Ecological geotechnics: Performance of benthos activities controlled by suction, voids, and shear strength in tidal flat soils

Écologique de la géotechnique: Performance de benthos activités contrôlées par succion, vide et force du ciseau dans les sols plats de la marée

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ABSTRACT
The present study aims to pioneer a new cross-disciplinary research field which we call “Ecological Geotechnics”. Recent findings about the salient physics involved in intertidal sediments made it possible to closely investigate the linkage between geophysical environment and benthic ecology in tidal flats. The results of a comprehensive set of field and laboratory experiments demonstrated that the waterfront suction, which thus far remained unexplored in soil mechanics, and the associated geophysical environments govern the performance of the basic living activities of benthos. These findings will enable engineering design and management for preservation and restoration of habitats with diverse benthic activity.

RÉSUMÉ
La présente étude vise à lancer une nouvelle recherche interdisciplinaire domaine que nous appelons "Ecological Géotechnique".Les conclusions récentes au sujet de la physique saillante impliquée dans les sédiments de l'intertidal l'ont rendu possible d'enquêter sur attentivement la liaison entre environnement géophysique et écologie du benthic dans les appartements de la marée. Les résultats d'un ensemble complet de champ et expériences de laboratoire ont démontré que la succion de front de mer et les environnements géophysiques associés gouvernent la performance des activités vivantes de base de benthos. Ces conclusions permettront dessin de l'ingénieur et gestion pour conservation et restauration d'habitats avec diverse activité du benthic.

Keywords : benthos; ecological geotechnics, geoenvironments, tidal flats, waterfront suction

1 INTRODUCTION

Tidal flats are vital elements in the sustainability of coastal environments since they foster rich natural ecosystems. Previous research in the fields of ecology and water science has been directed to understanding the diversity of ecosystems and their water purification functions. However, geoenvironments as habitats and their linkage with biological activity remain poorly understood, although their complete understanding is crucial to the preservation and rehabilitation of habitats.

We recently developed an integrated continuous observation system that enables close inspection of the geoenvironmental dynamics that take place in the zones relevant to benthic diversity and applied it to tidal flats (Sassa & Watabe, 2006). Through the combined use of field, experimental and theoretical investigations, we have found that the dynamics of suction associated with tide-induced groundwater level fluctuations play a substantial role in controlling the geophysical environments of habitats (Sassa & Watabe, 2007). Furthermore, the state of suction in association with the groundwater level is found to be closely linked with the performance of benthic activity (Sassa & Watabe, 2008).

The present study builds on, and extends the above research. We first describe the importance of waterfront suction and related geophysical environments in tidal flat soil. We then present and discuss the results of a range of *in situ* and laboratory tests designed to clarify the role of such geoenvironmental conditions in the ecology of two representative benthos living in tidal flats, namely, crabs and clams.

2 WATERFRONT SUCTION AND RELATED GEOENVIRONMENTS IN TIDAL FLATS

The suction in tidal flat soil is unique and different from conventional suction as commonly dealt with in unsaturated soil

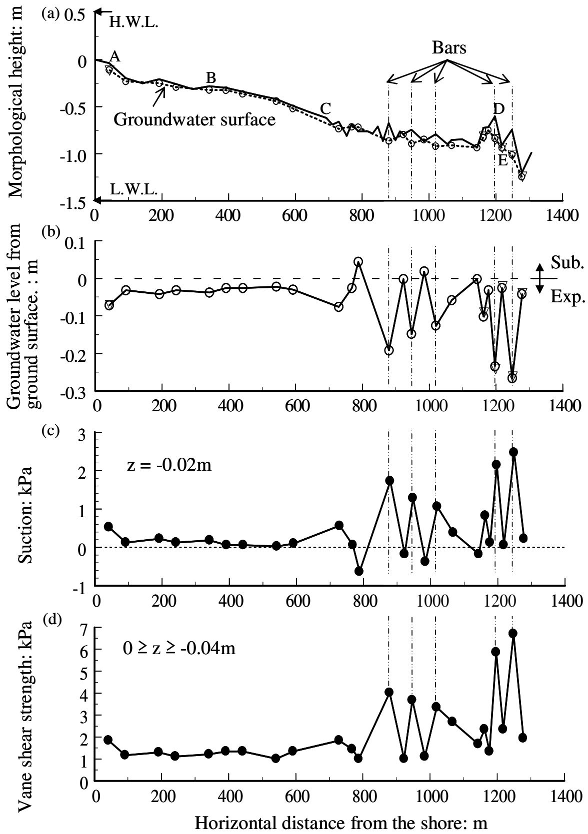

Figure 1. Waterfront suction and related geoenvironments at Banzu flat.

