Visualizing footprints on the beach effects with bearing capacity experiments on fine transparent soil

Ferran Parera Morales [1], Megan McKellar [2], Greg Siemens[3]*, and W. Andy Take[4]

[1] *Geological Risk Prevention and Geotechnics Department, Geographical and Geological Survey of Catalonia (Institut Cartogràfic i Geológic de Catalunya), Barcelona, Spain.*

[2] *BGC Engineering, Calgary, Alberta, Canada*

[3]*GeoEngineering Centre at Queen's-RMC, Department of Civil Engineering, Royal Military College of Canada, Kingston, Ontario, Canada*

[4]*GeoEngineering Centre at Queen's-RMC, Department of Civil Q2 Engineering, Queen's University, Kingston, Ontario, Canada*

**Corresponding author's email: siemens@rmc.ca*

Introduction

All beach goers have experienced the phenomenon of that walking on the edge of the swash zone is significantly easier and more comfortable relative to the submerged sand lake/ocean level or dry sand farther away from the beach. As each footstep descends into the sand temporary high bearing capacity is registered followed by a depression of the foot, a sand cone emerging around the depression, which is surrounded by a dilative fringe. Reynolds (1885: p. 475 [1]) may have been the first to describe this phenomenon in the scientific literature:

> A well-marked phenomenon receives its explanation at once from the existence of dilatancy in sand. When the falling tide leaves the sand firm, as the foot falls on it the sand whitens, or appears momentarily to dry round the foot. When this happens the sand is full of water, the surface of which is kept up to that of the sand by capillary attraction; the pressure of the foot causing dilation of the sand, more water is required, which has to be obtained either by depressing the level of the surface against the capillary attraction, or by drawing water through the interstices of the surrounding sand. This latter requires time to accomplish, so that for the moment the capillary forces are overcome; the surface of the water is lowered below that of the sand, leaving the latter white or dryer until a sufficient supply has been obtained from below, when the surface rises and wets the sand again.

From a geotechnical perspective, dilation-induced negative pore pressures provide temporary support during foot placement followed often by what appears to be a general shear failure. Parera Morales et al (2024 [2]) provided the first set of laboratory plate load tests on coarse transparent soil. They provided the first visualization of air entry during plastic collapse combined with simultaneous load, displacement, and pore pressure measurements. In this abstract, footprints on the beach experiments using fine transparent soil are reported, which provide a comparison to the coarse transparent soil with material that has a similar friction angle but with 2-3 times higher air entry value. Results show that tests on fine transparent soil with phreatic surface placed at the ground surface recorded the highest bearing capacity, which is approximately 4.6 times the pressure available for dry tests. Both tests with phreatic surface placed below and above the ground surface showed progressively decreasing bearing capacities.

Transparent soil is formed through the fluid-granular material with matched refractive indices that utilizes fused quartz and mineral oil mixture. The result is, when saturated the mixture appears homogeneous and the background (normally black) is visible. As the mixture desaturates and air enters the void spaces, the air phase is initially visible and at lower saturations sand particles appear white ([4]). Using a testing apparatus with a glass front and black background, observations can be made during failure with the ability to observe and quantify local saturation. Fine transparent soil has a refractive index of 1.459, and a gradation of 100% particles passing a 2.0 mm sieve. The pore fluid to be paired with the quartz is a mixture of two white mineral oils. To match the refractive index, Petro Canada Krystol40 (RI=1.450) and Life Brand™ Unscented Baby Oil (RI=1.463) are combined until the target refractive index is met.

Footprints on the beach using transparent soil test setup is shown in Figure 1 with end of test digital images showing failure modes and the effect of phreatic surface depth on air entry given in Figure 2. Experiments were completed within an 890x305x205 mm tank constructed from tempered glass and supported in an aluminium frame (Figure 1). The back of the tank was painted black for contrast between the soil particles when in an unsaturated state. This also ensured that all air voids below the phreatic surface were recognized and removed before testing to ensure the 100% saturation. The tank was instrumented with a load cell, linear variable displacement transducer (LVDT), and pore pressure transducer (PPT) as seen in Figure 1. High-speed imagery used to record experiments was captured by the Phantom® v.2512 at 500 fps in synchronization with the other data logger frequencies.

