EFFECTS OF SEASONAL VARIATIONS ON SANDY BEACH GROUNDWATER TABLE AND SWASH ZONE SEDIMENT TRANSPORT

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The hydrodynamics in the swash zone significantly affected the sediment transport mechanisms that mostly control beach face morphology especially under different weather conditions. Rainfall distribution patterns during dry and wet seasons in Peninsular Malaysia will influence groundwater table elevation and the beach profile. This study is aimed at investigating the effects of seasonal variations to beach groundwater elevations and surface profile changes. This work was undertaken at the Desaru Beach, Johor. Rainfall depth, groundwater table, tides, beach profiles, swash depth and swash velocity data were monitored and investigated at the study area. The results showed that the groundwater table was affected by rainfall patterns; higher during the wet season and lower during the dry season. The beach profile also showed erosive condition due to increasing of offshore sediment transport during the wet season, whereas in the dry season the beach profile showed accretion condition due to the increasing of onshore sediment transport. Swash properties like swash water depth and velocity were also monitored and analysed during this study in order to get a clear view about the saturation level effect due to seasonal variations into a infiltration processes at the swash zone. Finally the data showed that there is a lag time between rising and falling of groundwater tables and tides due to the lower hydraulic conductivity effect.

Keywords: swash zone, rainfall; groundwater; beach profile change; field experiment

INTRODUCTION

The relationship between beach groundwater dynamics and swash hydrodynamics provides a dominant factor for swash zone sediment transport, which affects the morphology of the beach especially by controlling the movement of offshore or onshore transport. Several authors have successfully shown in their field works, laboratory experiments or numerical simulations that beaches with a low groundwater table are expected to accrete while beaches with a high groundwater table tend to erode (Duncan, 1964; Grant, 1984; Baird and Horn, 1996; Li et al., 2002; Ang et al., 2004; Horn et al., 2007; Bakhtyar et al., 2011).

Infiltration and exfiltration are among the significant factors which are suggested by many researchers in order to explain clearly about why beaches with a high water table are likely to erode and low water table tend to accrete. The beach groundwater table position will affect the infiltration and exfiltration processes during the uprush and exfiltration. When the uprush reaches the beach face above the watertable's exit point, the water may infiltrate into the bed and consequently decrease the uprush volume, depth and velocity. It is totally different during the lower exit point (saturated condition), the backwash flow will increase due to the groundwater seepage (Horn, 2006). However, these two factors need to be understood carefully especially under different types of beach materials.

During the uprush flow, the seawater will spread quickly into the upper layers of the beach surface. At the end of the uprush process, the flow will turn to backwash and subsequent reduction in swash depth, there will be a rapid decrease of pore-pressure, producing forces acting vertically upwards just below the beach surface. This condition may lead to rapid groundwater outflow or exfiltration. If the upper layers of sediment become fluidised, then this might considerably increase the sediment transport since the fluidised layer would quickly become entrained by the seaward flow during the backwash. This hypothesis was tested using a model by Baird and Horn (1996), who concluded that fluidisation due to exfiltration may happen, especially in the final stages of the backwash process. Water may infiltrate into the sand at the upper part of the beach during uprush or backwash activities if the beach groundwater table is quite low. In contrast, groundwater ex-filtration may occur across the beach surface with higher water table. Such relations have been confirmed to have a big impact on the swash sediment transport in the past field studies by Duncan (1964) and Grant (1984). Water infiltration under lower water table is found to increase onshore sediment transport, while groundwater exfiltration under higher water table encourages offshore sediment transport. These field observations have theoretically guided or helped the beach dewatering technique to lower beach groundwater table in order to prevent the beach from erosion (Turner and Leatherman, 1997). Although some success has been achieved in

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the application of this method, the need to fully understand the fundamentals and processes involved should get higher attention by researchers nowadays. The interaction between the surface water and groundwater flow has been widely acknowledged as a key factor in controlling gravel beach morphology (Mason and Coates, 2001) but the exact nature of the relationship between surface flow, groundwater flow and cross-shore sediment transport is still not fully understood. The higher the groundwater level in the backshore, the higher the offshore sediment transport caused by reduction of the infiltration rate (Quick, 1991). The type of beach property material that mainly controls the level of infiltration is the permeability or hydraulic conductivity of the beach material (Masselink and Li, 2001). The average value of permeability for sand is about 0.0001 m/s and may increase to 0.01 m/s on coarser sand while permeability on gravel varies from 0.001 m/s to 0.1 m/s (Foote et al., 2002). This creates a significant difference in the magnitude of asymmetry in sediment transport efficiencies between sand and gravel beaches.

In Malaysia, basically the seasonal wind flow patterns coupled with the local topographic features determine the rainfall distribution patterns over the country. During the Northeast monsoon known as wet season starting from November to February, the east coast region of Peninsular Malaysia will experience heavy rainfall and storms plus energetic wave condition due to strong onshore wind which can contribute to a higher possibility of erosion rate at the beach area (Wong, 1981; Husain et al., 1997). This erosive condition has been driven by energetic uprush and backwash activities on higher saturated beach surface. In contrast, during the dry season, which usually starts from March to August annually, lesser rainfall events are recorded and this situation contributes to a significant drop of groundwater level and beach saturation degree. In this season also, it is believed that beach accretion process is increased due to calmer wave condition and higher infiltration process in the swash zone. From this unique particular condition, it is believed that the seasonal variations factor in Malaysia can significantly influence the sediment transport processes in the swash zone where beaches during the wet season are likely to erode and beaches during the dry season are likely to accrete.

