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Swash zone rapid adaptation to changing waves: a laboratory study

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Abstract:
The swash zone, defined as the interface between land and ocean, known to be a highly dynamics region of the nearshore. A fundamental parameter in swash dynamics is the beach-face slope (β) as it affects the relative influence of dissipation and reflection of wave energy at the coast, the excursion of wave run-up at the shoreline and therefore the direction of sediment net flux, i.e. accretion vs erosion as an exchange of sediment between land and sea. Due to the complexity of these processes the behaviour of the β is still unclear. It has usually been admitted that the beach face slope increases with the increase of the average sediment size (D_{50}), leading to a global classification of beach-face shape. Understanding the physical mechanisms at the origin of this relationship (β vs D_{50}) is the main goal of this study. For this purpose, a simple laboratory device modelling the swash zone from reflective to dissipative beach states is used to detail the beach-face slope response to wave forcing, starting from different geometrical initial conditions. This paper proposes a classification of β, and therefore of swash response as a function of Dean number (Ω), based either on swash or offshore characteristics of wave forcing (Ω_{SW} or Ω_0, respectively). A decreasing trend of the beach-face slope with increasing offshore Dean number (Ω_0) is found for Ω_0<2.5. For Ω_0>2.5 it is observed that the beach-face slope gradient is highly controlled by surf zone dynamics and it becomes necessary to define the Swash Dean number (Ω_{SW}) to classify the slope. The present results are also discussed in confrontation to field measurements presented in MINGO *et al.*, 2021.

Keywords: Beach-face slope, Swash zone dynamics, Dean Number, Swash Dean number, Sediment transport, Erosion, Bore impact, Wave energy dissipation.

1. Introduction

The swash zone is the part of the beach intermittently covered and uncovered by waves, forming the land-ocean boundary. According to several coastal scientists, this zone is considered to be the most dynamic region of the nearshore zone (PULEO *et al.*, 2000; KIKKERT *et al.*, 2013), characterised by strong and unsteady flows, high turbulence, large sediment transport rates and rapid morphological changes (MASSELINK & PULEO, 2006). Due to the complexity of the processes occurring in the swash, the beach-face slope (β) dynamics remains unclear. Therefore, this work aims to increase the knowledge and understanding of swash dynamics by using a simplified laboratory model allowing to identify and characterize specific processes occurring in the swash.

The morphology of the swash is partly characterized by the local beach-face slope (β), defined by (MASSELINK, 2001) as the section of the beach profile below the berm, normally exposed to wave action. This slope is considered to be one of the morphological key parameters of the swash zone as it controls the dissipation and reflection of wave energy, the excursion of wave run-up at the shoreline and the sediment exchange between land and ocean (MASSELINK & PULEO, 2006). It has been shown that the beach-face slope increases with the increase of average sediment size (BAGNOLD, 1940; BASCOM, 1951; TURNER, 1995; BUJAN *et al.*, 2019). This statement has been partly explained by the effect of swash infiltration on sediment transport in the swash zone (KEMP, 1975; TURNER, 1995; MASSELINK & HUGHES, 1998; MASSELINK & PULEO, 2006). A great deal of effort has been invested on this relationship (β-D_{50}), providing a significant amount of empirical equations to predict the slope. Most of these expressions show a power law dependency of the slope with the mean sediment size (RECTOR, 1954; SUMANURA & KRAUS, 1985; SOARES, 2003). In a recent work, BUJAN *et al.,* (2019) extracted over 2000 measurements of beach-face slope with associated grain sizes from available data in the literature and tested several empirical and numerical equations on this large data set. They proved that even the most representative of these equations cannot describe the full distribution of the data set. They proposed a new power law dependency from small slopes towards steeper slopes with increasing grain size for first order prediction of the beach-face slope. However, the data shows a large variability of β, probably due to the wide range of data sources and therefore beach specificities, as for instance their instantaneous state compared with equilibrium profile to wave forcing. A rising question from these results concerns the origin and dependency of the beach-face slope dispersion.

To approach this question, a simple swash laboratory model has been designed to focus specifically on swash morphodynamics (see section 2 for details). This work proposes, the dimensionless fall velocity, also known as the Dean number, Ω_0 (DEAN, 1973) as the main control parameter. This parameter (Ω_0) is chosen based on the assumption that suspended sediment is the main mode of sediment transport in the swash. This dimensionless number controls suspended sediments transfers and direction by relating offshore wave amplitude H_0 and period T_0 with sediment fall velocity W_S (the equation is defined in Table 1). This approach follows recent results obtained by analysing field data on low tide terrace (LLT) beaches in which a correlation between the beach-face slope and the Dean number was highlighted (MINGO *et al.,* 2021). This relationship (Ω_0-β) requires a better understanding of the dominant physical mechanisms controlling the β. In particular, the question of equilibrium and out-of-equilibrium concept during a given time scale requires specific attention. The present work uses a laboratory device to study the relation Ω_0-β on a relatively short time scale, over which the beach-face slope rapidly adapts to wave forcing. Results are also discussed in confrontation to field observations of two LTT beaches, one at Nha Trang Vietnam (NT) and the other at Grand Popo Benin (GPP) presented in MINGO *et al.,* (2021).

