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Dynamic centrifuge model study on liquefaction mitigation in Jumunjin standard sand treated with polysaccharide-based biopolymers

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ABSTRACT

Biopolymer-based soil treatment offers a sustainable alternative to traditional ground improvement techniques, yet its effectiveness under seismic loading remains a key concern for field application. Previous laboratory-scale studies confirmed that polysaccharide-treated Jumunjin sand exhibits enhanced resistance to dynamic loading, particularly in mitigating liquefaction-related effects. Building upon these findings, this study conducted dynamic centrifuge experiments to validate the liquefaction mitigation performance of biopolymer-treated coarse coastal sand under seismic conditions. Centrifuge tests were performed using both untreated and biopolymer-treated specimens, with accelerometers installed to capture acceleration histories and pore pressure responses during shaking. Results indicate that biopolymer-treated sand exhibited significantly reduced excess pore pressure generation and attenuated acceleration amplitudes compared to untreated sand. These outcomes confirm the efficacy of polysaccharide-based biopolymers in suppressing liquefaction-induced ground deformation. The study provides empirical support for the application of biopolymer treatment in seismic ground stabilization and underscores its potential as an environmentally viable solution for coastal geotechnical engineering.

1. INTRODUCTION

The stability of infrastructure founded on loose, cohesionless soils has been a longstanding concern in geotechnical engineering. This issue becomes particularly critical under seismic loading conditions, especially when the soil is fully saturated. During seismic events, saturated loose sands are prone to a drastic reduction in shear strength due to the buildup of excess pore water pressure, resulting in the collapse of the soil fabric. Consequently, the soil mass may behave like a fluid, leading to a phenomenon known as soil liquefaction. In this process, relatively lightweight pore water tends to migrate upward, while heavier soil particles settle, causing ground

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surface deformation. The liquefaction event recorded in Pohang, South Korea, in 2018—the first officially reported case in the country—demonstrated the destructive potential of such behavior, with observations of sand boils, ground settlement, and structural cracking (Choi, 2024).

To mitigate the hazards associated with loose saturated sands, a wide range of conventional ground improvement techniques have been employed. However, these methods often involve high costs, environmental concerns, or limited adaptability to site-specific conditions. In recent years, bio-inspired ground improvement methods have attracted considerable attention as sustainable alternatives. One of the most extensively studied methods is Microbially Induced Calcite Precipitation (MICP), which has been shown to enhance the stiffness and strength of sandy soils, thereby mitigating excess pore pressure generation and associated settlement during seismic excitation (Montoya et al, 2014). Moreover, MICP-treated ground has been found to significantly reduce settlement beneath overlying structures subjected to liquefaction-inducing loads (Ham et al, 2024).

Beyond MICP, biopolymer-based soil treatment techniques have emerged as another promising category of bio-inspired solutions. Jang (2024) reported that soils treated with agar gum exhibited reduced strain accumulation and excess pore pressure development under cyclic triaxial loading compared to untreated specimens. Park (2025) demonstrated that crosslinked xanthan gum (CrXG), when evaluated through cyclic direct simple shear tests, led to higher cyclic resistance ratios than untreated soils or those treated with other types of biopolymers. Furthermore, CrXG-treated soils have shown superior performance in terms of unconfined compressive strength (Lee et al, 2022), shear strength and permeability (Lee et al, 2023), and long-term durability (Bang et al, 2025), making CrXG a particularly promising biopolymer for seismic ground improvement applications.

Building upon this body of knowledge, the present study aims to evaluate the liquefaction mitigation potential of CrXG-treated soils under realistic seismic loading conditions. To this end, a series of dynamic centrifuge experiments were conducted to simulate earthquake-induced ground response. The performance of CrXG-treated sand was assessed based on excess pore pressure generation, and acceleration response. with the goal of advancing the application of biopolymer-based ground improvement for liquefaction resistance.

2. MATERIALS AND METHODS

2.1 Materials: Jumunjin standard sand and crosslinked xanthan gum (CrXG)

Jumunjin sand, a well-known standard sand in South Korea, was used in this study. It is classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS). This sand is readily available from coastal areas and is widely recognized for its susceptibility to liquefaction under saturated and seismic loading conditions. As illustrated in Figure 1, Jumunjin sand falls within the range of soils considered most susceptible to liquefaction. The mean particle size (D_{50}) of the sand is approximately 0.52 mm.

Xanthan gum is a type of biopolymer widely used across various industrial applications. In its powdered form, it readily mixes with water, exhibiting high viscosity and significant swelling behavior. In this study, a crosslinked form of xanthan gum (CrXG) was employed. Unlike pure xanthan gum, which does not exhibit sufficient mechanical strength under submerged conditions, the crosslinked xanthan gum was synthesized by incorporating a cationic aqueous solution to induce crosslinking, thereby enhancing its stiffness and mechanical performance for geotechnical applications.

