Pore pressure monitoring of surficial coastal sediments on wave–resolving scale with outlook on liquefaction risk prediction at offshore wind and marine hydrokinetic energy converters

Nina Stark and Brandon Quinn
Department of Civil and Environmental Engineering
Virginia Tech
Blacksburg, Virginia 24061
Email: ninas@vt.edu

***Abstract*—Offshore and ocean renewable energy gain increasingly in importance with the global race to explore and exploit new green energy options. They also represent a novel way to bring energy independence and reliability to remote places which are off the grid and currently depend on fossil fuel generators. Yakutat, Alaska, is one of the currently investigated sites with regard to the harvesting of wave energy. However, many offshore and ocean renewable energy projects are still facing a number of different challenges. One of these challenges can be the sediment specific pore pressure response to wave action, structure vibration and earthquake shaking, which governs the risk for higher sediment erodibility and liquefaction. In this study a set of two pressure sensors complemented by an acoustic Doppler current profiler (ADCP) and an underwater camera were tested to investigate pore pressure evolution on wave- and tide-resolving scale in the lower intertidal zone of Cannon Beach, Yakutat, Alaska. The following observations were made. Groundwater dynamics were noticeable at a sediment depth of 20 cm before and during the passing of the swash zone. Wave characteristics of the surf and swash zone were reflected and deviations between the signals recorded at the different sediment depths noticed. Wave damping of the surf with increasing sediment depth was observed, as well as single pore pressure peaks which were often associated with wave irregularity. Sustaining of pore pressure and incomplete pore pressure relief in wave troughs was noticed and increased with wave irregularity. The results led to the development of a concept of a novel pore pressure lance with options for complementary instruments such as a commercial Cone Penetration Test (CPT) tip and/or an ADCP that would contribute to the understanding of pore pressure evolution at beaches and in the vicinity of coastal structures, and especially, near offshore and ocean renewable energy converters in coastal areas and the nearshore zone.**

I. Introduction

Offshore wind and marine hydrokinetic energy have been recognized for their large potential with regard to the harvesting of renewable energy in the future. Offshore wind resources were characterized as abundant, stronger and more consistent than land-based wind resources in the U.S., and more than 4,000,000 MW of capacity was identified at the U.S. coast and in the Great Lakes (http://energy.gov/eere/wind/offshore-wind-research-and-development). The Electric Power Research Institute (EPRI) stated that 1,170 TWh/year could be harvested from wave energy in U.S. waters, and Haas et al. (2011) identified multiple "hotspots" for the harvesting of tidal energy with an average kinetic power density $>500\,\mathrm{W/m^2}$ in the U.S. [1], [2]. Despite the large potential of offshore wind and marine hydrokinetic energy and successful demonstrations of technologies worldwide, the harvesting of offshore and ocean energy still faces a number of challenges [3]–[5]. Some of these challenges are related to the anchoring or foundation systems of the energy converters, including aspects of site assessment, deployment and long-term durability [6], [7]. A site characterization of physical and geotechnical properties of the seabed at the target location and the surrounding area is of importance for the design of the foundation or anchoring system and the development of a deployment strategy. To secure the long-term durability of an offshore or ocean renewable energy converter, the assessment of the stability of the seabed regarding bearing capacity and susceptibility to liquefaction, as well as sediment transport and scour is crucial. However, such a site characterization can be difficult, time- and cost-intensive in energetic coastal and offshore areas [8], [9].

A concern regarding the sediment stability of a foundation or anchor –particularly in sandy sediments– is the risk of liquefaction resulting from earthquake shaking, storm wave action, vibration of the structure, or a combination of these mechanisms [10]–[12]. Momentary liquefaction has also been discussed as a risk resulting from tsunami drawback [13]. In the U.S. a large number of areas which hold a high potential for the harvesting of offshore wind or marine hydrokinetic energy are prone to storms and hurricanes, and/or earthquakes and tsunamis. Thus, the risk of high pore pressures and liquefaction at offshore and ocean renewable energy converters (ORECs) has to be recognized and addressed to secure long-term durability of ORECs in such areas.