mechanics (Fredlund & Rahardjo, 1993). In fact, it is waterfront suction that develops and changes in essentially saturated states below the air-entry suction of the soil (Sassa & Watabe, 2007).

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-316

Table 1. *In situ* void properties of the tidal flat soils.

	Shore side			Bar	Trough
Soil Void Property	A1	B1	C1	D1	E1
e	0.77	0.79	0.8	0.73	0.87
e_{max}	1.05	1.04	1.14	1.03	1.07
e_{min}	0.64	0.65	0.72	0.64	0.65
D_r	67.8	64.4	80.8	75.6	46.5
Soil Void Property	A2	B2	C2	D2	
e	0.85	1.05	0.93	0.74	
e_{max}	1.07	1.2	1.15	1.05	
e_{min}	0.66	0.76	0.71	0.65	
D_r	52.4	35.7	50.4	77.3	

The letters A to E correspond to the locations denoted in Fig. 1. The suffixes 1 and 2 denote the soil depths -0.2m and -0.4m respectively.

We describe here the results of our recent field observations and surveys performed at the Banzu intertidal flat located in the east coast of Tokyo Bay, Japan. The cross-shore profiles of morphological heights, groundwater level, suction, and vane shear strength during spring low tides are shown in Fig. 1. Here, suction and shear strengths were measured using a tensiometer and a pocket vane apparatus, respectively. The soils were homogeneous with $D_{50} \cong 0.2$ mm, but the geophysical environments varied significantly in space. First, the morphological profile gently inclined downward and exhibited repeated bar–trough regions on the offshore side. The bar–trough topography induced significant changes in the groundwater level, giving rise to the variation of suction in the soil. This development of suction was found to be closely linked with the stiffness/softness variation as represented by the vane shear strength. Furthermore, the results of *in situ* soil sampling and physical soil tests (Table 1) indicate that the soils were denser at shallower depth, and bars with higher suction were more densely packed than the troughs. These *in situ* void state structures can be consistently explained as a consequence of the suction-induced cyclic elastoplastic contraction in the repeatedly exposed yet saturated soil (Sassa & Watabe, 2007).