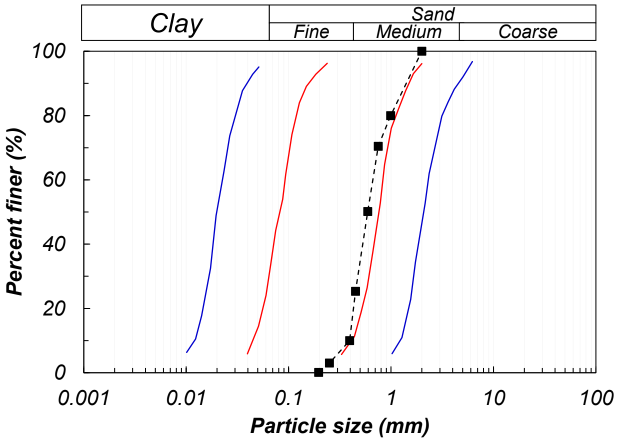

Fig. 1 Particle size distribution of Jumunjin standard sand

2.2 Method: Dynamic centrifuge test

In this study, dynamic centrifuge testing was conducted to evaluate the liquefaction mitigation effect of biopolymer treatment. The experiments were performed using the setup illustrated in Figure 2. Accelerometers and pore pressure transducers were installed within the model box to monitor dynamic responses during shaking. The test specimen was prepared at a relative density of 50%, representing a loose, fully saturated sand condition.The centrifuge tests were conducted at a gravitational acceleration level of 60g, which corresponds to a prototype ground depth of 12.6 meters. The model ground was divided into two distinct zones: an untreated zone and a CrXG-treated zone, with sufficient spacing maintained between them to minimize interaction effects. A single impact loading was applied using a tapered sinusoidal input wave.

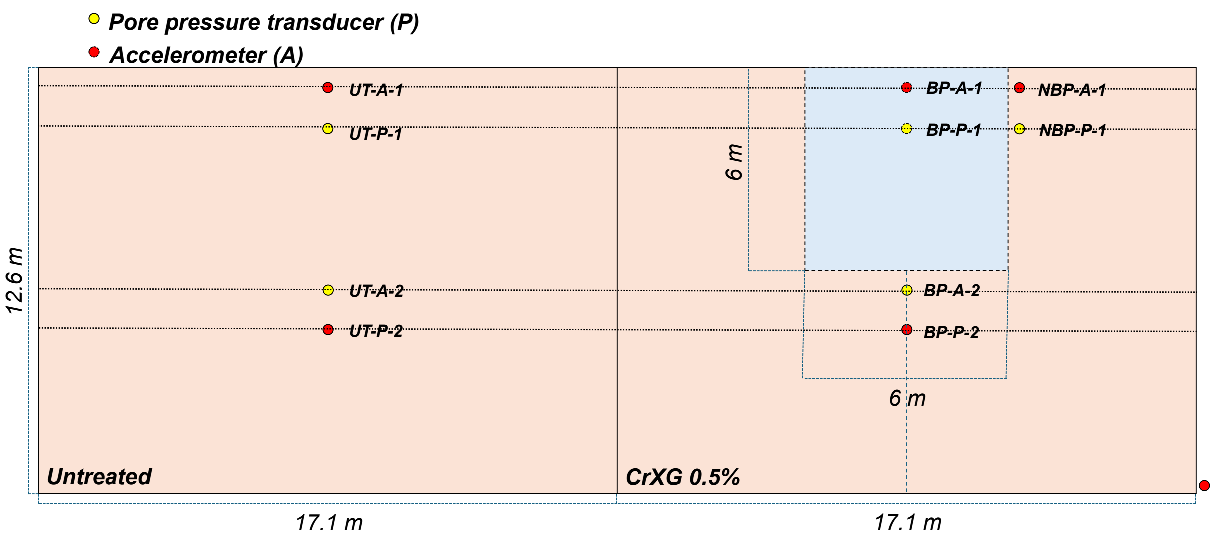

Fig. 2 Cross section view of centrifuge model

3. RESULTS AND ANALYSIS

3.1 Excess pore water pressure

Figure 3 presents the excess pore water pressure ratio (r_u) measured at the ground surface after the seismic event, for three different zones: (a) untreated (UT), (b) within the CrXG-treated block (BP), and (c) adjacent to the CrXG-treated block (NBP). As shown in Figure 3(a), the r_u value in the untreated zone exceeds 1.0, indicating the occurrence of liquefaction. In contrast, Figure 3(b) demonstrates that the r_u values within the CrXG-treated block remain significantly lower, with minimal variation throughout the shaking event, indicating that liquefaction was effectively prevented. In the zone adjacent to the CrXG-treated block (Figure 3(c)), the r_u value does not exceed 1.0; However, large fluctuations in excess pore pressure were observed, along with limited dissipation over time. These observations suggest that while liquefaction did not occur in the adjacent zone, the pore pressure response was unstable. Overall, the results confirm the effectiveness of CrXG treatment in mitigating liquefaction. Furthermore, even the untreated sand located next to the CrXG-treated block exhibited r_u values below 1.0, indicating a reduced liquefaction potential compared to the fully untreated zone. This implies that the CrXG treatment may exert a spatial influence beyond its direct application zone, contributing to improved ground performance in nearby untreated areas.