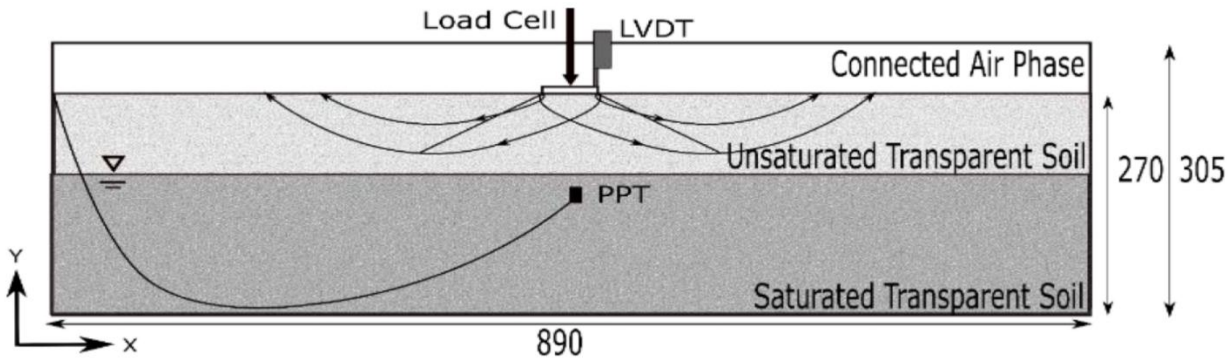

Figure 1: Footprints on the beach test setup.

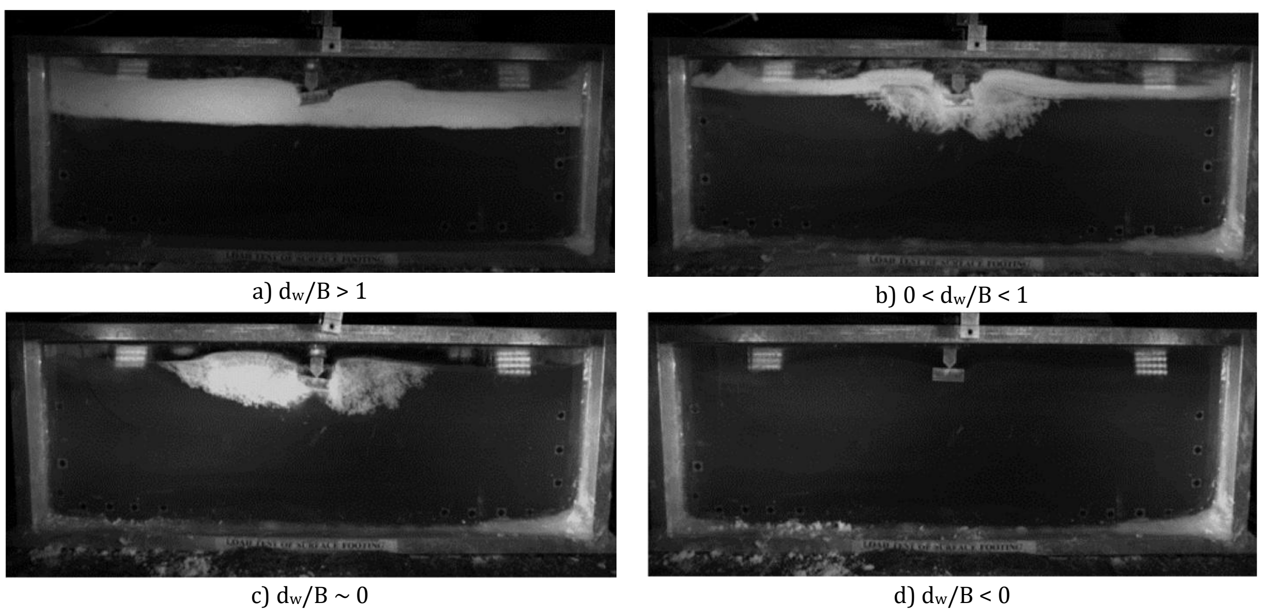

Figure 2: Digital images of footprints on the beach experiments showing the effect of phreatic surface depth on air entry after plastic collapse: a) $d_w/B > 1$ with failure in the unsaturated zone, b) $0 < d_w/B < 1$ with a combined failure surface through the unsaturated and saturated zone along with visually confirmed air entry, c) $d_w/B \sim 0$ with air entry coincidental with the Prandtl-type failure zone, and d) $d_w/B < 0$ with no air entry as overlying fluid fills the dilation zone.