Laboratory testing of the susceptibility of marine sediments to liquefaction as well as numerical simulations of different scenarios have significantly advanced within the last years [14]–[18]. However, there are only few field data sets that include pore pressure monitoring in coastal and marine environments, or in the vicinity of offshore or coastal structures. Such information would be useful to calibrate and validate models, to investigate the impact of rotor vibration in the case of wind and tidal energy converters, and to fill gaps

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in understanding, particularly with regard to the interaction between in-situ pore pressure and ongoing sediment dynamics. With regard to the latter, uppermost seafloor sediment layers can be subject to rapid and frequent changes in density and packing due to ongoing erosion and deposition processes, and thus, may vary in geotechnical characteristics with ongoing sediment dynamics [19]. However, undisturbed samples are difficult to obtain, particularly in cohesionless sediments, and may only represent a snapshot in time [20]. It follows that pore pressure monitoring coupled with sediment dynamic observations would give new insight into the interaction between pore pressure evolution and sediment dynamics.

Stark and Hay (2014) presented pore pressure data obtained at a sediment depth of 0.5 m at a mixed sand-gravel mega-tidal beach in the Bay of Fundy, continuously sampled at a rate of 4 Hz over 15 consecutive days, using a pT sensor designed as an oceanographic wave gauge [21]. The data set allowed to investigate and quantify tide- and wave-resolving pore pressure features (e.g., characteristic drainage rates, damping of wave energy, delayed and incomplete pressure relief in wave troughs, changes in wave skewness and asymmetry). Motivated by the results, a smaller wave gauge recording at 10 Hz was chosen for further tests at a sandy wave dominated beach in Yakutat, Alaska, in 2014 [9].

The purpose of this article is to present the results of a vertical arrangement of a high resolution acoustic Doppler current profiler (ADCP) over a pore pressure sensor at a sediment depth of 5 cm and a pore pressure sensor at a sediment depth of 20 cm close to a proposed wave energy converter site at Cannon Beach, Yakutat, AK (Fig. 1). Furthermore, an outlook will be given on a more advanced follow-up instrument array design and its possible future application for offshore wind and marine hydrokinetic energy developments.

II. Methods

A frame was instrumented with a *Nortek AquaDopp HR* ADCP and a *GoPro Hero 3* underwater camera at 30 cm above the beachface, and two *RBR Solo* wave gauges buried at sediment depths of 5 cm and 20 cm, respectively (Fig. 2). The frame was deployed in the lower intertidal zone of Cannon Beach on 28 July 2014 shortly after low tide, and recovered approximately 8 hours later.

The two *RBR Solo* wave gauges were continuously recording pressure at a sampling rate of 10 Hz. The memory and the battery allow up to one month of continuous monitoring at the same sampling rate, while the device is only about 25 cm in length and about 3 cm in diameter. The small dimensions enable burial with minimized disturbance of the surrounding sediment. In the case of the test deployment at Cannon Beach, the probes were pushed into the sediments until the sensor water inlets were located at sediment depths of 5 cm and 20 cm (in the following p_5 and p_{20}), respectively. The pressure transducer face was protected by a perforated plastic shield, and a geo-textile to avoid clogging and sediment pressure on the transducer face. The frame legs were flat, L-shaped metal sheets approximately 5 cm wide and 0.5 cm in thickness. They were pushed into the sediment to a depth of approximately 40 cm. Digging was avoided to minimize disturbance of the sediment. The pressure sensors and the ADCP were facing seaward, while the underwater camera was directed seaward–downward. All systems were entirely autonomous and synchronized to the same computer clock.

The ADCP was sampling at 1 Hz. Flow speed and direction was determined at distances of 13-97 cm with a bin size of 3 cm. It was directed parallel to the beachface. The underwater camera recorded at 30 frames per second to visualize sediment remobilization. At this setting the battery was depleted after approximately one hour. This enabled coverage of the swash and parts of the surf zone during flood tide only.

The deployment represented a proof-of-concept. For more detailed investigations a longer deployment with a larger number of pressure sensors in the vertical as well as cross- or long-shore direction may be desired, depending on the research question.

