EFFECTS OF CONSTITUENT MATERIAL PROPERTIES ON EROSION OF FLAT BED AND RECESSION OF BLUFF

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INTRODUCTION
Seashores and river bottoms are constantly eroded by the flow processes. Grains of various types, including gravel, sand, silt, and clay, mixed at different ratios, and demonstrating varying characteristics, are the constituent materials of these eroding land features. The present study quantifies the importance of the geomechanical properties of soils, with a large fraction of granular material and a smaller portion of fine grain particles, on the incipient motion of the sediment under steady-state flow. Further, it highlights the implications of the soil properties on the erosion and recession of steep beach and bluff systems.

MATERIALS AND METHODS
Soil samples were collected for laboratory experiments from Montauk on Long Island, New York, where the steep shores composed of low fines content soils, have been undergoing chronic erosion and recession.
Laboratory tests include: (1) soil mechanics tests to measure the soil strength indices, (2) steady flow flume tests to estimate the initiation of erosion of the soil, and (3) wave flume tests to understand the processes of erosion, failure, and recession of the beach-bluff system.
Test specimens were prepared by sieving the collected soils and remixing them to reach different fines and coarse grains ratios. A total of 20 soil mixtures, consisting of five different fines-coarse ratios, ξ_f = 0, 5, 10, 15, and 20%, two relative densities, D_r= 39% and 68%, and two initial water contents, ω = 7% and the optimum water content (ω_{opt})—which varied for the different soil mixtures. The shear strength parameters of each soil mixture including the effective cohesion (C') and the effective angle of internal friction (ϕ'), were determined using the Consolidated Undrained (CU) triaxial tests.
In the following, the soils with $D_r = 39\%$ and $D_r = 68\%$ are referred hereafter as loose and dense soils, respectively. The water contents of ω = 7%, ω = ω_{opt} are referred to as dry and wet, respectively.
For the initiation of erosion tests, the near-bed velocity profile for each sample was continuously measured during using a Vectrino profiler (Figure 1). The measured velocity profile corresponding to the onset of erosion was used to fit a logarithmic velocity profile. The profile was used to determine the critical shear velocity and stress normalized by the submerged weight of the sediment particle, the critical Shields parameter (Ghazian Arabi and Farhadzadeh, 2022)

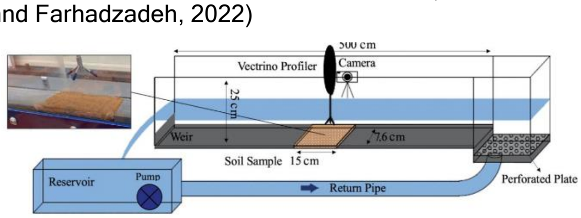

Figure 1 - Schematic of experimental setup including flume, in-situ mold for soil sample, and measuring instruments.

For the bluff recession tests, bluff models were constructed in a wave flume of 3.6 m long, 11 cm wide and 30 cm deep, equipped with a flap-type paddle that generated monochromatic waves (Figure 2). Each bluff model consisted of a steep beach and a vertical-front bluff and was subjected to varying sinusoidal waves and a staged rising surge, for a total duration of 36 hours. The beach had a slope of $tan(\theta) = 1/4.2$ extending 55 cm in the offshore direction, from the toe of the bluff which was 9 cm high. The initial still water level was set 1.5 cm below the bluff toe in Phase 1. Then monochromatic waves which had a height of H = 4.5 cm and period of T = 0.51 s were run for a duration of t_d =12 hours. In Phase 2, the water level was risen 1 cm. The wave height was increased to H = 5.8 cm and run for another 12 hours. Subsequently, in Phase 3, the surge level was risen an additional 1 cm and the wave heigh increased to H = 6.7 cm and run for another 12 hours. The wave period during the three phases remained unchanged. As the bluff was attached by the breaking waves, the beach and bluff profile images were taking at the rate of 10 images/second and used to extract the beach-bluff profiles during the test.

