Measuring Wave Impact on Coastal Structures with High Spatial and Temporal Resolution – Tactile Pressure Sensors a Novel Approach

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ABSTRACT: Wave impact forces on coastal structures have been measured and studied both in the laboratory and in the field since the last century. Traditionally, pressure measurements in laboratory studies are performed by using an array or few arrays of pressure transducers placed in the middle of the structure, where the maximum pressures are commonly assumed to occur. The impact forces are then calculated by spatially integrating the point measurements of pressures. Thus, the existing knowledge on the vertical distribution of impact pressures on vertical/sloped walls is quite well established. However, for breaking wave impact on coastal structures producing impulsive loads with very short duration, the pressure distribution is not well known. This is because the impact pressures resulting from breaking waves are highly variable both temporally and spatially, and often far from being two-dimensional. As a result, current predictions of resultant forces from one dimensional array may considerably vary from the actual loads and therefore give conservative or under predicted loads. Hence, there is a strong need for a pressure measurement system with very high spatial and temporal resolution, which could be met by tactile pressure sensors. In a collaboration between the University of Southampton, UK and Forschungszentrum Küste (FZK), Germany within the framework of the HYDRALAB IV project the wave impact pressure distribution on a sea dike of 1:3 slope was mapped by use of a tactile sensor over an area of 42 cm x 48 cm. Preliminary experiments were carried out in the Large Wave Flume (Grosser Wellenkanal, GWK) in Hannover. This paper describes the details of this novel measurement technique and its application in laboratory experiments. A calibration procedure for dynamic loads, which is an indispensable matter as the sensors response differently on static and dynamic loads, has been developed. Challenging issues of employing the sensor in large scale experiments such as removing the entrapped air or making the system water proof have also been explored.

KEY WORDS: Tactile sensor, Impact forces, Pressure distribution, Sampling rate, Dynamic loads.

1 INTRODUCTION

Coastal structures such as seawalls, breakwaters and storm surge barriers are often damaged by wave action each year. Wave impact loads may vary between slowly-acting pulsating loads and more intense impulsive loads. Particularly, the breaking wave impact loads on such structures can be extremely high in comparison to the pressures exerted by non-breaking waves, and can lead to structural failure. Since the 19th century much research endeavor has been devoted to wave forces on seawalls. Although, loading due to non-breaking wave is well understood (e.g. Goda’s method), the assessment of impact loads due to breaking waves is still an open issue. This is mainly due to the highly stochastic nature of the wave impact forces and the underlying processes, which are very difficult to understand and interpret. Because
of the uncertainties involved in theoretical modelling of breaking wave impact loads, the phenomenon is often investigated in laboratories.

In most of the laboratory experimental studies, pressure measurements are acquired by using an array of pressure transducers, placed vertically at the middle of the structure as shown in Figure 1. Forces acting on the structure are then calculated by integrating the point measurements, assuming a uniform pressure distribution between the sensors. Although there is considerable knowledge existing regarding the vertical pressure distribution of impact pressures, present knowledge of the spatial pressure distribution is very limited.

![Figure 1 Traditional way of measuring pressure distribution on structures (Cuomo et.al., 2010).](image)

Recent field and laboratory investigations verified that unexpectedly high pressures may locally occur, e.g. Bullock et al. (2003, 2007). Even for high aeration impacts, which were often thought to result in reduced impact pressures, overall forces and impulses can become significantly larger due to the presence of pressure regions with increased spatial extent and duration (Bullock et al., 2007). This highlights the importance of spatial resolution of the pressure measurements in laboratory experiments. However, using a large number of pressure transducers is neither practical nor cost effective. Hence, there is a need for a novel measurement technique with high spatial and temporal resolution in order to investigate the impact pressure distribution in more detail.