III. Results

The water levels were calculated from the pressure data, and displayed at a wave-resolving rate (10 Hz) and a tide-resolving rate (5 minutes averages) in figure 3. Overall the tidal curves recorded by the respective pressure sensors were in good agreement. No shifts or distortion of the tidal curve were observed. p_5 measured a high water level of $\sim$1.06 m, with waves reaching a height of 1.6 m. p_{20} measured at high water 1.2 m, being in accord with the difference in burial depth. The highest recorded water level at p_{20} equaled 1.73 m, but did not correspond with the largest pressure event of p_5. Some other differences were noticeable between the recordings of the two buried pressure sensors. p_{20} recorded a rapid increase in pressure at a recording time of 54 minutes, reaching a pressure equivalent to a water level of 5 cm above the sensor. The pressure remained approximately constant for another 36 minutes before it started to increase further. At this time p_5 also recorded a strong increase in pressure. Both sensors displayed only small and irregular wave activities until a recording time of $\sim$2.4 hours. Then, wave activity increased significantly at p_5, showing particularly some strong wave troughs almost draining the beachface. Wave activity also increased at p_{20}, but the strong irregularities as observed closer to the surface were not reflected. Overall, the recordings of p_5 and p_{20} were characterized by some noticeable differences until a recording time of about 3 hours and a water level of $>$30 cm above the beachface. Differences were also noticed after a recording time of $\sim$8 hours. At a water level of only centimeters above the beachface the swash exhibited a less distinct wave signal that was clearly reflected by p_5, but appeared to be significantly damped at p_{20}. After a recording time of $\sim$8.5 hours the pressure dropped significantly at both sensor. It should be emphasized that the pressure at p_{20} dropped almost instantaneously and at the same time as at p_5.

In figure 4, water levels on wave-resolving scale at p_{20} and p_5(+ 15 cm for easier comparison to p_{20} were compared for four different times during the tidal cycle. The wave signatures varied for the different times. During the early rising flood tide and an average water level of 30 cm above the beachface (Fig. 4 upper left) long-period oscillations ($\sim$15 s) superimposed by shorter period, irregular waves ($\sim$4-6 s) were observed. The long-period and larger amplitude oscillations were reflected

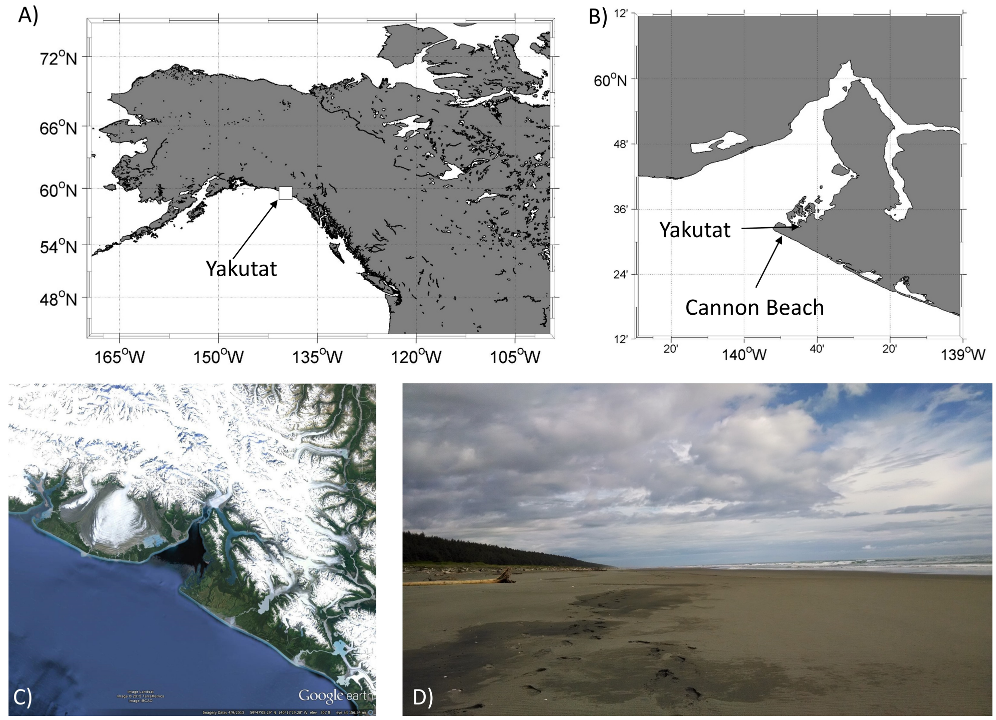

Fig. 1. A) Location of Yakutat, AK. B) Zoom into the Yakutat Bay area indicating the city of Yakutat and the survey area Cannon Beach. C) Google Earth image showing the presence of mountain ranges and glaciers. D) Photograph of Cannon Beach.