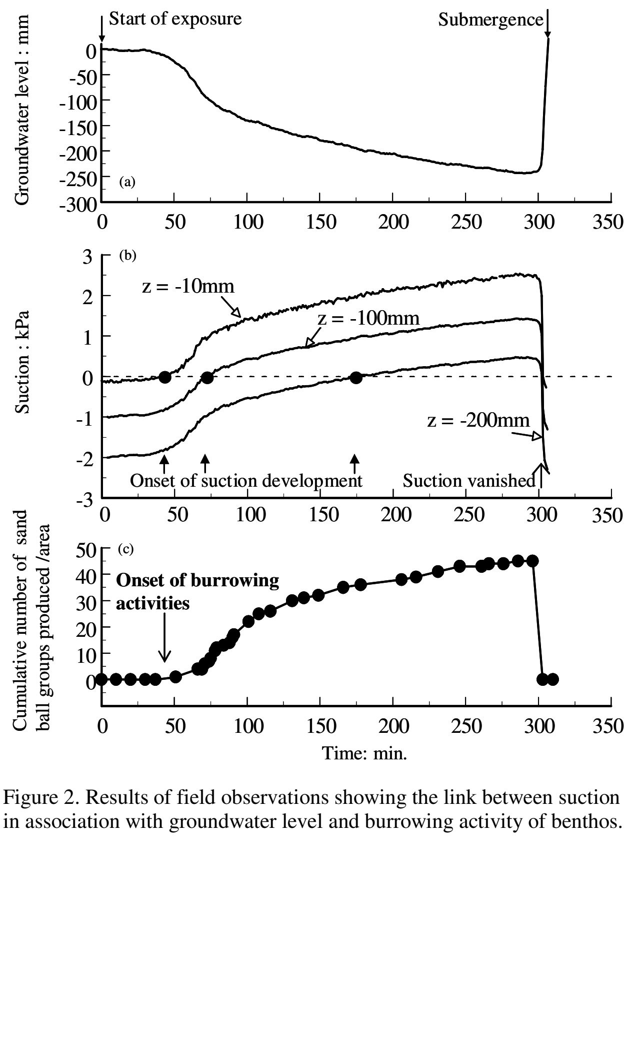

Figure 2. Results of field observations showing the link between suction in association with groundwater level and burrowing activity of benthos.

Our field observations also indicated that the initial development of suction was a trigger responsible for the onset of the burrowing activity of benthos, as shown in Fig. 2. Indeed, one can see that there was a close link between the progress of the burrowing activity and the state of the suction in the soil.

3 ROLE OF GEOENVIRONMENTAL CONDITIONS IN BURROWING ACTIVITY OF CRABS

On the basis of the field results described above, we performed sets of controlled laboratory experiments, first to clarify the geophysical environmental characteristics of the tidal flat soils, and second to closely look at the response of benthos to it. For both experiments, a transparent cylindrical chamber set in a water tank was used. The suction in a given soil deposit with a prescribed packing state was controlled by changing the groundwater level, and the vane shear strengths were measured with the same apparatus as used in the field.

3.1 *Interrelationships between suction, voids, and shear strength of tidal flat soils*

The measured interrelationships between suction, voids, and shear strength (VSS) are shown in Fig. 3. It is clear that the vane shear strength increased markedly with increasing suction and with increasing sediment relative density. By contrast, when suction was absent (negative suction), the vane shear strength depended only on the sediment relative density. In essence, there exists a relationship VSS = VSS (s, D_r).

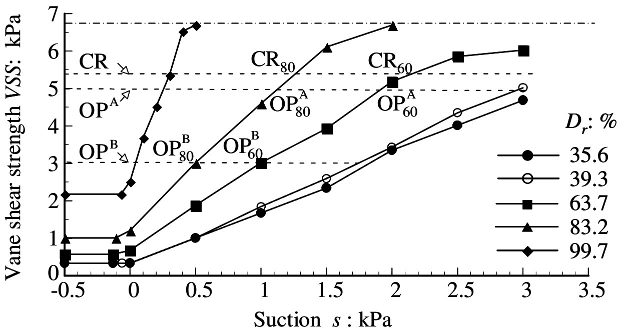

Figure 3. Vane shear strength versus suction for five different relative densities of tidal flat soils.

3.2 *Burrowing experiments*

The crabs *Scopimera globosa* taken from the Banzu flat were used in the burrowing experiments. The water environment was kept constant, with air and water temperatures at 25 and 21–23 °C, respectively, and water/pore water salinity at 2.7%. Then, we simulated a range of geophysical environmental conditions on the basis of the above interrelationships and observed the progress of the burrowing activities of ten individual crabs for 6 hours in each case, in a total of 35 cases.

The experimental results are shown in Fig. 4. Under a given sediment relative density, the burrows started to develop once suction was present and reached peak depths, but declined rapidly with an increase in suction. This stemmed from the tradeoff relationship due to the contrasting effects of suction. Namely, the effective cohesion produced by the suction made burrowing physically possible, but the suction-induced enhanced shear strength made the burrowing more difficult, yielding the critical state CR for the burrow development. With increasing sediment relative density, the burrow depths became much shallower. Interestingly, there were two optimum states OP^A and OP^B for the burrow development, depending on two distinctive regions of burrowing activity above and below the