In order to understand a seasonal variation effect to beach morphological change, other researchers (Hayes and Boothroyd, 1969; Davis and Fox, 1972; Masselink and Pattiaratchi, 2001) have successfully conducted field investigations to study a localized seasonal effect (winter versus summer) by using the variability of the incident wave energy level such as wave height. This assumption is used to predict the occurrence of beach erosion (and bar formation) under energetic wave condition (winter) and accretion (and berm formation) under calmer wave condition (summer). However according to Short (1978), this assumption is more suitable to the site-specific and not ready to be applied outside the region for which it is defined.

FIELD SITE AND METHODOLOGY

The field monitoring study was conducted at Desaru beach, Johor located in the southeast of Peninsular Malaysia, which is located about 380 km & 80 km from Kuala Lumpur and Singapore, respectively. The beach is composed of fine sand (D_{50} = 0.2 mm – 0.4 mm). It is experiencing semidiurnal tides, with a tidal range of approximately 0.6 m - 1.2 m. During the experiment, the average slope for upper beach is quite steep ($\tan\beta \approx 0.11$) and the lower beach is gentle ($\tan\beta \approx 0.03$). Visual observations made during this study showed that the wave heights on the east coast of Peninsular Malaysia during the Northeast monsoon period are generally between 1.0 m – 1.6 m with a wave period average at 10 seconds but this can vary greatly due to the alternating periods of strong and calm winds. About 80% of the waves observed during this monsoon approach the beach from between 30 to 60 degrees. After that period, waves are more calm and steady with the height of Southwest monsoon wave usually ranges from 0.5 to 1.0 m and wave periods are usually at average of 5 seconds. During the Southwest monsoon period usually from May to August, wave approach is predominantly from the southeast.

Several field experiments were conducted during dry and wet seasons in order to monitor and investigate the effect of seasonal variations on Desaru's sandy beach profile changes. All data for swash zone properties such as bed level, water depth and velocity were collected during the spring tidal range condition.

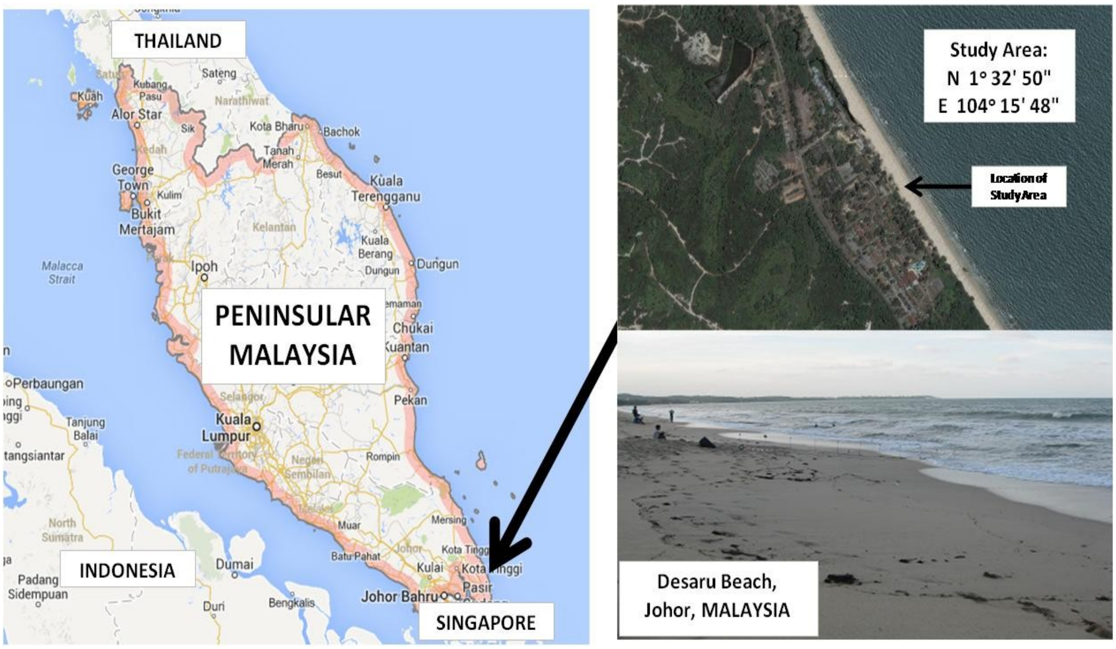

Figure 1. Location map of the study area at Desaru beach, Johor, Peninsular Malaysia

For beach profile measurements, as suggested similar field method by Jensen et al. (2010), several steel rods were placed in a cross-shore transect along the beach with a space of 1 m. In order to estimate the net accretion or erosion across the beach face for this monitoring, volumetric change were recorded with the assumption that changes in elevation at each rod represents the average bed level changes within half meter square. The rods were measured daily using a total station during low tides under the spring tidal range condition based on standard surveying techniques.