Tactile pressure sensors are a relatively new technology, which has already been well established majorly in the field of medical and automobile researches, where the type of load is essentially quasi-static, measured in dry environments. The application in water, especially for highly dynamic measurements like breaking wave impacts, is very challenging and has not been tried until recently. For the first time, Stagonas et.al (2011) achieved simultaneous mapping of the horizontal and vertical distribution of wave impact pressures at the face of a vertical seawall in a small scale model. Following the first application of tactile sensors in a water environment, a further step has been taken within the framework of the HYDRALAB IV project, where an improved calibration procedure was developed and the challenging application of the sensor in large scale experiments was explored for the first time.

The experiments were carried out on in the Large Wave Flume (Großer Wellenkanal, GWK) of Forschungszentrum Küste (FZK) in Hannover, Germany. Stagonas et al. (2012) briefly describe the experimental set-up and calibration procedure and also present some of the first results from pressure mapping. The aim of the current paper is to thoroughly describe the tactile sensor technique with regard to breaking wave impact pressure mapping, to provide more details on the calibration procedure for dynamic loads and to point out the challenges and limitations when applying the sensor in large scale physical model experiments on breaking wave impacts on coastal structures.
2 TACTILE SENSORS

2.1 Introduction
A tactile sensor is a device or system that can measure a given property of an object or contact event through physical contact between the sensor and the object (Lee and Nicholls, 1999). These sensors are employed when the interaction between a contact surface and the environment needs to be measured and registered. Tactile sensors are extremely thin (0.1 mm) and flexible, available in a wide range of sizes, shapes and spatial resolutions. The matrix based sensors are able to record real-time static and dynamic loads with very high spatial resolution at a reasonable sampling rate. Sensing locations within a matrix can be as small as 0.04 mm², which means an area of one square centimeter can contain up to 248 of these locations. The sensors are capable to measure pressures ranging from 0-15 kPa to 0-175 MPa with a maximum sampling rate up to 20 kHz in a 44 load cell configuration (www.tekscan.com). However, each application requires an optimal match between the measurement area, spatial resolution and the pressure range provided by the manufacturer.

2.2 Typical layout
A sensor consists of two thin flexible polyester sheets, with silver conductive electrodes printed on them. One sheet has a semi-conductive “ink” deposited in a pattern of rows while the other sheet has the “ink” deposited in a pattern of columns. These two sheets of polyester are glued together at the edges. A typical layout of a basic sensor and its main components is shown in Figure 2(a). The intersection between a row and a column creates a sensing cell referred to as ‘sensel’ (Tekscan, 2003). A detailed view of such an intersected area forming a sensel (blue square) is shown in Figure 2(b). Within a sensel, a portion is “live”, and the rest of the area is “dead” or non-responsive. The live area of a sensel is where the silver traces of a row and a column intersect (indicated in red). The system reports pressure related to the entire sensel area, regardless of what percentage of the active sensel area is being loaded or in physical contact. The area outside of intersection is dead, because it lacks contact between the two pressure sensitive layers of ink.

The intersecting area is thicker as it has four layers in addition to two substrates: two of silver traces and two of pressure sensitive ink. The non-responsive area/dead area is the thinnest portions between the sensing areas. Careful consideration needs to be given for the material interface when loading the sensor with an object, which has a hard surface. It is recommended to use a compliant material such as foam rubber. This will distribute the load uniformly over the loading area by cushioning the high points of contact, and filling-in low points of contact. In other words, a compliant material improves the contact between the surface of the sensor (the thinnest portions) and the load. A cross-sectional view of a sensor loaded with infinitely compliant material is shown in Figure 3.

![Figure 2](attachment:figure2.png)

**Figure 2** (a) Typical layout of a tactile sensor (b) Detail view of intersection (Tekscan, 2003).
Matrix-based tactile sensors have entrapped air between the two layers of thin films, which can produce a ‘cushioning effect’ when the sensor is loaded larger than the active sensing area. This means that the entrapped air bears part of the applied load, and the active parts of the sensels are not loaded properly. This will lead to influence the sensor output as the system tends to deliver lower pressures than the actual load. Therefore, it becomes crucial to set up a method to remove out the trapped air inside the sensor. A careful consideration has been given in this study to reduce the influence of the entrapped air.