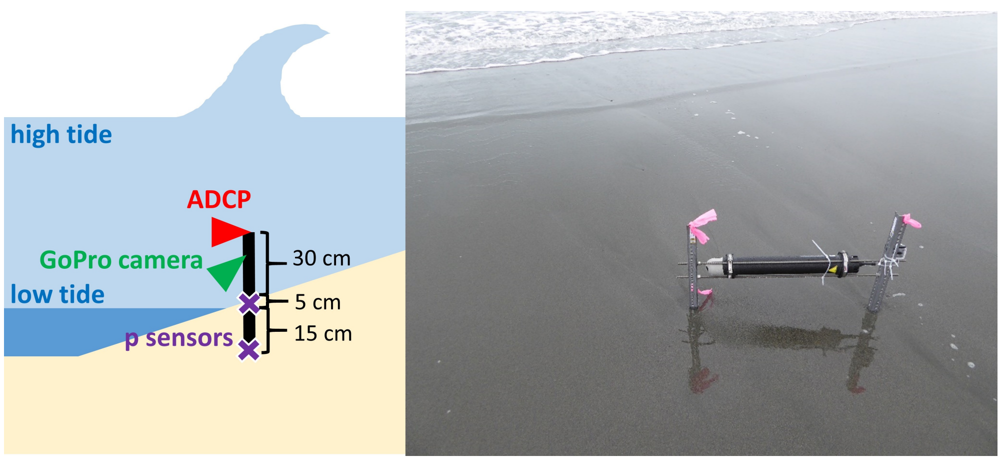

Fig. 2. Left) Conceptual sketch of the instrumented frame (not to scale). Right) Photograph of installed frame.

by both sensors. However, a number of deviations between the records were noted. With regard to the wave troughs, p_{20} often did not undergo the full pore pressure relief as indicated by p_5. Instead, pressure was more sustained. In some cases, the pressure peaks associated to wave crests at p_{20} exceeded the recorded values of p_5. Generally, the disagreement was most obvious with regard to the short period fluctuations. However, a phase shift was not noticeable. Around high tide (Fig. 4 upper right), the wave signals were more regular and were characterized by a wave period of $\sim$6.5-7.5 s. They exhibited a pitched-forward sawtooth shape. As observed on the rising flood tide, p_{20} was often characterized by sustained pressures under the wave troughs, but at this time, also damped pressures under the wave crests. Increased pressure peaks at p_{20} as noticed earlier were not observed. During the falling ebb tide and water levels of approximately 50 cm above the beachface (Fig. 4 lower left) wave signals became more irregular again. With occurrence of such irregularities, deviations between the two sensors were also more distinct. In this case, three pressure peaks of p_{20} exceeded the wave crest height recorded by p_5. In one of these cases, a significant pressure peak indicating 20 cm of water elevation corresponded to only 2 cm of water elevation measured by p_5(+15 cm). This followed an insufficient pressure relief in a wave trough. However, in another case, 20 cm of pressure head were sustained during a large wave trough, but no significant increase in pressure for the following crest was observed. With the approach of the swash zone of the retreating ebb tide (Fig. 4 lower right), a rapid increase of water level was observed with the incoming uprush, followed by a short sustaining of the water level and then

