shear stress of the biopolymer-based reinforcement method was derived on the basis of the velocity, water depth, elevation head, velocity head, total head, and energy slope obtained from the experiments. The biopolymer-based levee reinforcement maintained an undamaged condition even under the maximum discharge condition tested (maximum energy slope of 0.7908). Through the shear stress force calculation method, the material demonstrated a resistance of at least 372.37 N/m², approximately 4.1 times higher than the target performance requirement of 90 N/m². The maximum flow velocity (approximately 9.4 m/s) exceeded or was comparable to the design flow velocity (7 m/s) and permissible shear stress associated with many conventional revetment materials such as vegetation and gabions, indicating outstanding durability. Therefore, the proposed method shows strong potential as an economical, efficient, and environmentally friendly reinforcement method capable of replacing conventional revetment systems while exhibiting superior performance.

Despite these promising results, several limitations regarding practical design and field implementation must be discussed owing to the idealized laboratory conditions. First, the experimental constraints of using a fixed, controlled flume under steady flow cannot fully replicate the highly dynamic, unsteady hydraulic loadings and multidirectional wave actions found in real river environments. Second, potential scaling effects inherent to laboratory models may affect the real-scale soil–structure interactions. Lastly, this study focused primarily on peak short-term hydraulic resistance, leaving the long-term durability and potential environmental weathering (such as wetting-drying cycles or UV exposure) unassessed.

To address these limitations, future research directions must focus on field-scale validation via testbeds and comprehensive long-term durability assessments under natural conditions. Future work should also include destructive testing conducted until specimen failure to quantitatively determine the absolute ultimate flow velocity and shear stress, alongside a direct cost–benefit and performance comparison with conventional revetment methods. Furthermore, future studies will actively explore the performance and additional complementary improvements of this technology when applied to actual levee surfaces through levee overtopping hydraulic model experiments and the sensor-based monitoring of internal physical changes. Ultimately, applying conservative design criteria, such as minimum safety factors, will ensure the engineering reliability and stability of this eco-friendly revetment method.

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## References

1 D. Ko and J. Kang: Water **12** (2020) 1070. https://doi.org/10.3390/w12041070
2 W. Kang and D. H. Lee: Nat. Hazards Risk **15** (2024) 2300811. https://doi.org/10.1080/19475705.2023.2300811
3 H. S. Jeon, Y. Oh, Y. Koo, W. J. Yoon, D. Ko, and J. S. Yoon: J. Korean Soc. Civ. Eng. **73** (2025) 44. https://www.ksce.or.kr/ebook/default.asp?YM=202509#&gid=1&pid=44
4 D. H. Lee and M. H. Kim: Proc. 3rd Int. Conf. Protection against Overtopping (London, 2018) 6–8. https://eprints.hrwallingford.com/1301/1/32_D_H_Lee.pdf
5 S. J. Kim: J. Korea Acad. Ind. Cooperation Soc. **22** (2021) 411. https://doi.org/10.5762/KAIS.2021.22.12.411
6 ASTM D6460-07: Standard Test Method for Determining of Rolled Erosion Control Product (RECP) Performance in Protecting Earthen Channels from Stormwater-Induced Erosion (2007).
7 ASTM D7276-06: Standard Guide for Analysis and Interpretation of Test Data for Articulating Concrete Block (ACB) Revetment Systems in Open Channel Flow (2008).
8 ASTM D7277-08: Standard Test Method for Performance Testing of Articulating Concrete Block (ACB) Revetment Systems for Hydraulic Stability in Open Channel Flow (2008).
9 B. H. Cooley and C. Thornton: 2nd Int. Seminar on Dam Protection Against Overtopping (Colorado, 2016). https://api.mountainscholar.org/server/api/core/bitstreams/e71e23cb-3615-4c0e-8e5c-479efc994aac/content
10 H. Takahashi, Y. Morikawa, N. Mori, and T. Yasuda: Soils Found. **59** (2019) 1787. https://doi.org/10.1016/j.sandf.2019.08.008
11 J. Okuda, Y. Shimizu and T. Kyuka: Proc. 22nd IAHR-APD Congress (Sapporo, 2020). https://www.iahr.org/library/infor?pid=7677
12 M. S. Lee, J. H. Jeong, M. Hasegawa, W. J. Yoon, J. S. Yoon, and D. Ko: J. Korean Soc. Civ. Eng. **73** (2025) 46. https://www.ksce.or.kr/ebook/default.asp?YM=202511#&gid=1&pid=46

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