Figure 3 Sensor loaded with infinitely compliant material (Tekscan, 2009).

2.3 Working mechanism

The sensor works with a resistive-based technology, which means the resistance of the active sensing area varies inversely with the applied load. Figure 4 shows the typical performance of a tactile sensor. When there is a force being applied on the sensor surface, the system isolates the location where the pressure sensitive ink layers (in rows and columns) come into contact, which completes the circuit. Each sensel is a force sensitive variable resistor, whose resistance changes from above 10 Mega Ohms (with no load) to less than 20 Kilo Ohms (when fully loaded). The applied force is determined by the change in resistivity through the circuit and the distribution of the force over the active area is thus determined. The sensor system provides a digital output with 8-bit resolution, which means that each sensel records a raw value between 0 and 255. The cell is considered as saturated when it reads 255, which is the highest pressure indicated by the system. The system linearises the sensor output into digital counts on a scale from 0-255 over the measurement range, the output resolution depends on the capacity of the sensor (i.e. the upper limit of the pressure).

Figure 4 Typical sensor performance (www.tekscan.com).

2.3.1 Scanning rate (sampling frequency)

The sensor reads out the applied load similar to a scanning system, which means the sensor array and its sensels are read-out in a time-by-time manner. The individual sensel has a response time of about 20 µs (50 kHz). However, all the sensels of a sensor are not detected at exactly the same time. For example, if the scan rate is 100 Hz, and the sensor has 43 rows and 51 columns, then the signal of the first detected cell (located in row 0, column 0) would be 10 ms older than the signal detected at the last cell.
(located in the row 43 and column 51). The order of which row or column is scanned depends on the sensor model and electronic routing of the lines inside the sensor. The sampling rate of the sensor is linked to the total number of rows and decreases with increasing amount of rows. For instance, a sensor with only one row and 44 columns can sample at a rate of 20 kHz and this will reduce to 3-4 kHz with 6 rows. There is a time lag associated with scanning from one row to other row because of the existence of residual voltage from the previous time step.

2.3.2 Sensor pressure range

The pressure range label of most of the sensors represents the pressure corresponding to a digital output of 200 instead of 255. This pressure range label is called “P200”. This provides some ‘headroom’, which allows registering peak pressures even if the applied load exceeds the upper limit of the sensor. Furthermore, the pressure range of the sensors can be changed by adjusting the sensitivity, i.e. the amplification of the sensor output. This feature is available for some Tekscan scanning electronics, such as Evolution Handles. The adjustable sensitivity can change the P200 value up or down, typically by a factor of 2 up and factor of 5 down. For example, a sensor labeled as 100 PSI (i.e. P200) with a resolution of 0.5 PSI (100/200); with lower sensitivity, it might be able to behave as a 200 PSI sensor with a resolution of 1 PSI; alternatively with higher sensitivity, it may be able to behave as a 20 PSI sensor with a resolution of 0.1 PSI.

2.4 Pressure mapping method

The sensor system consists of several components, which are essential to record a measurement. A simplified sketch of the whole pressure mapping system is shown in Figure 5. Each sensor has a tab which must be clipped into the Data Acquisition Handle, containing the measurement electronics. The detected signal is then passed into a hub acting as a gateway between the handle and the PC (Tekscan, 2009). The hub allows parallel recording of 8 sensors in one system. Special software on the PC enables the user to record, store and analyze the data later. The software records the data as a movie, which consists of several frames. In each frame, every sensel of the sensor records pressure as a raw digital value between 0 and 255. The software also provides a pressure-time history for each movie, where the pressure is termed as contact pressure representing the sum of the entire digital outputs divided by the number of active sensels.

![Figure 5](image_url)  
**Figure 5** Simplified sketch of tactile sensor pressure mapping system.