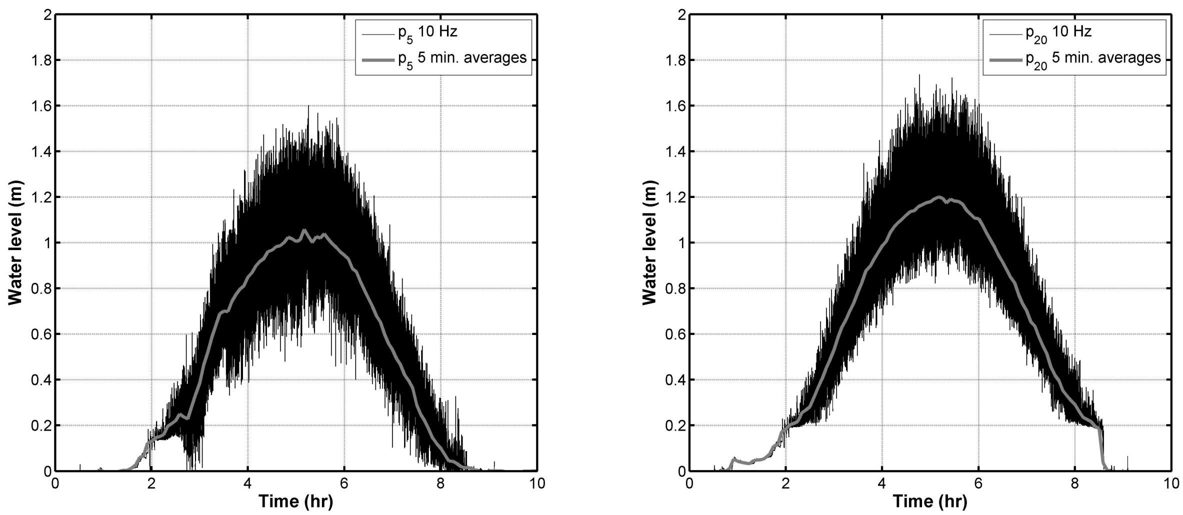

Fig. 3. Left) p_5 recordings and 5 minutes averages. Right) p_{20} recordings and 5 minutes averages.

	h_{s5} **(cm)**	h_{s20} **(cm)**	h_{sADCP} **(cm)**
flood	45	40	47
high	59	56	58
ebb	31	28	32
swash	6	17	

TABLE I. SIGNIFICANT WAVE HEIGHT DETERMINED FOR AN HOUR DURING FLOOD, HIGH AND EBB TIDE, AND THE RETREATING EBB TIDE BEGINNING SWASH, RESPECTIVELY.

a slower pressure decrease with the backwash. These signals were overall quite irregular in water level and superimposed fluctuations, but higher pressures were consistently recorded by the p_{20} sensor compared to p_5(+15 cm).

The significant wave heights h_s were determined for one hour of wave recordings during flood, high, ebb tide and the beginning swash zone of the ebb tide (Tab. I). Consistently with the above described observations the waves were damped at a sediment depth of 20 cm compared to a sediment depth of 5 cm for the surf zone. The significant wave height was found to be 3-5 cm smaller at the deeper buried sensor. However, this was not true during the approaching swash when $h_{s20} \gg h_{s5}$ (Tab. I). Significant wave heights were also determined from the pressure recordings of the ADCP. Due to the different sampling rate and possibly small shifts in the timing of the respective hours, some deviations must be expected, but overall the $h_{sADCP} \approx h_{s5}$ (Tab. I).

The ADCP recorded cross-shore flow velocities in excess of 1 m/s with the highest flow velocities being $\sim$1.4 m/s. The sieving of sediment samples confirmed medium sand (d_{50}=0.3 mm). Thus, sediment mobilization can be anticipated according to the Hjulstrom diagram [22]. This was confirmed through the underwater videos. Due to the short battery life, videos were only recorded over the first hour after the camera was switched on when the average water depth reached about 20 cm and it was still feasible to wade out to the frame. Over the recording time, the videos documented a significant amount of sand that was transported as bedload and suspended load with the back- and forward motion of the waves (Fig. 5). A net transport direction could not be determined from the video, while rather short and intensive shoreward and slower but longer seaward transport was noted, in accordance with the wave signals.

IV. DISCUSSION

The installation of the sensors suite was quick and simple. The data was acquired as desired. A number of observations were obtained from the data set. Regarding infiltration and exfiltration on the tidal scale, the development of a small and constant head of water was observed at a sediment depth of 20 cm noticeably earlier than pressure was recorded at a sediment depth of 5 cm. This likely represented the water table that is known to extend from the instantaneous water level as well as the mean water surface further up and into the beachface [23]. The rapid exfiltration was more unexpected and differed significantly from the observations by Stark and Hay (2014) at a mixed sand-gravel mega-tidal beach. It may be explained with the development of a seepage face that would allow a rapid drainage as soon as the mean water level sank below the measured elevation [24], [25]. No indication for distortion or asymmetry of the tidal curve as described by e.g. Nielsen (1990) was observed [24]. This may also be associated to the rapid drainage behavior.