Figure 2. Photograph showing the steel rods were installed cross section with spacing 1 meter at Desaru beach

Data on swash water depths were obtained by using three pressure transducers (PTs), which were deployed during this monitoring near to the Mean High Water Spring (MHWS) shoreline at the lower (x = 40 m), middle (x = 35 m) and upper (x = 30 m) part of the beach area at a separation distance about 5 meter. For this experiment, only one Acoustic Current Meter (ACM) was deployed to record swash velocities during uprush and backwash at the beach middle point (Figure 3). The ACM was installed as close to the bed as possible, about 1 cm above the bed. Both the PTs and ACM were synchronized at a same sampling time at 1 Hz or every 1 sec per data and operated continuously throughout the experiment. For this paper, only the data from the middle point (x = 35 m) will be discussed. From this monitoring station, the data for swash water depths and velocities were analyzed and separated for the selected period of uprush and backwash activities during spring tidal condition. All these experiments were also recorded by a video camera as a backup for a data analysis processes. The separation processes for every single uprush or backwash activities were analyzed by the direction of fluid velocities and also rechecked by using recorded video for every experiment. The position of sampling based on the beachface point (x = 35 m) and the tidal elevation (MHWS at 1.56 m LSD) at the field work were selected at approximately as the same high tide condition during the dry and wet periods. This situation setup is very important for this experiment in order to get a clear view about beach morphological changes at the same sampling point but under difference periods of seasonal variations in Malaysia.

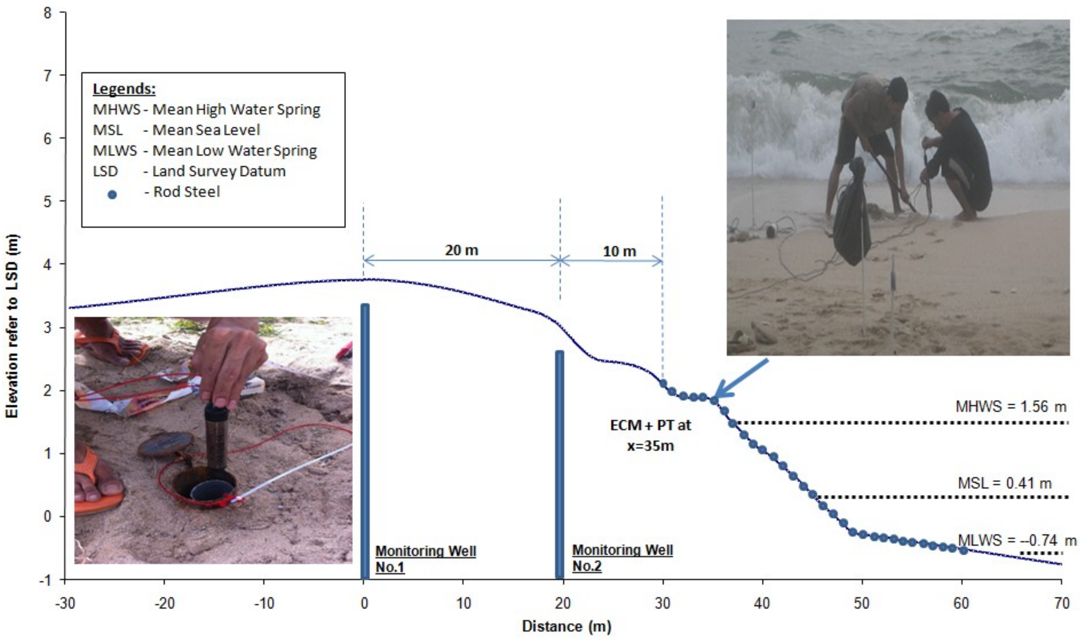

Figure 3. Experimental setup at Desaru beach

For the effects of Malaysia's seasonal variations, one rain gauge station was installed close to the study area to record rainfall depth data for every 10 minutes during the observation period. This rainfall depth data is very important for this study in order to relate the contribution of the rainfall characteristics during the dry and wet seasons to the beach morphological changes due to the different patterns of swash zone sediment movement. This station was monitored monthly by a researcher in order to make sure this rain gauge operated successfully and the data from this station was downloaded at the same time by using a laptop (Figure 4). This data also was double-checked with a data taken from the nearest rainfall station from Malaysia's local agency, Department of Irrigation and Drainage (DID) at Bandar Penawar rainfall station, which is about 10 km from the study area.

For beach groundwater table data, two monitoring wells with 10 m depth were constructed inland along the monitored beach profile. The wells were made of 50 mm diameter PVC pipes and covered by locked steel cap at the upper part of the wells for the protection of the wells safety from beach visitors. This groundwater table data was recorded using a water level logger at 10 minutes intervals and monitored monthly by a researcher. All data in the water level logger was extracted by using a special docking station through a laptop. Manual reading was also conducted for every visit by using a water level indicator in order to ensure the quality of the field data as shown in Figure 4.