2.5 Sensor model/map used for the current study

The sensor model/map (5315) used in this study is shown in Figure 6. This sensor has a matrix area of 42 cm x 48 cm, with a sensel density of 1 sensel/cm² and a number of 2016 sensels in total. The active portion of a sensel is about 38% of the entire sensel area. However, this is unimportant for the present study since the loading area is several times larger than the area of one sensel. This sensor model is able to sample the data at a maximum rate of 680 Hz, with a pressure range from 0 to 5 PSI (0 to ca. 35 kPa). The tab length is only 13 cm, which means that the handle is close to the actual sensing area. This is one of the major challenges to be faced for the present application as the handle needs to be protected from water and wave action during the experiments.
The sensor has external vents by production, to allow the trapped air inside the sensor to escape when a part of the active sensing region is loaded. Water or liquids can quickly enter through these vents, which may lead to end the useful life of the sensor. This creates another major challenge for the present study, since the sensor has to be submerged in water throughout the experiment, an extra precaution is required when sealing the sensor edges.

![Figure 6 Tactile sensor model used for the present study (www.tekscan.com).](image)

### 2.6 Limitations of the sensor

Although the tactile sensor technique provides various unique features, which are a benefit for the users in several fields of study, there are certain limitations that should be kept in mind when employing the sensor in water for wave impact studies. The main limitations of the sensor with regard to the pressure mapping on coastal structures under breaking wave impact are discussed in the following.

**8-bit system:** As previously mentioned, tactile sensors are an 8-bit system, opposed to traditional pressure transducers, which are natively analog and usually digitized with 16-bit data acquisition systems. The tactile sensor system linearizes the sensor output into digital counts on a scale from 0 to 255 and a calibration factor (or curve) converts the raw output into engineering units, like kPa. In this present study the pressure range is from 0 to 35 kPa, which gives a resolution of 0.175 kPa (35/200). This is approximately equivalent to 1.8 cm water column. When using a sensor with a higher pressure range, for instance 0 to 1000 kPa, the resolution would increase to about 50 cm water column. Simultaneous measurements of high impact and low quasi-static pressures therefore become a challenging task and careful consideration needs to be given for the pressure ranges when selecting a sensor.

**Sampling frequency:** The sampling frequency of the sensor is related to the number of sensing elements (actually the number of rows) and decreases with the increasing amount of sensing cells. Although smaller sensors (eg. 10 cm x 10 cm) with high scanning rates (4 – 20 kHz) are available, they are too small for wave impact studies on a large scale. On the other hand, going for larger sensors will end up with having smaller sampling rates (100 - 700 Hz). Studies related to wave impact essentially require a measurement system with higher sampling rate (in the range of several kHz) as the impact loads are often
shorter in duration. An optimization is required between the sampling rate and the matrix size when selecting a sensor model. Considering the standard sensor models available presently, with a number of 2000 sensing elements (matrix size about 0.5m x 0.5 m) a maximum sampling rate of 680 Hz can be achieved. This rate is still not sufficient to capture very high impact loads (in a large scale physical modelling).

**Entrapped air inside the sensor:** Unlike static loads, dynamic loads (impact loads) are much shorter in duration. Moreover, when the loading area is larger than the active sensing area, the trapped air inside the sensor has no way to escape and can produce a ‘cushioning effect’ during loading, which can influence the sensor output significantly. Thus it is highly important to make sure there is no entrapped air inside the sensor during the (dynamic) loading process. Otherwise, severe errors in the measured values cannot be avoided. A vacuum pump can be used for this purpose, yet it is a challenging task to maintain a stable vacuum throughout the experiment.

**Waterproofing the sensor:** Although, according to the manufacturer, tactile pressure sensors are splash proof they are not waterproof. This is related to both the presence of air-vents and the nature of the material used for manufacturing the sensor. As such, the sensor requires tight waterproofing before it is exposed to water. In addition, the handle (the most expensive component of the whole system) needs to be protected against water and also from the wave action. It becomes even more challenging when the handle is close to the sensing area (i.e. in the impact zone) as it can be washed away with violent action of waves.