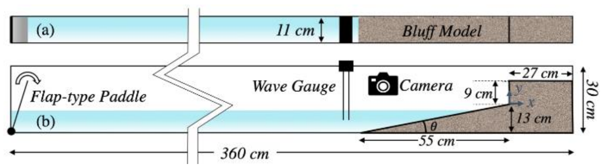

Figure 2. Schematic of experimental setup for wave flume tests on bluff recession.

RESULTS AND DISCUSSIONS
Initiation of Erosion
The velocity in the viscous sublayer where the viscosity dominates the vertical transport of momentum, has a specific characteristic. In this region, the turbulence intensity fades away to zero at the bed level ($y = 0$). Above the viscous sublayer, however, the turbulence becomes the dominant mechanism controlling the vertical transport of momentum. There, the velocity profile is different from that of the viscous sublayer. The turbulent boundary layer and near-bed velocity profile are influenced by the bed roughness. Above the viscus sublayer, the velocity profile follows a logarithmic shape which is a function of the friction velocity, u_*, and the bottom roughness.

$$\frac{U}{u_*} = \frac{1}{\kappa} \ln\left(\frac{y}{y_0}\right) \quad (1)$$

where U is the velocity at an elevation y above the bed, and $\kappa = 0.4$ is the von Kármán's constant and

$$y_0 = \frac{k_s}{30}\left[1 - \exp\left(\frac{-u_* k_s}{27\,\nu}\right)\right] + \frac{\nu}{9u_*} \quad (2)$$

where k_s is the Nikuradse roughness height, and v is the kinematic viscosity of water.
The critical shear stress, τ_{cr} , is expressed as

$$\tau_{cr} = \rho u_*^2 \quad (3)$$

The dimensionless critical shear stress of the soil mixture¯the critical Shields parameter¯θ_{cr} which is a function of the dimensionless grain diameter, D_* is

$$\theta_{cr} = \frac{\tau_{cr}}{(\rho_s - \rho) g D_{50}} \quad (4)$$

$$D_* = \left[\frac{g(s-1)}{\nu^2}\right]^{\frac{1}{3}} D_{50} \quad (5)$$

where ρ_s is the density of the sediment, g is the gravitational acceleration, and $s = \rho_s/\rho$ is the specific gravity of the sediment.

The analysis showed that the wet soils exhibit a higher critical Shields parameter than those of the dry soils. Also, the soils of a smaller dimensionless grain size (D_*)–those are the soils with a higher fines content–exhibited a higher Shields parameter. Thus, the increase of fines content in the soil mixture leads to a higher Shields parameter. Figure 3 shows the critical shear stress as a function of the soil's fines content–the soil composition indicator–and the effective cohesion, which is a strength index. The correlation between the effective cohesion and critical shear stress is like that of the fines content and critical shear stress. The critical shear stress increases with fines content. A higher critical shear stress can be observed for the wet soils compared to that of the dry soils. For the dry soils, the erosion resistance seems to vary consistently with the increase of both the relative density and bulk density. The erosion resistance of the dense soils is not as significantly influenced by the fine-grained material as that for the loose soils. While increasing the fines content from 0 to 20%, in the loose dry soils, leads to 1,200% increase in the critical shear stress, the dense soils demonstrate approximately a 20% increase. The critical shear stress of the wet loose soils increases more than 640% when the fines content increases from 0 to 20%. The wet dense soils, on the other hand, are almost insensitive to the material composition.

Bluff Erosion

The initial planar beach was rapidly adjusted by the incident waves to an equilibrium state for the set surge level (Ghazian Arabi et al. 2020a). The beach material eroded by the breaking wave and resulting swash flow actions was transported offshore by the undertow current. Consequently, the wave runup was able to reach further landward and remove more sediment from the bluff face forming a notch at the bluff toe. The growth of the notch destabilized the bluff and led to a failure, and recession. Consequently, the material was transported and deposited offshore by the combined swash and undertow flow, leading to an equilibrium beach profile in as well as the formation of offshore sandbars. The cycle of beach adjustment, notch formation, slope failure and equilibrium beach, is shown in Figure 4.
The bluff models of with loose soils of low fines content underwent multiple episodic failures during the test duration. The number of failures reduced as the strength of the beach and bluff forming material was enhanced through densification. For the loose material, the strength enhancement was associated with the increase of the fines content beyond 10%, i.e., $\xi_f > 10\%$ when the initial water content was dry of optimum, and 5%, i.e., $\xi_f > 5\%$, when the soil was prepared at its optimum water content. On the other hand, the bluffs with the dense soil, irrespective of the fines content and moisture level, demonstrated a much higher erosion resistance and stability. The rise of the water level, in the following phase, led to a rapid and extensive slope failure, particularly for the bluffs composed of the loose soils.