Figure 4. Photograph showing the (left) monitoring well with water level indicator and (right) rain gauge station

The tidal elevation data of the study area was recorded by a tide gauge which was installed near a jetty within the study area. This gauge was set up for recording data every 10 minutes and all data was adjusted based on Malaysia's Land Survey Datum in order to make sure all measurements for all experiments were synchronized based on one reference datum.

In order to ensure the quality of data for this experiment was at the highest level, all equipment was calibrated every time before and after experiment especially for the PTs and ACM in the swash zone due to higher concentration of sediment movement and difficult hydrodynamic processes compared to other areas. For this experiment, the maximum uprush velocity was the most difficult to measure accurately because of one sampling point only (1 cm from the bed). For the backwash velocity and depth, the readings were always lower due to infiltration effects at the upper part of swash zone area. The data collected at the end of swash cycle during backwash or before uprush were difficult to measure due to very thin layer of the backwash water depth (< 1 cm) and this situation made the field monitoring very interesting and challenging to conduct.

RESULTS AND DISCUSSIONS

Rainfall and Groundwater Levels

Figure 5 illustrates the relationship between the monthly rainfall at the field study area and the beach groundwater table measured in monitoring wells no. 1 and 2. From this figure, it can be classified that the wet period occurred between November 2013 and January 2014, with December 2013 found to be the wettest month with 399.2 mm was recorded. In contrast, the dry period occurred between February and March 2014 with February recorded as the driest month with no rainfall data (0 mm) was detected. The monitoring work for this study started in June 2013 with the initial groundwater level reading were 220 mm and 180 mm for well no. 1 and 2 respectively. The groundwater tables reading for both wells cap increasing until September 2013 although the rainfall data was decreasing. This unique condition was largely contributed by the effect of higher saturation level on beach face due to the heavy rainfall distribution during that period especially in July and August 2013. In October 2013, the monthly rainfall data was recorded lower at 26 mm and this condition had affected the beach groundwater level to slightly drop. During the wettest month in December 2013, the beach groundwater level significantly rose up to 360 mm and 300 mm in well no. 1 and 2 respectively. This situation can be clearly seen in Figure 5 based on the highest +ve slope value for the groundwater level line. This statement also was hugely supported by the highest -ve slope value was occurred in February 2014 which is the driest month during this monitoring works.

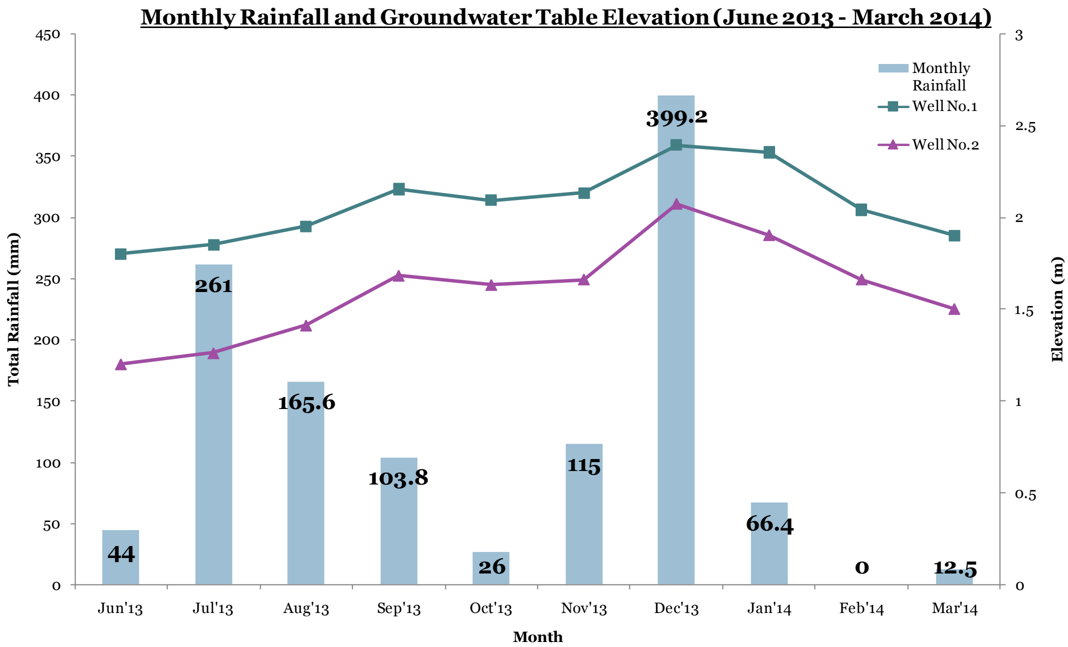

Figure 5. Relationship between monthly rainfall data and beach groundwater table elevation