### 3 CALIBRATION

#### 3.1 Need for a dynamic calibration

Calibration is the method by which the digital sensor output (raw output) is converted into actual engineering units (kPa). The standard static calibration procedure consists of applying a known weight over the sensing area and correlating the digital output to the applied load. Although this calibration procedure is simple, it cannot be used when dynamic loads are involved in the actual application as also pointed out by Stagonas et.al (2012). This is mainly because of the duration of the load involved, which is much shorter in the case of dynamic loads (few milliseconds), and longer in the case of static loads (seconds to minutes). Therefore, it is extremely important to ensure that the calibration load applied resembles the nature of the load expected in the application as closely as possible. Since the present study aims at measuring wave impact loads, which are dynamic in nature, an appropriate method is required to calibrate the sensor for dynamic loads.

#### 3.2 Calibration set-up and procedure

Developing such a calibration procedure for dynamic loads is a challenging task since the calibration load must mimic the nature of the application. The main controlling factor is the sampling frequency of the sensor, which is limited to 680 Hz. This means the rising time of the load should not be shorter than 15 ms, keeping in mind that at least 10 data points are necessary to define the pressure peak accurately (10/680 Hz). Furthermore, full contact must be achieved over the loading area, i.e. the sensor must be evenly loaded.

Ideally, the calibration should be done for loads produced by water impact since the application of the sensor in the present study involves impact loads due to breaking waves. This implies a liquid-solid interaction. However, calibrating the sensor against waves is practically impossible as the applied load during the impact over the sensing area must be known, which is very difficult to measure accurately and cannot be calculated as no reliable formula exists. Hence, a calibration method has been developed with the use of a pendulum, which produces dynamic loads at the sensor surface. Although the loading interface in this case does not resemble the liquid-solid interaction, the response of the sensor to calibration loads is kept to be as close as to the nature of the dynamic loads expected during the experiment.
3.3 Pendulum set-up

The experimental set-up of the pendulum and the pressure sensor is illustrated in Figure 7(a). A picture taken during the experiments is given in Figure 7(b). The pendulum mass and the length of the rod are designed by taking into account the pressure range of the sensor. The upper end of the pendulum is mounted on a rigidly fixed vertical plate, while the lower end is left to swing freely. The tactile sensor is placed on the plate with the sensor tab facing downwards where it is connected to the handle. The location of the pressure sensor is fixed, while the hinge of the pendulum is constructed to be movable both horizontally and vertically, so that loading can be applied at different positions of the sensor. The lever arm of the pendulum can also be adjusted, so that the contact surface becomes parallel to the sensor surface during the impact.

The pendulum is equipped with a force transducer with a nominal load of 2 kN and a sampling frequency of 2000 Hz. The dimensions of the square plate (6 cm x 6 cm) have been chosen, by taking into account the lateral force limit of the transducer. The loading area during impact in this case is limited to 0.0036 m², in other words only 36 sensels out of 2016 sensels can be loaded. Nevertheless, the above experimental setup allows repeating the procedure at different locations of the sensor surface. In this way, the validity of the calibration over the whole sensing area can also be verified. A sponge material with the same dimensions as the metal plate is fixed on the impacting surface to achieve good contact with the sensor surface during loading. Two more layers of such sponge material are added to improve the contact while damping out very short peaks during the impact. This enables the sensor to capture the peak pressures even with the comparably low sampling frequency of 680 Hz.

3.4 Calibration curve

The required load range is achieved by increasing the drop height of the pendulum mass gradually to a point where the sensels are about to saturate. Initially a vacuum pressure equivalent to 10 DO (or 5 % of the full range) is applied. The calibration curve is then obtained by comparing the peak forces recorded by the transducer with the corresponding peak pressure (digital output) delivered by the tactile sensor system (Figure 8). The vacuum pressure is subtracted from the peak values and the resulting values in digital

![Figure 7 (a) Simplified sketch of the pendulum setup (b) Experimental setup.](image-url)
counts (0-255) are displayed on the x-axis. Peak forces measured by the force transducers are divided by the contact area (of the sponge material) to convert them into pressures, and are shown on the y-axis. The final calibration function is obtained by fitting a second order polynomial through the data points. The curve as well as the function and the regression coefficient are also given in the figure.