The change from sinusoidal to nonlinear and irregular waves with wave shoaling and in the surf zone has been documented by many authors before. Elgar and Guza (1985) showed water elevation versus time profiles being characterized by a more sawtooth shape and bispectral signals [26]–[28]. The observed wave signatures at Cannon Beach exhibited similar characteristics. Bispectral signals, as well as the forward-pitch were obvious in the wave signals. Focusing on the pore pressure response, damping of the wave energy with sediment depth was observed in the inner and middle surf zone (here represented by the observation periods during flood, ebb and high tide). This is consistent with field results presented by Stark and Hay (2014) and Stark et al. (2014), as well as

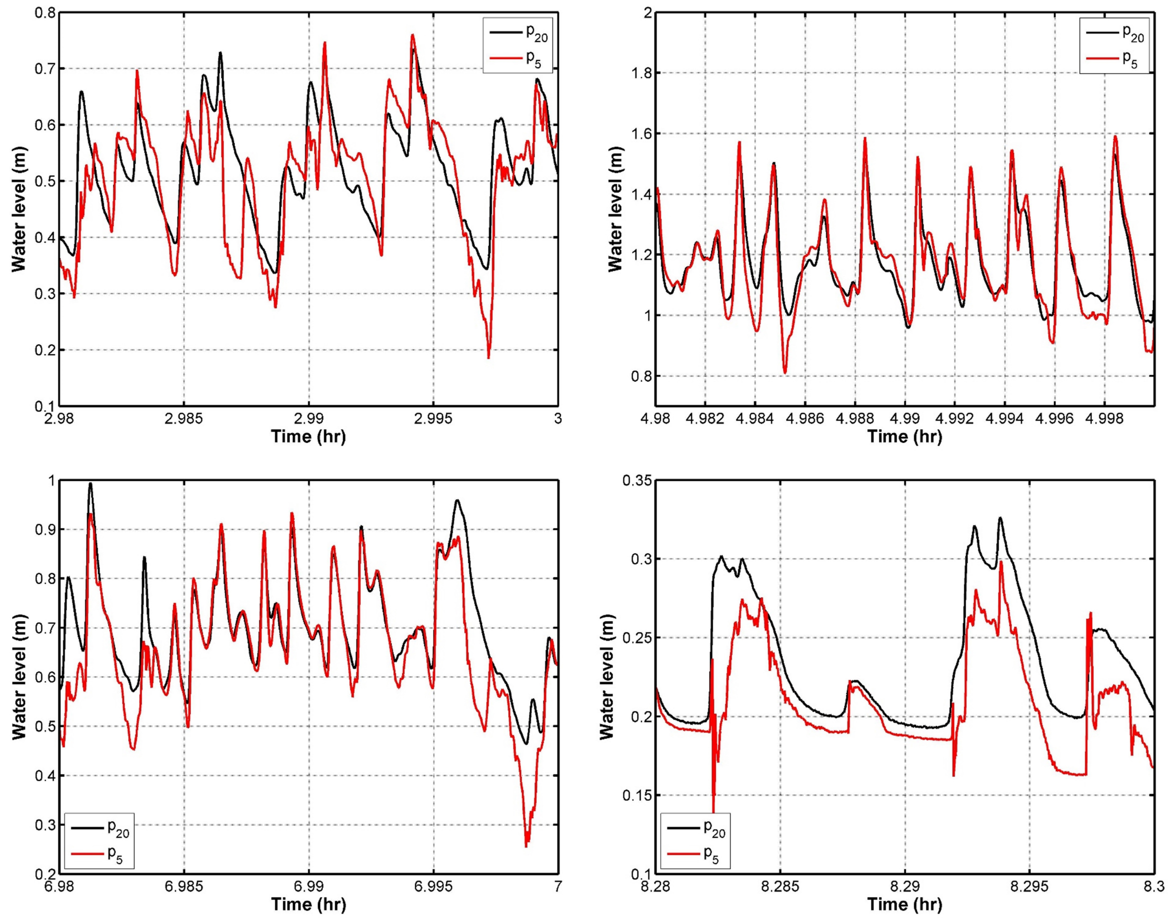

Fig. 4. Water levels at p_{20} (black) and p_5+15 cm (red) at wave-resolving scale derived from at four different recording times (see Fig. 3). Each graph represents 1.2 minutes of recordings. The original values of p_5 were added by 0.15 m for easier visual comparison.

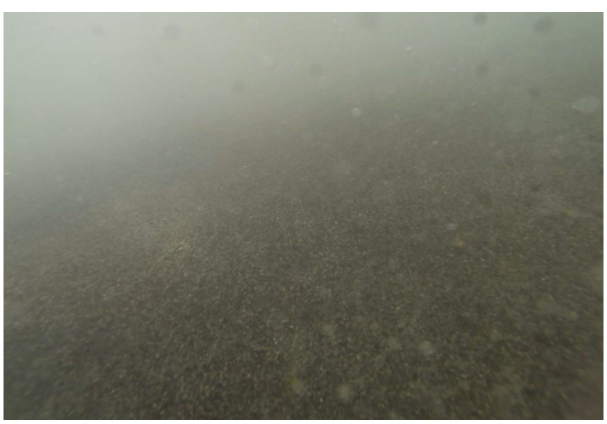

Fig. 5. Extracted frame from the GoPro video.

the laboratory and computational work by Yamamoto (1982) [9], [21], [29]. However, while the latter author pointed out that the wave damping by sand was rather small, here wave damping was noticeable even at small sediment depths of only 20 cm.

Pore pressure build-up due to ocean waves have been investigated by a number of authors [10], [11], [30]–[34], and is still focus of many recent and and ongoing studies [14], [16], [18]. Also, the issue of the irregularity of ocean waves has been recognized in this context. Lee and Focht (1976) suggested to translate the actual irregular wave record into equivalent uniform stress cycles which could then be tested more easily in the laboratory [35]. However, the