The result showed that the rainfall distribution plays a vital role in controlling the beach groundwater level but the saturation degree for the beach is also important. It can be clearly seen that in September 2013 and November 2013, approximately the same monthly rainfall data was collected, however different +ve slope lines were recorded. Both slopes for the raised groundwater table in September 2013 is higher than in November 2013 due to the level of beach saturation effect by different monthly rainfall. For example, in September 2013, both groundwater tables in wells no. 1 and 2 were raised quickly due to the heavy rainfall happened in August 2013 which directly increased the beach saturation level at study area. It is different situation if compared with data in November 2013. Both groundwater tables in the wells on that month also responded with approximately same of monthly data in September 2013, but raised slowly due to the lower monthly rainfall in October 2013 which extensively effected the saturation values in the beach area. The effect of monthly rainfall distribution pattern on the beach saturation degree and the groundwater level can also be clearly found during the lesser of monthly rainfall rate. For example in October 2013 and March 2014, both months have approximately the same lower monthly rainfall rate (26 mm and 12.5 mm respectively) but have a significantly difference in the decrease of groundwater level. In October 2013, groundwater levels had slightly dropped due to the higher monthly rainfall in September 2013. In contrast, the groundwater levels in March 2014 had significantly dropped and this condition was largely contributed by lower saturation degree in the beach due to no rainfall data was detected during the previous month. These results implied that the variations of monthly rainfall distribution play an essential role on the response of beach groundwater table elevations.

Beach Profiles

Three days of beach profiles were selected at Desaru beach on 27 June 2013, 25 January 2014 and 16 March 2014 as shown in Figure 6. The profile on 27 June 2013 was selected as an initial profile for this study in order to compare and analyze the effect of beach groundwater level to beach profiles changes during the wet period on 25 January 2014 and the dry period on 16 March 2014. The mean level for beach groundwater table at monitoring wells no.1 and 2 for these days were compared to investigate the relationship with the rainfall distribution and beach profile changes.

The data for both beach profile and groundwater level on 25 January 2014 was considered to be the wet period at the study area. The highest erosion rate occurred in January due to the heavy rainfall depth between November and December 2013 which recorded data as 515 mm. This condition significantly increased the beach groundwater level and enhanced the offshore transport due to higher saturated beach face. The beach groundwater level also increased higher with about 0.6 m in well no. 1 and 0.8 m for well no. 2.

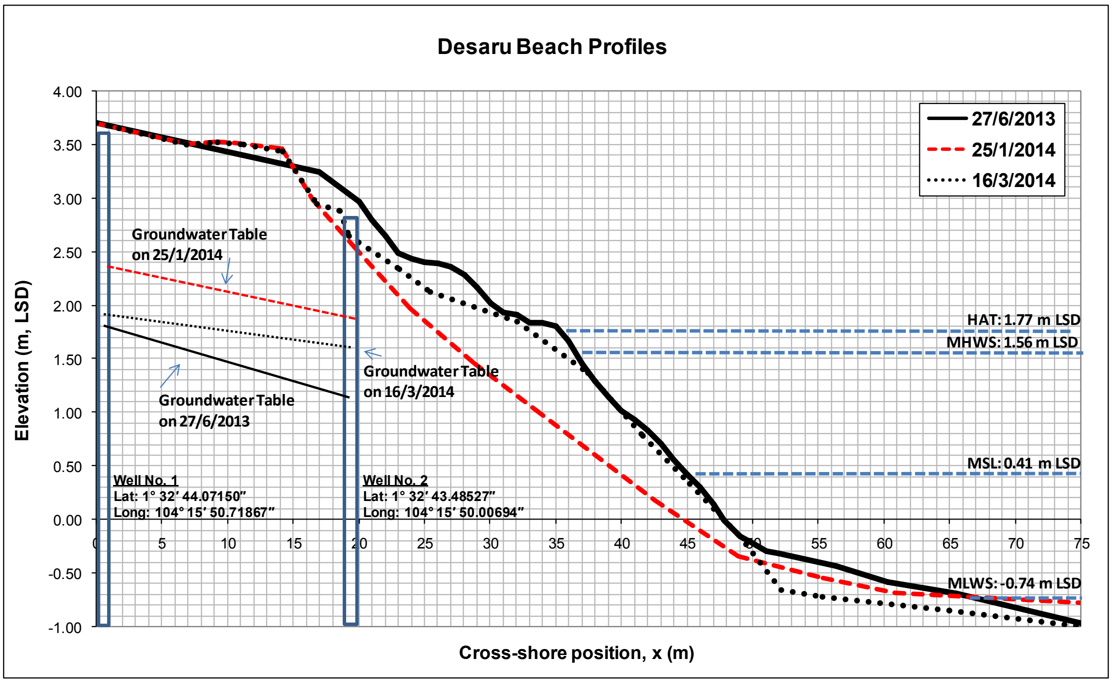

Figure 6. Beach profiles and mean groundwater level for 3 different days of monitoring

Figure 6 also shows that the beach was mainly eroded on the upper part and slightly accreted on the lower part especially below the MLWS. The highest erosion depth occurred at point x = 35 m with nearly 1.0 m depth of beach surface was eroded. At this point also, the highest tidal level happened with HAT at 1.77 m LSD and MHWS at 1.56 m LSD. During this wet period, almost all the beach surface was eroded except at the upper part of the beach where a small berm had developed on the upper part of beachface which was strongly believed to be established by the effect of greater uprush flow during this period. The entire amount of eroded sand beach was removed by greater backwash flow activities to offshore because lower infiltration level due to the raised groundwater level affected sediment transport on the beach. This effect of the raised groundwater level on beach profile was consistent with the reported observation of laboratory experiments (Horn et al., 2007; Ang et al., 2004) which show that infiltration was reduced due to the raised groundwater level resulted in offshore transport on the fine beach.