Digital images showing visual recordings of air entry along with summary graph in Figure 3 show how dilation induced negative pore pressures limited by air entry lead to the highest bearing capacity recorded when the phreatic surface is located at the ground surface (d_w=0). Also included in Figure 3 are the coarse transparent soil results as well as bearing capacity profile calculated by Terzaghi (1943 [3]) equation. When the phreatic surface is deep (Figure 2a) failure occurs in the unsaturated material and no air entry is visible. This is associated with the lowest bearing capacity, which serves as the value to normalize all other bearing capacity measurements in Figure 3. As phreatic surface is moved upwards air entry is visible in Figure 2b and 2c and bearing capacity increases, which contradicts both saturated and unsaturated bearing capacity theory. When a submerged footing is tested (Figure 2d) no air entry occurs as the mineral oil fills any dilation induced increase in voids and bearing capacity, once again reduces.

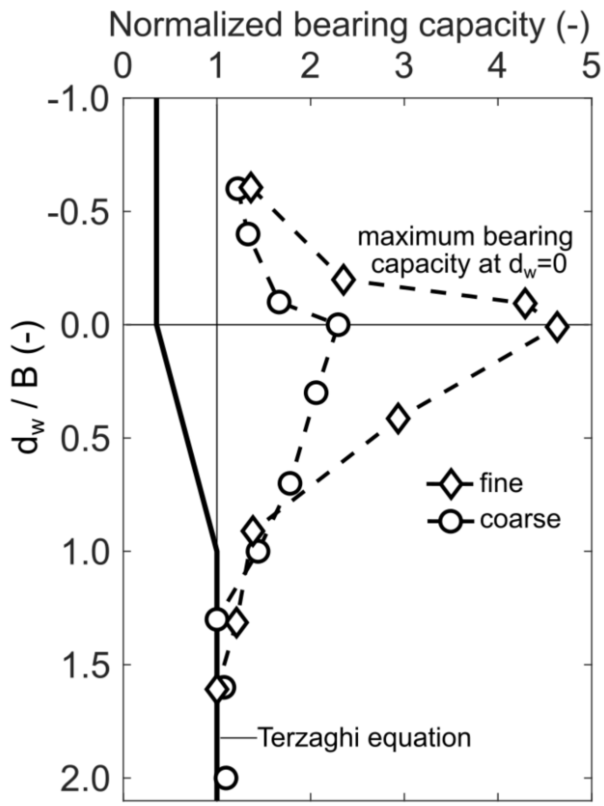

Figure 3: Summary of fine and coarse transparent soil results normalized to footing width B and dry bearing capacity (failure mode of dry bearing capacity shown in Figure 2a).

Everyone's experience of walking on the beach conflicts with both saturated and unsaturated bearing capacity theory, which predict the minimum bearing capacity occurs when the phreatic surface is coincidental with the ground surface (suction = 0). Bearing capacity theories, with assumptions of either drained or undrained pore pressures, are formulated for use in engineering design and analysis rather than to explain the science behind an enjoyable stroll. Walking on the beach when the water table is at the surface is an inherently coupled process with variable pore pressure boundary conditions. At negative pressures below air entry, dilation effects result in negative pore pressures causing increased bearing capacity. If load is applied quickly and increases past the capillarity-limited air entry upper bound, bearing capacity is reached and failure around the foot looks visually like the laboratory plate load test photo in Figure 2c.

Results in this abstract add to the existing database of tests using transparent soil [2], which investigate coupled dilation-induced temporary negative pore pressure effects on bearing capacity. The database of tests are unified in providing a reasonable geotechnical explanation of the footprints on the beach application. Although dilation effects occur in both the dry and saturated cases, capillarity effects at the soil surface in saturated experiments provides further strength owing to negative fluid pressures. Further loading overcomes available capacity of the dilation-induced negative pore pressures, which leads to air entry and bearing capacity failure. The unsaturated storage functions explain the relative differences between the coarse and fine tests. The soils have similar friction angles [5] but fine transparent soil has an air entry value 2-3 times that of coarse soil. Therefore the increase in bearing capacity of fine tests relative to coarse tests (4.6x rather than 2.3x) is due to additional capillarity forces available at the air-mineral oil-soil surface in fine transparent soil. Similar phenomena were identified by [6] to understand grain-size and pore pressure response of collapse of dense saturated granular columns. For further advancement of where these phenomena are applicable to engineering analysis and design, additional experiments and coupled numerical modeling are required.

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