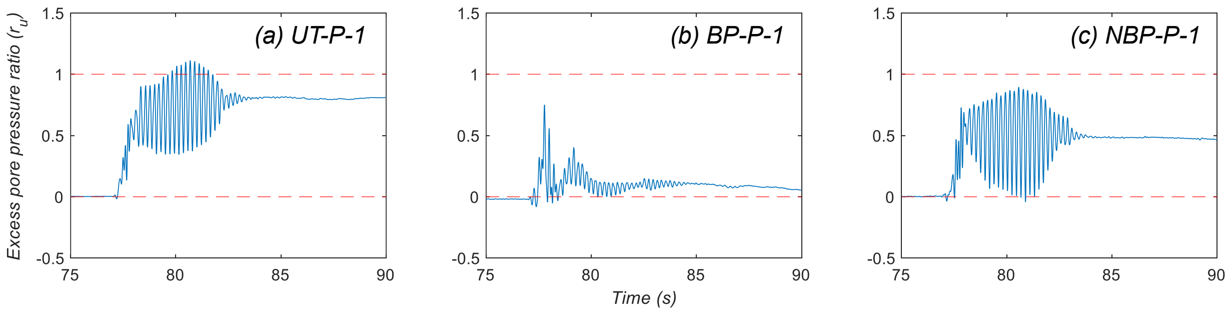

Figure 3. Excess pore water pressure ratio (r_u) comparison at surface
(a) Untreated, (b) CrXG treated, (c) Next to CrXG treated

3.2 Acceleration response

Figure 4 presents the input earthquake motion used in the centrifuge tests. The input consisted of a tapered sinusoidal wave with a frequency of 2 Hz and a total of 30 cycles. An acceleration of 0.3g was applied at the base of the model box.

Figure 5 shows the response spectra measured at three locations: the base input motion, the surface of the untreated zone, and the surface of the CrXG-treated zone. Compared to the black curve representing the input motion, the blue curve corresponding to the untreated surface shows a clear shift toward higher frequencies. This shift can be interpreted as a reduction in soil stiffness due to the progression of liquefaction, resulting in the alteration of the soil's dynamic characteristics. In contrast, the response spectrum of the CrXG-treated zone exhibits only a slight decrease in the amplitude of the resonant frequency compared to the base input, while largely maintaining the overall spectral shape. This indicates that the CrXG-treated soil preserved its stiffness and structural integrity under seismic loading conditions, in stark contrast to the untreated soil.These observations demonstrate that CrXG treatment is effective in maintaining soil stiffness and mitigating the structural degradation typically induced by liquefaction.

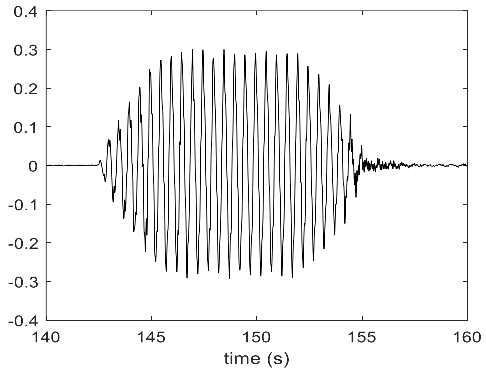

Figure 4. Base input motion

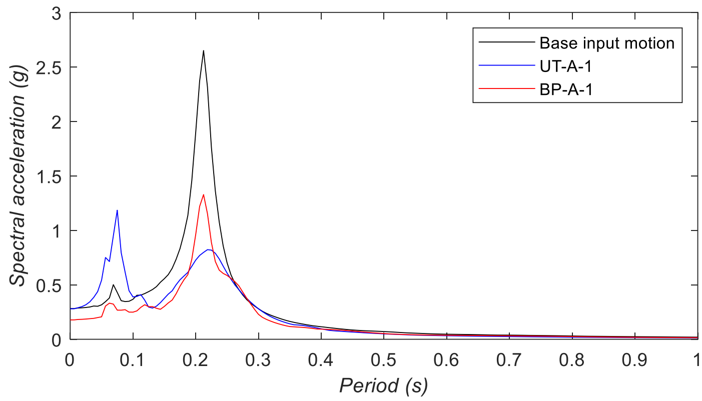

Figure 5. Response spectra for surface UT and CrXG

4. CONCLUSION

This study evaluated the effectiveness of crosslinked xanthan gum (CrXG) in mitigating liquefaction in loose, saturated Jumunjin sand using dynamic centrifuge testing. The untreated zone exhibited typical liquefaction behavior, with ru values exceeding 1.0 and a shift in response spectra toward higher frequencies, indicating stiffness degradation. In contrast, the CrXG-treated zone showed suppressed pore pressure buildup and preserved spectral characteristics, confirming the retention of soil stiffness under seismic loading. Additionally, adjacent untreated zones exhibited partial improvement, suggesting a spatial influence of CrXG. These findings demonstrate that

CrXG treatment effectively enhances seismic resistance and structural stability of liquefiable sands, offering a promising bio-based solution for sustainable ground improvement.

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