As for the beach groundwater table, during the dry period on 16 March 2014, the reading was significantly decreased compared with the level during the wet period on 25 January 2014. The depth was decreased to 0.5 m and 0.3 m in wells no. 1 and 2, respectively. In contrast to the situation during the wet period before this, the beach during the dry period with lower groundwater table showed onshore transport and majority of the accretion was established above the MSL or between point x = 20 m and 60 m but the small berm developed during the wet period still remained at the point between x = 7 m and 17 m. This condition which was observed along this monitoring was largely contributed by lower energy of swash velocity during the dry season. During this period, wave energy from the offshore became slower and calmer due to end of the Northeast monsoon. This reason largely contributed to swash zone properties like a swash velocity and uprush length maximum limit, which are the velocity tend to flow more slowly and the length become shorter. So the uprush length during this period is limited at point x =17 m and higher to the upper of the beach during the wet season with x = 7 m. For this study, saturations data in the beach was not measured during these monitoring but the suggestion by Horn et al. (2007) that fine sand beach is only unsaturated when the groundwater level in the beach is lowered or vice-versa give reasonable exemption for this situation. So, the rainfall distribution in this study was the important factor in controlling the beach groundwater level with higher elevation during the wet season and lower during the dry season.

Swash Water Depth and Velocity

In this section, the aim is to compare and analyze the 300 seconds of selected swash properties profiles likes swash water depth and velocity for this study under different seasonal variations (wet and dry seasons). In order to investigate the effect of seasonal variations in Malaysia, the swash water depth and velocity profiles were selected for the same highest tidal elevation during the wet and dry seasons in the study area as shown in Figure 7 and Figure 8 respectively.

During the wet period in Figure 7, the average depth was 7.14 cm with the maximum and minimum values were 27.0 cm and 0 cm respectively. For the velocity data, the highest values of uprush and backwash were recorded at 3.76 m/s and 2.13 m/s respectively. The sampling point for data profiles during the wet period, when the uprush flow came, there was always a maximum instantaneous acceleration in uprush velocity and followed by more steadily decrease until zero velocity at the end of the uprush flow. During this moment, it clearly showed that the maximum water depth always occured when zero velocity reading at the end of uprush flow. In contrast, when the backwash flow took the action in the swash zone, the velocity increased gradually until it reached its maximum value. After that, the backwash flow depth and velocity decreased to zero until the new uprush flow came. This observation was consistent with other field study work by Hughes (1997).