![Figure 8 Tactile sensor calibration curve.](image)

As can be seen in Figure 8, there are no data points for lower and higher ranges of pressures (i.e. below 20 DO or 10% and above 170 DO or 85% of P200). This is due to the following difficulties encountered during the calibration procedure. It is hard to achieve good contact with the sensor surface for very low loads, which consequently leads to poorly distributed loads. On the other hand, when loading the sensor with too high loads, one or more sensels get saturated (showing a value of 255). Once a sensel reaches saturation, the actual load on it can be more than the upper limit of the sensor, which can be anything more than a factor of 1. This will lead to high uncertainties in the results, and therefore these data with saturated sensels have been omitted from the calibration curve. Despite this, when extrapolating above calibration curve/function to a x-value of 200 gives a pressure value close to 35 kPa, which satisfies the fact that the upper pressure limit of the sensor corresponds to a digital output of 200. However, the limitation with the lower pressure range should be kept in mind when applying above calibration equation for loads, below the curve range shown above.

### 3.5 Effect of vacuum

The effect of trapped air inside the sensor has been studied by performing the above calibration procedure with vacuum and without applying vacuum. During the experiments without vacuum, the foil (covering the sensor) was removed and the vacuum pump was disconnected. The data points for the calibration curve without vacuum were obtained in the same manner as explained above. Figure 9 shows a comparison of the two calibration curves obtained under the two conditions, with and without vacuum. In this plot the x-axis represents the applied load in kPa while the y-axis indicates the digital output of the tactile sensor.

The results clearly indicate that for a given applied load, the sensor delivers significantly lower output when there is no vacuum compared to the one with vacuum. This is because the entrapped air inside the sensor bears a part of the load, which in turn reduces the sensor output. This implies that the sensor output will largely underestimate the applied loads when the trapped air inside the sensor is not removed efficiently. The results obtained confirm that producing a vacuum is extremely important to attain reliable outputs, particularly when measuring impact loads.
The measurements were repeated with different levels of vacuum pressure (equivalent to 25, 40 and 60 digital outputs, i.e. 12.5%, 20% and 30% of P200) in order to ensure whether the amount of vacuum pressure has any influence on the sensor output. The results are compared to those obtained for a vacuum level of 5% (Figure 7) in Figure 10. The x and y axis are similar to Figure 8 and polynomial regression lines (2nd order) have been drawn for each data set. All levels of vacuum provide very similar results, suggesting that increasing the vacuum above 5% (10 DO) does not influence the sensor output. However, a minimum vacuum level of 5% is mandatory to obtain a reliable output. If measurements are going to be over a longer duration, it is advisable to produce an even higher vacuum level in the range of 10% - 15%.

3.6 Comparison of signals obtained by transducer and tactile sensor

The calibration measurements were performed with two different instruments at different sampling rates; tactile sensor system (680 Hz) and force transducer (2000 Hz). Above calibration curves were obtained by simply correlating the peak values acquired by both equipments, assuming that the peak values are accurately captured and coincide. To validate this assumption the characteristics of the time series are compared in the following.
Figure 11 presents pressure-time histories recorded by the force transducer and the calibrated tactile sensor during several impact events. A detailed view of a single impact event is shown in the same figure. The vacuum pressures corresponding to each impact are deducted from the recorded time series of the tactile sensor before applying the calibration equation. The rising time of the impacts recorded by the tactile sensor are in the range of 30-50 ms, and are comparable to those obtained by the transducer. This confirms that the tactile sensor has captured the peak impact events despite the lower sampling rate. After the peak value, the pressures recorded by the transducer drop to zero quicker than the tactile sensor pressure signal, i.e. just after an impact the tactile sensor requires some time to return to its original state. The longer falling time might be attributed to the decompression of the sponge material used at the loading interface, but further research is required to analyze the different behavior of the two sensors.