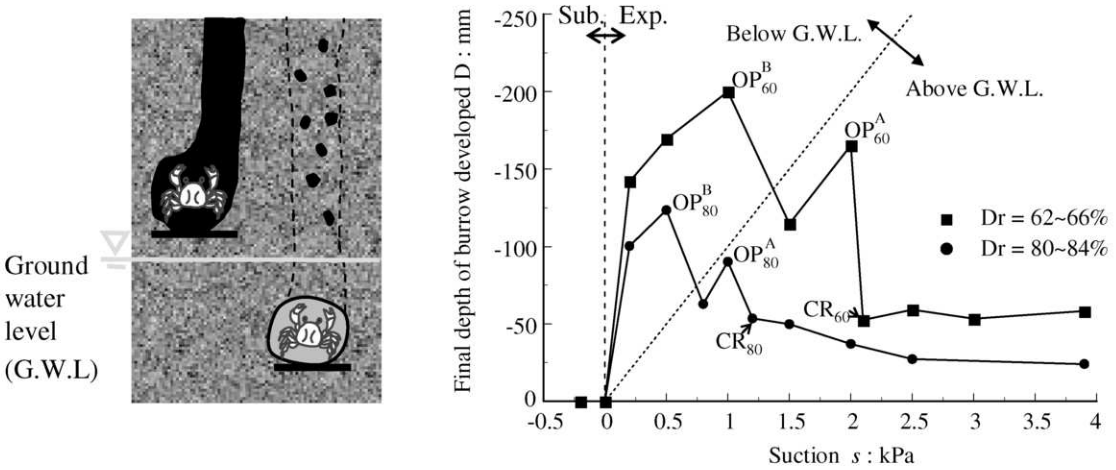

Figure 4. Results of burrowing experiments showing the link between burrow development, suction and related geoenvironments

groundwater level, as illustrated in Fig. 4. Notably, all of these states occurred according to the state-particular shear strengths as functions of both suction and sediment relative density in view of Fig. 3.

Overall, the above results demonstrate that the performance of the burrowing activities was in fact controlled by the suction, void, and shear strength of the tidal flat soils.

4 ROLE OF GEOENVIRONMENTAL CONDITIONS IN SELF-BURIAL ACTIVITY OF CLAMS

In conjunction with the burrowing experiments described above, we closely examined the response of the self-burial activity of clams to a range of geophysical environmental conditions. The difference between the experiments was that we focused here on the uppermost layer of soil, where their self-burial activity took place.

4.1 *Surface shear strengths of tidal flat soils and agar*

In order to capture the surface shear strength of a given bed material, we adopted a high-resolution vane shear system employing a torque meter with low capacity (2 kgf·cm) and vane blades with a depth of 10 mm, as illustrated in Fig. 5. For the materials, we used the sandy soils taken from the Banzu flat and agar simulating cohesive soil. In this respect, it is instructive to note that in the tidal flat restoration projects, it is

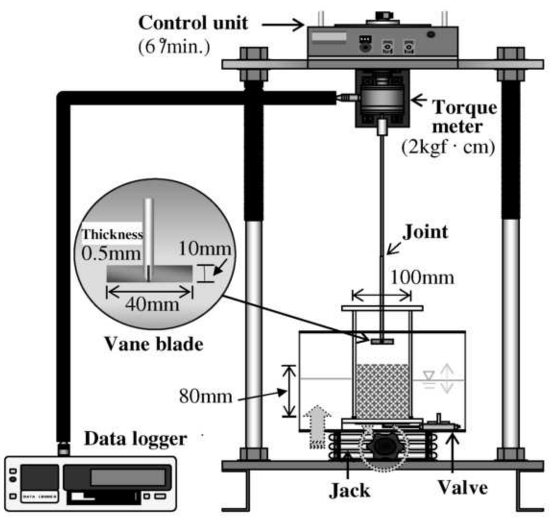

Figure 5. High-resolution vane shear system for surface materials

a common practice to use dredged clay together with sandy soils for bed materials for clams (MLIT, 2003).

The experimental results are shown in Fig. 6. For both materials and conditions imposed, the vane shear stresses increased with increasing shear angles, and reached peaks, namely, the vane shear strengths. The strength characteristics will be discussed below in light of the observed clam responses.