issue of pore pressure response due to surf zone hydrodynamics has not been addressed by many studies. While this has not been of large interest for offshore structures such as oil and gas rigs, this issue may become more important for structures which may be located in the nearshore zone or on shoals. The very limited data set obtained here seemed to suggest that particularly wave irregularities, and possibly also the bispectral nature of waves in the surf zone may lead to a higher susceptibility to the sustaining of pore pressure and/or pore pressure peaks. A larger record of pore pressure data would allow more detailed insights into this question, and may represent a suitable data set to develop a numerical model of the issue. Unclear is also the interaction to ongoing sediment dynamics. Even if liquefaction does not occur, pore pressure peaks may weaken the sediment matrix and make it more susceptible to erosion.

The pore pressure records of the swash zone are similar to records presented by Turner and Nielsen (1997) who investigated the impact of rapid water table fluctuations on swash zone sediment dynamics [36]. These authors deployed a vertical pore pressure sensor array in the swash zone with sensors buried at a sediment depth of 4 cm, 19 cm and 34 cm. Similarly, to the records from Yakutat, each sensors displayed very similar signals with regard to shape. Differently to the observations at Cannon Beach, the pressure fluctuations decreased in magnitude from the sensor at 4 cm to the one at 19 cm, and remained stable from the sensor buried at 19 cm to the sensor buried at 34 cm. The reason for increased pressure at the deeper buried sensor in the swash at Cannon Beach cannot be clarified here, but groundwater dynamics are likely playing a role here. More investigations and discussion are required to explain this process in detail.