![Figure 11](image.png)

**Figure 11** Comparison of pressure-time histories recorded by the transducer and tactile sensor.

4 EXPERIMENTS

4.1 Experimental set-up

For the large scale test application of the tactile sensors in GWK, which has a length of about 300 m, a width of 5 m and a depth of 7 m, the limitation of the sensor were carefully considered. Since the tactile sensor available for this study had a limited sampling frequency (680 Hz), it was decided to perform experiments on a sloping dike (1:3 slope) for which previous experiments (e.g. Grüne 1992) suggest that wave impact loads are less violent and associated with longer durations compared to the loading on vertical walls.

A lot of preparations were required before deploying the tactile sensor inside water. Since the sensor was deployed in a large scale physical model for the first time, many challenges were encountered during this experimental study. The dike surface is made of concrete tiles, which means there is no continuous smooth surface where the sensor can be placed. Therefore, the sensor was initially attached to a smooth, thin aluminum plate and covered by a special foil (Kapton). A top view of the tactile sensor placed under water on the dike surface is shown in Figure 12, a cross sectional view of the dike is given in Figure 13.
All four edges of the foil are glued to the aluminum plate by using a special water proof adhesion (Tacky tape). Underneath the foil a vacuum equivalent to 25 DO (12.5 % of the upper pressure range of the sensor) has been produced, in order to remove the trapped air inside the sensor and to ensure the foil is in constant contact with the sensor surface. A thin tube connecting the vacuum pump was inserted into a tiny hole through the aluminum plate.

Protecting the sensor handle against water and wave action has been one of the major challenging tasks since it had to be connected to the sensor tab, which is very close to the sensing area. For this reason, the handle was secured in a tightly sealed box which was placed underneath the dike surface and the sensor tab was sent through a small slit in the aluminum plate and clipped into the handle, as shown in Figure 13.

### 4.2 Wave conditions
Experiments were performed with regular waves. Wave heights (H) ranging from 0.6 m to 1.0 m and periods (T) between 3 s to 6 s were considered. A summary of the wave conditions and water depths used for the experiments can be found in Stagonas et al (2012). Since the location of the sensor was fixed, the water level was adjusted to have plunging breakers of different wave heights breaking within the measuring area of the sensor. Wave parameters were recorded by 4 wave gauges installed along channel. Pressure measurements were conducted with the tactile sensor system and the impact events were also recorded by a video camera from the top of the flume.
4.3 Typical results of pressure mapping

A typical plunging wave impact event on the dike (H = 0.7 m, T = 4 s, water depth = 4.3 m) is analysed here in terms of force-time history, 2-D pressure distribution plots and pictures from the video. The force time history, obtained by multiplying the calibrated contact pressure with the contact area, is given in Figure 14 and pressure distributions at different stages (1-4 marked in Figure 14) are presented as 2D contour plots in Figure 15. Corresponding snapshots from the video data are also shown on the right of the figure. Since the frame rate of the camera was just 30 frame/s, these snapshots are not very accurately synchronized with the pressure records and just demonstrating the location and shape of wave breaking. The orientation of the pressure mapping plots in Figure 15 has been rotated to correspond to the orientation of the sensor during the experiments with the wave direction from top to bottom as marked by the arrow on the right.

The force time history shows a high peak followed by two small secondary peaks. The low force just before the high peak is indicated by stage 1 and the corresponding pressure mapping plot in Figure 15 shows very low pressures in the whole region of the sensor. It can be seen from the video snapshots that the wave front is not straight and has lots of irregularities. Hence, in the 2nd stage the plunging breaker tongue impacts the sensor surface on the left (in wave direction), which is clearly captured by the tactile sensor with a peak pressure of about 20 kPa. The force time history shows that the peak force is about 1.4 kN and has a rising time of about 45 ms, which is in the typical range for breaking wave impact loads on dikes, e.g. Grüne (1992).