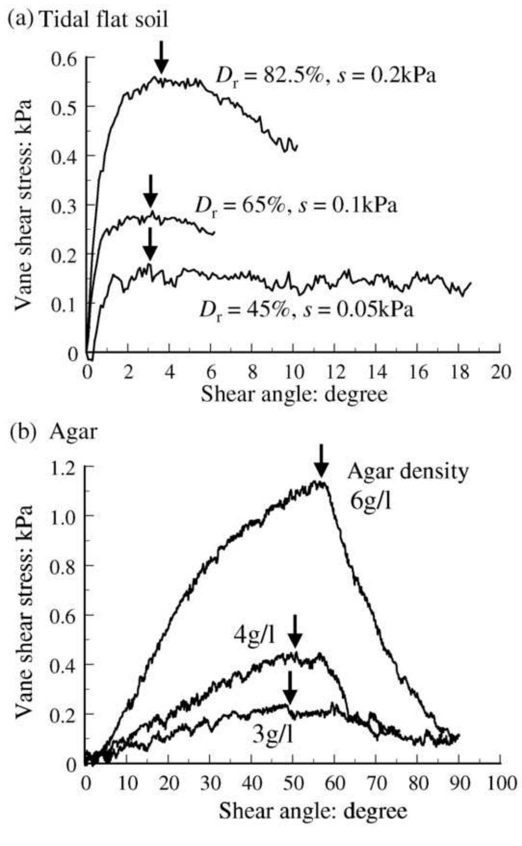

Figure 6. Results of vane shear tests on the tidal flat soils and agar.

4.2 *Self-burial experiments*

In the self-burial experiments, we used five clams *Ruditapes Philippinarum* (Japanese littleneck) with a shell length of 20 mm in each case, in a total of 33 cases. The observed typical patterns of their behavior are shown in Fig. 7. One can see that in the successful cases, the clam inserted its foot in the bed material and subsequently buried itself.

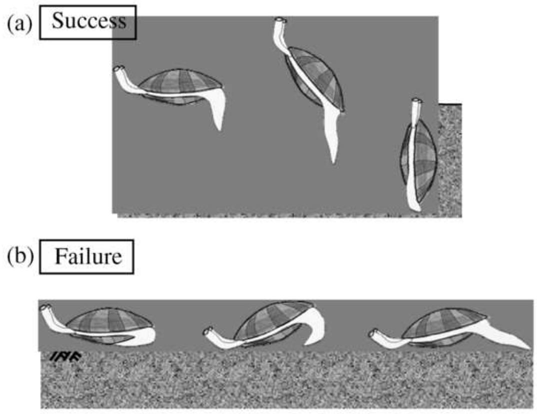

Figure 7. Observed typical patterns of successful and unsuccessful self-burial activities of the clams.

The experimental results are plotted in Fig. 8. For the tidal flat soil, the clams exhibited self-burial under both submerged and exposed conditions. However, the clams could not bury themselves at higher suctions for lower relative densities of the soils. These results indicate that both suction and relative density affected the self-burial capability of the clams. For the agar, one can see that the clam activities shifted in order from sinking, successful burial, to unsuccessful burial in response to the increase in the bed shear strength.