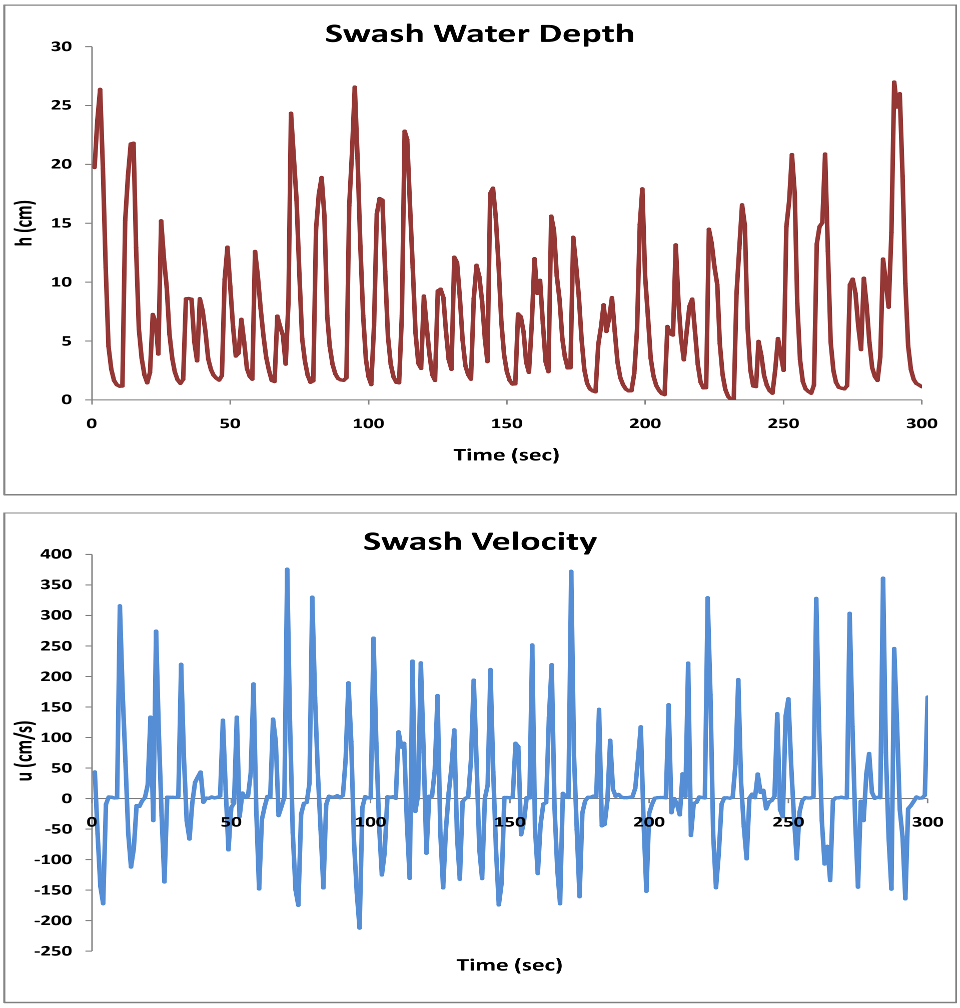

Figure 7. Profiles of swash water depth and velocity during wet season

In Figure 8, the profiles data for swash depth and velocity taken at the same high tide elevation on 16 March 2014 have shown the effect of seasonal variations on swash properties. During this month, the study area was experiencing the dry period and the end of the Northeast monsoon which has a lower wave attack and energy. This condition totally affected the swash water depth and velocity levels to become lower than during the wet season. For the swash water depth comparison, it clearly showed that decreasing of swash energy happened during this period with an average depth was 2.05 cm with the maximum and minimum values were 12.3 cm and 0 cm respectively. This an important condition can explain why the developed berm in Figure 7 during the wet season before did not change due to wave attack with the limitation of observed uprush length occurred as far as at point x = 17 m, which is shorter 10 m if compared with the furthest uprush length during the wet season (x = 7 m). For the velocity data during this period, the highest values of uprush and backwash were detected at 2.85 m/s and 1.58 m/s respectively. It clearly found that the swash velocity was decreasing for the uprush and backwash flow but the backwash velocity was significantly reduced by greater infiltration effect due to high value of unsaturated beach surface. This unique condition has played a major role in accretion processes in the swash zone due to high infiltration effect. In this condition, the sediment or sand carried by swash water during the uprush and backwash flow has settled down easily on the beachface due to high infiltration process and this situation put the beach in the accretion mode.

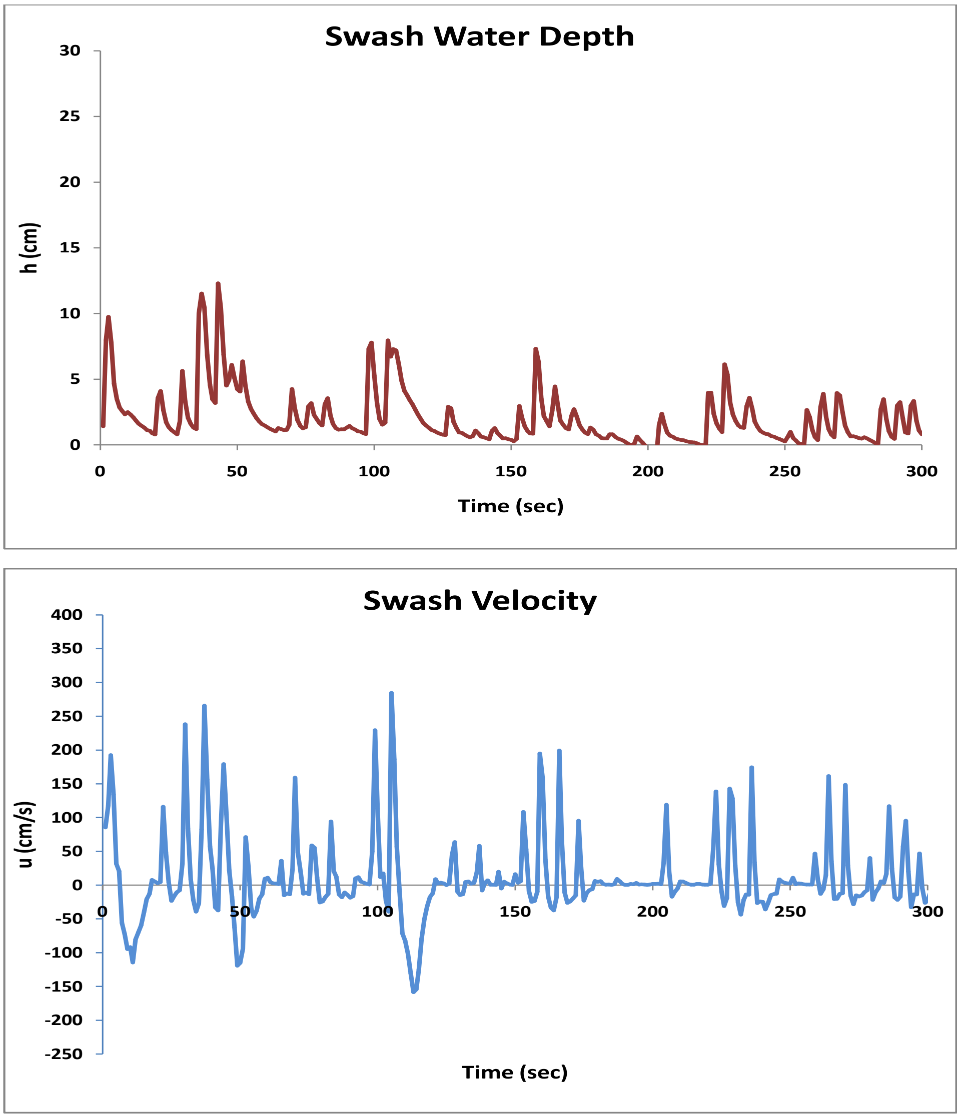

Figure 8. Profiles of swash water depth and velocity during dry season

However, in order to understand swash zone processes clearly and how these affect beach profile response, Horn (2006) stresses the importance of direct measurements of key parameters such as hydraulic conductivity, moisture content and infiltration rates which must be carried out in the field.