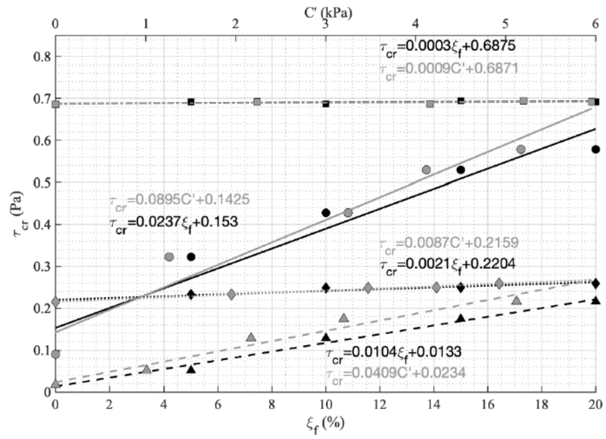

Figure 3 - Critical shear stress vs. fines content and effective cohesion for different soil mixtures. Black markers and lines represent data and fitted curve corresponding to critical shear stress (vertical axis) vs. fines content (lower horizontal axis), and gray markers and lines represent data and fitted lines for critical shear stress vs. effective cohesion (upper horizontal axis). Triangles represent loose dry soils, diamonds indicate dense dry soils, circles are wet loose soils, and squares correspond to wet dense soils.

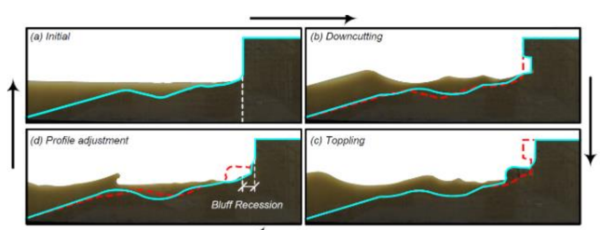

Figure 4 - Cycle of bluff downcutting, toppling and beach adjustment. Initial profile for each stage: Red dashed line; Final profile for each stage: light blue (Ghazian et al, 2020b)

In general, the beach erosion rate was the highest during Phase 1. Once the bluff failed, the wave energy was spent on transporting the resulting deposit offshore resulting in temporary protection and, in turn, a reduced bluff recession rate. For the beach-bluff models of a larger fines content, the higher relative density and optimum water content, the nearshore beach profile appeared to follow a concave down curve while for those with the loose soil or a low fines content, the profile curved concave up (Figure 5).
The bluffs composed of the wet soil exhibited a reduced crest recession compared to those with the dry soil. This reduction was more significant with the loose soil. For

example, for the loose dry soil, adding only five percent fine-grained material to the cohesionless soil (i.e., from ξ_f = 0, C'=0 kPa to ξ_f = 5%, C'=1.01 kPa) resulted in more than 24% reduction in the recession rate. With the wet soil, the bluff recession rate was less than that with the dry soil and nearly the same as that of the cohesionless soil. The recession rate of the bluffs with the loose dry soils was reduced by about 70% when the fines content increased from ξ_f = 0 to ξ_f = 20% (and $C' = 0$ to C'= 5.12 kPa). Further, increasing the soil moisture of the loose soils with ξ_f = 20% to the optimum value resulted in a 63% recession rate reduction compared to the loose wet cohesionless soil. The recession rate for the dense soils was different from the that of the loose ones. The increase of the fines content, up to ξ_f = 20%, did not make a noticeable change to the recession rate of the bluffs composed of the dry soil. However, when the water content increased to the optimum value, the recession rate was reduced rapidly with the increase of the fines content.