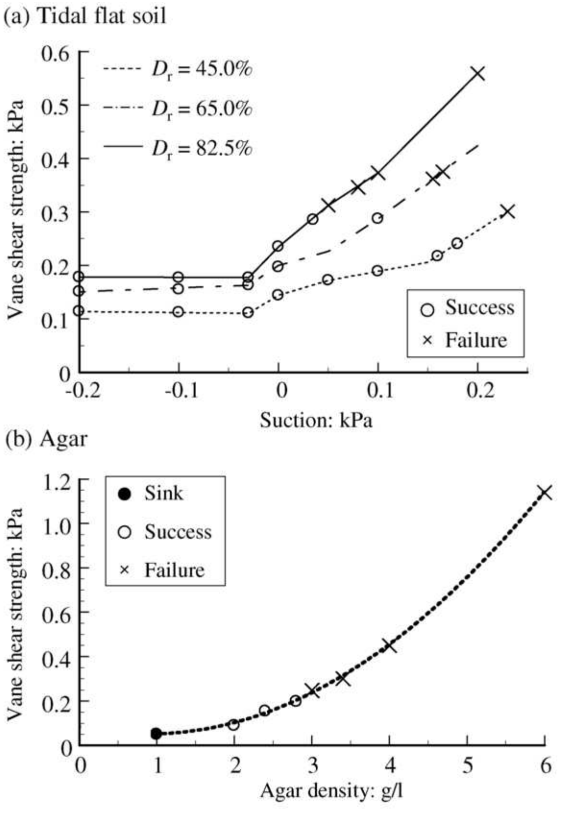

Figure 8. Results of self-burial experiments in the tidal flat soils and agar.

It is interesting to note that the observed forms of the unsuccessful self-burial activities were different between the different materials, and were closely linked to the way in which the material shear strengths manifested themselves. Namely, with reference to Fig. 6, the shear strengths appeared very slowly with shearing in the agar, but appeared almost instantly with shearing in the tidal flat soil. As a consequence, the clams withdrew their feet upon contacting the soil with high strength, whereas in the agar, they repeatedly attempted self-burial, as shown in Fig. 7(b).

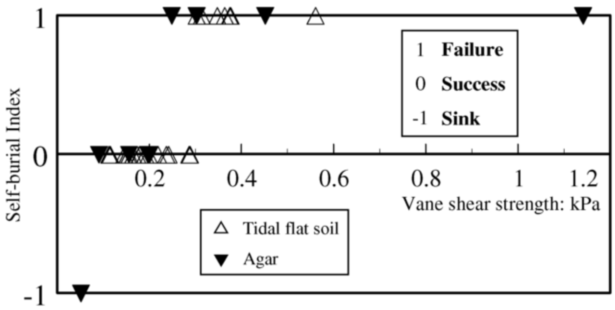

Figure 9. Summary plot showing the self-burial index versus vane shear strength.

The experimental results are summarized in the form of Fig. 9. It is clear that, irrespective of the bed materials, there existed a critical surface shear strength above which the self-burial activity became physically impossible. Under such situations in the field, the clams would be transported away due to waves and currents, and also exposed to the fatal risks of predators, both of which make survival profoundly difficult.

Overall, the above results clearly indicate that the performance of the self-burial activities depended strongly on the surface shear strength of the given bed materials.

5 CONCLUSIONS

A comprehensive set of *in situ* and laboratory tests were performed to investigate the geophysical environmental characteristics of tidal flat soils. Notably, the waterfront suction, which changed with topography and groundwater level, was found to play a substantial role in the formation of voids and shear strengths of tidal flat soils, and to be closely linked with benthos activity.

We clarified the responses of two representative benthos, crabs and clams, to a wide variety of geophysical environmental conditions in the laboratory. The results demonstrated that the characteristics of the suction, voids, and shear strengths governed the performances of the burrowing and self-burial activities, both of which constitute the basic living activities of the benthos.

These findings will therefore contribute to realization of performance-based geoenvironmental assessment, design and management for preservation and restoration of habitats with rich natural ecosystems, pioneering the new field of “Ecological Geotechnics”.

REFERENCES

Fredlund, D.G. & Rahardjo, H. 1993. *Soil Mechanics for Unsaturated Soils*, New York; Wiley, 544p.

MLIT. 2003. Handbook for Nature Restoration in the Ocean, Vol. 2, Tidal Flats, 138p.

Sassa, S. & Watabe, Y. 2006. The dynamics of tidal flat geo-environments in an estuary. *Proceedings of Coastal Dynamics ’05*, Am. Soc. Civ. Eng., in CD.

Sassa S. & Watabe, Y. 2007. Role of suction dynamics in evolution of intertidal sandy flats: Field evidence, experiments, and theoretical model. *Journal of Geophysical Research* **112**, F01003, doi:10.1029/2006JF000575.

Sassa S. & Watabe, Y. 2008. Threshold, optimum and critical geoenvironmental conditions for burrowing activity of sand bubbler crab, *Scopimera globosa*. *Marine Ecology Progress Series* **354**: 191-199.