The presented instrument configuration delivered detailed information on the pore pressure response to wave action in the surf and swash zone. As the sensors were rated to a water depth of up to 50 m, this sensor suite could also be deployed in coastal areas with deeper water depths. Based on the interesting results, a pore pressure array possibly complemented by a horizontal- or upward-looking ADCP seems to be a tool of high interest for further investigations of pore pressure response in the nearshore zone, as well as at offshore and ocean renewable energy converters. Different configurations could be imagined. A lance could be developed having a number of vertically arranged and synchronized pressure sensors (Fig. 6). A sharp tip of the lance would allow deployment through pushing into the sediment, suggesting the addition of a Cone Penetration Test tip that would measure tip resistance and sleeve friction upon penetration for further interpretation of soil mechanical properties in-situ. The lance concept would also allow most direct contact to the soil and limited disturbance during deployment. The pressure sensors could be arranged at desired sediment depths through a variable inlet system and the lance could also be variable in length through extension rods, for example. The addition of an ADCP would deliver additional information on flow conditions. A camera could also easily added to monitor sediment transport. Batteries could be housed within the lance or in a buried support package at a few meters distance. Data could be stored internally or a release mechanism may support a buoy that sends data through the mobile network or the Iridium satellite system. The latter could especially be realized if a support package would be deployed. For beach applications or applications close to structures also cabling may be considered. Such an instrument would be helpful for the detailed investigation of ongoing sediment dynamics and corresponding pore pressure evolution, providing data sets for calibration and validation of simulations, and may at the same time serve as a long-term monitoring tool to identify risky sea states ahead of time to possibly apply mitigation strategies.

V. Conclusion

A preliminary study recording pore pressures at a sediment depth of 5 cm and 20 cm at a wave-dominated medium sand beach in Yakutat, Alaska, was presented. The measurements covered approximately eight hours from the accelerating flood tide over high water to the decelerating ebb tide, and water levels from a dry beachface to about 1 m, due to its fixed position in the lower intertidal zone. The recordings of the buried pressure sensors were complemented by pressure recordings and flow velocity measurements using an ADCP

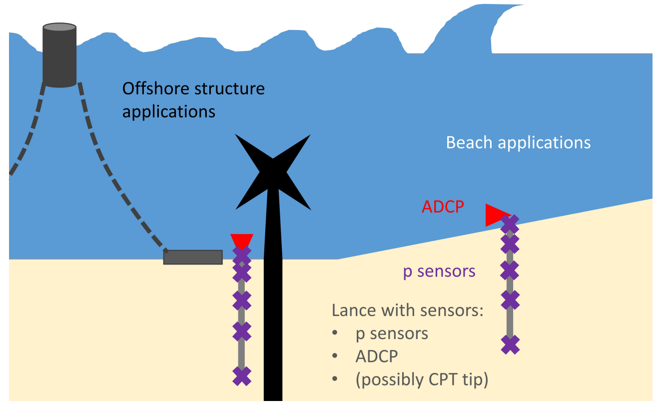

Fig. 6. Conceptual sketch (not to scale) of concept and possible application of a instrumented pore pressure lance.

and by underwater video recordings. It succeeded to derive tide and wave characteristics, and their deviations at the respective sediment depths and tidal phases. Specifically, the following observations were made:

- No shift or distortion of the tidal curve was noted with increasing sediment depth.
- During the rising flood tide, groundwater reached a sediment depth of 20 cm before the actual water level reached the location. However, drainage was rapid.
- Inner and middle surf zone wave characteristics featured a forward-pitched sawtooth signature and bi-spectral behavior. Wave irregularity was increasing with lower water levels.
- Wave damping with sediment depth was observed in the surf zone, while the pressure at a sediment depth of 20 cm exceeded the pressure at 5 cm in the swash zone. The latter is possibly related to the groundwater dynamics.
- Sustaining of pressure and incomplete pressure relief in wave troughs was observed and increased with wave irregularity. The latter also led to some pore pressure peaks at a sediment depth of 20 cm.

The study represents a proof-of-concept for a sensor configuration to investigate pore pressures at the beach, in the nearshore zone and in coastal areas, being also suitable for deployment in the direct vicinity of structures. Next steps will include the acquisition of longer data sets, the investigation of specific questions resulting from the presented study, the development of a lance system and the deployment in the vicinity of structures of interest. A concept was presented for a novel pore pressure lance with options for complementary instruments such as a commercial Cone Penetration Test (CPT) tip and/or an ADCP that would contribute to the understanding of pore pressure evolution at beaches and in the vicinity of coastal structures, and specifically, offshore and ocean renewable energy converters in coastal areas and the nearshore zone.

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