![Figure 14 Force-time history of a breaking wave impact (H= 0.7m, T=4 s, WL=4.3 m).](image)

The rising time is also within the range of those recorded during the calibration measurements. As the wave plunges over the surface of the dike, a large amount of air is being trapped; this is then compressed and stretched as the wave proceeds forward, which gives a rise in the force indicated by the second (stage 3) and third small peak (stage 4) in the force-time history.

Overall, 2D pressure mapping plots provide realistic distribution of pressures, linking the shape of the wave during breaking. Some of these results have already been reported in Stagonas et.al (2012). It should be kept in mind that the area of measurement in this study is limited to 0.42 cm x 48 cm, which has a length of 0.42 m in the direction of wave. This area does not fully cover the impact zone of a plunging breaker on the dike surface. The maximum impact pressures are reported to occur over the location from -1.0*H to +0.5*H with respect to SWL, which implies a vertical distance of 1.5*H. Therefore the measurement area in the present study is not really sufficient for an in-depth analysis of the processes related to the breaking wave impact. In future experiments, the measurement area must be increased by several times compared to the current study.
Figure 15 2D Pressure mapping contour plots and pictures of impact event at 4 stages shown in Figure 15.
5 CONCLUDING REMARKS

In this study an investigation has been made to explore the application of tactile sensor in mapping pressure distribution on coastal structures. Calibrating the sensor against impact loads has been a major challenging task as there is no standard procedure available for this. A calibration method for dynamic loads was developed by use of a pendulum. Various measurements conducted during the calibration phase improved the understanding of sensor behaviour for impact loads. Removing the entrapped air inside the sensor is an essential step when measuring impact loads; this was done by using a vacuum pump. Maintaining a steady vacuum pressure during the measurements is important and a minimum vacuum of 5% (of P200) is mandatory. Furthermore, increasing the vacuum level does not influence the sensor output, but might be advisable for longer running tests.

Application of tactile sensor in water, especially for highly dynamic events like breaking wave impacts requires high level of precaution against water and wave action. The challenging issues related to the installation of the tactile sensor including the data acquisition handle and waterproofing the whole equipment have been addressed in this study. The experiments with regular waves were performed in the Large Wave Flume (GWK) in Hannover on a dike (slope of 1:3). Pressure mapping was conducted with tactile sensor over an area of 42 cm x 48 cm, which consists of 2016 number of sensing elements, sampled at a rate of 680 Hz. Plunging breaking waves over the sensor surface were considered during the analysis. Such impact events resulting from different wave conditions have been analyzed in terms of 2D pressure mapping plots, video data and force-time histories. The tactile sensor pressure mapping results proved to give realistic distributions of the impact loads, which also follow the shape of the impacting wave tongue.

Pressure mapping acquired by the tactile sensor provides unique highly resolved spatial information of the load distribution, which can play a key role in interpreting the physical processes related to the wave impact. Yet, the sensor has certain limitations, such as being only an 8-bit system (output scale of 0 – 255), leading to rather low output resolutions and having a rather low sampling frequency (680 Hz), which may not allow to capture high pressure peaks. In addition, the measurement area in the current experiment was limited to the sensing area of the sensor, which covered only a portion of the impact zone below SWL. Although in most of the tests the breaking waves have impacted on the sensing area, the maximum pressures may have occurred outside of the sensor. Therefore, the pressure mapping results obtained in this study cannot be used to derive any general conclusions in terms of spatial pressure distribution due to breaking wave impact and more detailed investigations need to be carried out in the future.

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References

Stagonas, D., Müller, G., Batten, W., and Magagna, D., 2011. Mapping the temporal and spatial distribution of experimental impact induced pressures at vertical seawalls: a novel method. 5th International Short Conference on Applied Coastal Research. RWTH Aachen University, Germany.