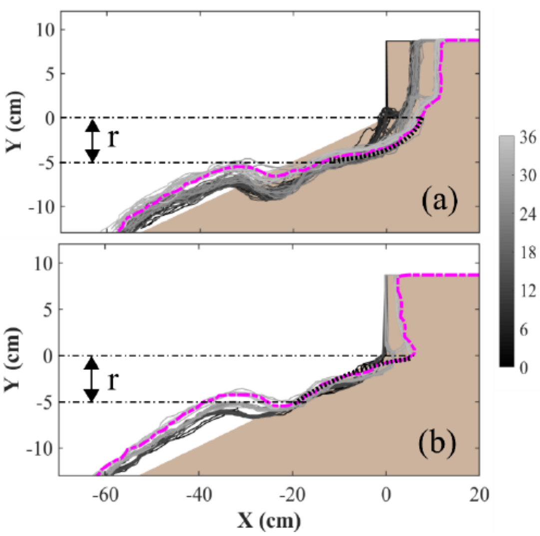

Figure 5 - Evolution of beach-bluff profiles for Dry loose soils containing (a) with 0% fines, C0L, (b) 15% fines, C15D. Brown color shows initial bluff. Purple dashed line shows final profile. Thick black dotted curves show: (a) concave up, and (b) concave down. Dash-dotted lines indicate vertical range (r) of curves from bluff toe.

The trend of the recession rate (R_c), considering the soil's initial water content, relative density and fines content are depicted in Figure 6 where R_c is plotted versus the fines content and effective cohesion. The recession rate decreases with the increase of the effective cohesion. The data also suggest that for a given fines content or alternatively an effective cohesion, the recession rate is significantly influenced by the relative density of the soil. The recession rate exhibits a trend with the effective cohesion like that with the fines content–a decreasing R_c with the increase of C'.

CONCLUSIONS

The critical shear stress was found to linearly increase with the fines content. Furthermore, the soils compacted at their optimum initial water content, in general, demonstrated a higher erosion resistance compared to those with the initial water content dry of optimum. The wet dense soils showed the highest resistance against erosion. Moreover, the mixtures' critical shear stress increased with the fines content and effective cohesion.

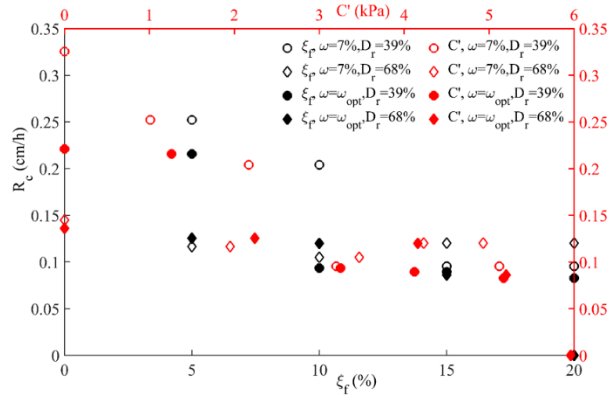

Figure 6 - Bluff recession rate (R_c) versus fines content (ξ_f) and effective cohesion (C'). Black and red markers are associated with fines content (lower horizontal axis) and effective cohesion (upper horizontal axis), respectively.

The bluff recession rate decreased with the increase of the effective cohesion–which increases with the fines content. The recession rates exhibited a trend with the effective cohesion like that with the fines content. The impact of the effective cohesion on the recession rate for the loose soil was significantly greater than that for the dense soil. Following the incremental rise of the surge and incident wave height, the toe erosion in the bluffs of loose and low fines content soils led to a shear failure model. On the other hand, the failure mode of the bluffs composed of the dense soils, the greater fines content, and compacted at the optimum water content, was tensile failure. Finally, the packing reflected in soil's relative density was shown to be a more significant factor in soil resistance both in terms of erosion resistance of flat and sloping bottoms.

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