Beach Groundwater Response to Tidal Cycles

Figure 8 shows the relationship between tides and groundwater level in monitoring well no. 2 which the nearest well from MSL shoreline for the selected 4 days of monitoring starting from 29 June until 3 July 2013. It was found that the lowest groundwater table in well was on high tide and highest groundwater table was on low tide. These 6 hours of lag time could be due to the location of the well from the shoreline (20 m) and also the type of beach material that will affect the hydraulic conductivity value. Therefore, rising or falling tides may not directly affect the groundwater table in well no. 2 as the infiltrated water needed time to fill and leave the soil. This result is consistent with Nielsen (1990), that a lag time is mainly due to the response of the hydraulics conductivity of the beach sediment and sandy beach groundwater table takes a longer time to response due to a lower value of hydraulics conductivity.

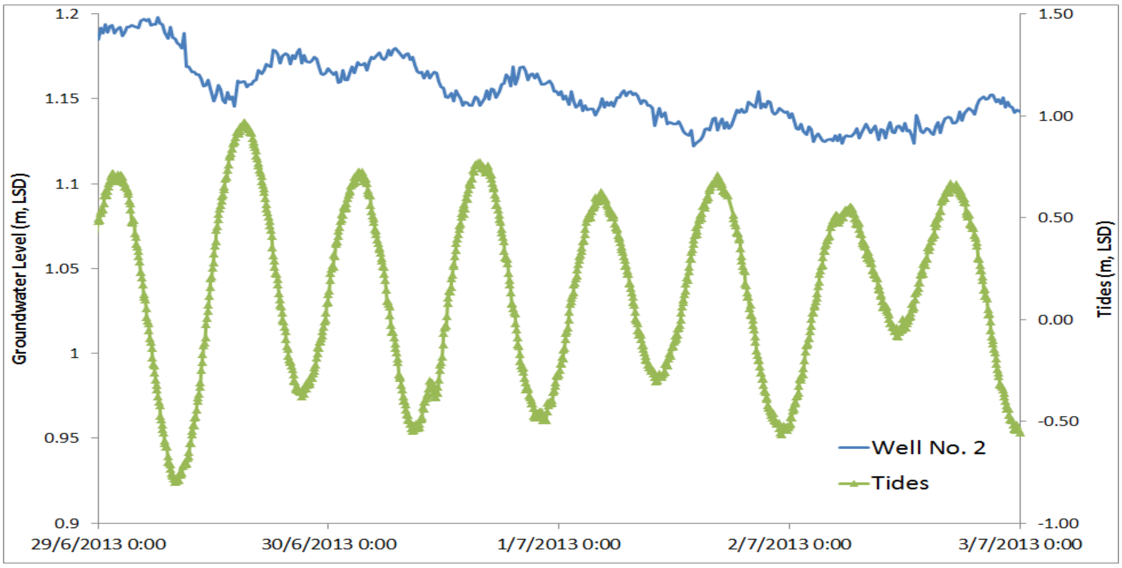

Figure 6. Groundwater table in well no. 2 and tidal elevation

CONCLUSIONS

Beach groundwater table was highly affected by the patterns of rainfall distribution which were significantly increased and decreased in the wet period and dry period, respectively. The increasing of beach groundwater level has led the beach to become more saturated and enhanced the offshore sediment transport during the wet season as the profile was eroded. However, during the dry season, the beach was accreting and the groundwater level was lower in comparison to the groundwater level during the wet season.

For the swash water depth and velocity profiles, data during the wet period was higher than the dry period due to higher wave energy and saturation level effect on infiltration processes on the beach surface. Due to saturated beach condition, the swash velocities for backwash was slightly lower than up-rush in the wet period but significantly lower or none during the dry period.

Near to the shoreline, groundwater level was highly affected by tidal fluctuations but the parameter like hydraulic conductivity was critically suggested to be measured in the study in order to explain clearly about the response of groundwater table due to the tidal effect especially under different seasonal variations in Malaysia. Also the importance of beach saturation level in this study and its effect need to be monitored during the dry and wet periods.

Field study or research in the swash zone related to groundwater table effect have been relatively few in numbers (none in Malaysia to date) and there is a clear need to improve current available field equipment in order to get high quality data for better understanding of this complex process. Current work will continue the field observation for a long term monitoring in order to get a clear view of swash zone sediment transport due to the groundwater table effect under Malaysia’s seasonal variation. Also the important of other parameters such as wind speed, wave height, wave period and wave direction need to be observed and analysed in order to enhance the understanding of this complex seasonal sedimentation process.

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