2. Description flume experiments and similitude conditions

2.1 Experimental setup

This model is designed to understand the main behaviour of the swash zone under wave action. The nearshore model is built into a laboratory wave flume (12.65m long, 0.3m high and 0.15m width). Due to the multitude of parameters involved in this problem, it is necessary to fix certain ones and vary the others gradually in order to identify the influence on the beach-face slope. For this reason, monochromatic waves are generated at one side of the flume using an oscillating wave paddle (see figure 1).

The innovative aspect of this physical model is to only focus on the swash zone and its beach-face slope, very specific zone, disregarding the morphodynamics of the surf zone. Then a controlled wave breaking mechanism is imposed to keep the breaker position fixed around x=0 (with the axis x being aligned with the wave propagation along the flume). This mechanism consists on a rigid bottom (non-erodible) with a gentle slope (see figure 1), maintaining the interactions between the wave shoaling and the seabed constant. The only erodible part of this model is the beach-face. Thus, this physical model allows to focus our attention on the quick beach-face slope response to bore impact, including both the dissipative region from the breaking zone to the beach-face and the sediment transport process on this region.

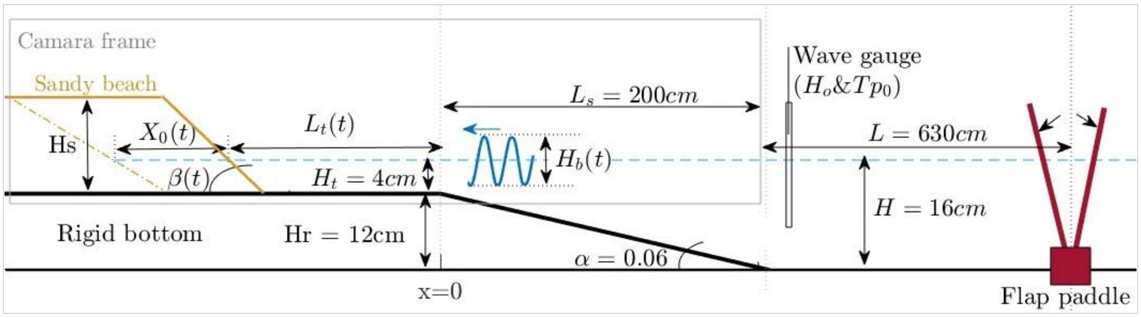

Figure 1. Swash laboratory model sketch.

The evolution of the shoreline due to wave action is characterized by the following time dependent parameters :

- $L_t(t)$: distance from shoreline to the fixed breaking point (x=0).
- $X_0(t)$: is the shoreline retreat due to wave action. $L_t(t) = X_0(t) + L_i$, being L_i the initial shoreline position to breaking point (L_i=L_t(t=0)).
- β(t) : is the beach face slope.
- $H_b(t)$: wave amplitude evolution from the breaking point to the beach profile (dissipation of the bore on the terrace).

For this study, the average sediment size (D_{50}) is kept fixed to study the dispersion of the beach-face slope values due to wave action and not to sediment size. The beach-face is entirely made of natural sand of median size D_{50} = 80μm and relative density s = 2.65. The mean water level (H on depth water and Ht on the terrace) is constant during the entire experiments as the focus of this work is to study the evolution of β on short time-scales, order of a few hours corresponding to one tidal cycle.

The off-shore waves generated are characterized by their wave height (crest-to-through) and period (H_0 & T_0), measured with a wave gauge at the toe of the rigid bottom slope (see figure 1). The wavelength (λ_0) is related to T_0 through the dispersion relation obtained for surface wave in the linear and long wave approximation.

Depending on the shoreline and beach face slope initial positions (L_i and β_i), reflective to dissipative conditions can be recreated in the flume.

To scale this experimental device several dimensionless parameters have been calculated and compered to field data from an LLT beach at Nha Trang (MINGO *et al.*, 2021; THUAN *et al.*, 2019). Nha Trang is a sandy beach located in a semi-closed bay in the south of Vietnam with a microtidal range from 0.4m to 1.7m and a low to moderate energy wave climate where waves show seasonal variability. The annual significant wave height is 0.95m with an associated average peak of 6.2s and the sediment size is medium-to-coarse with a mean grain size of 0.6mm. The scaling parameters are summarized in Table 1, the laboratory model covers a wide range of most of these dimensionless parameters, mainly β_i, Ω_0 and L_t/λ_0.

Table 1. Important dimensionless parameters characterizing the nearshore dynamics for scaling the laboratory swash model. Field data refers to seasonal mean values of Nha Trang LTT beach (THUAN et al., 2019).

Scaling parameter	*Parameter symbol and equation*	*Field values (Nha Trang)* *laboratory values*
Surf similarity parameter or Iribarren	$\xi_0 = tan(\alpha)/\sqrt{H_o/\lambda_0}$	*0.1* *0.24 - 0.71*
Dimensionless sediment fall velocity or Dean number	$\Omega_0 = H_0/(Tp_0 W_s)$	*2 - 5* *1.50 – 10.7*
Wave steepness	H_0/λ_0	*0.056 – 0.092* *0.01 - 0.063*
wave amplitude / Terrace water depth	H_0/H_t	*1 - 3.88* *0.62 - 1.17*
Terrace length / wavelength	L_t/λ_0	*0.4* *0.06 - 1.5*
Initial beach face slope	$tan(\beta_0)$	*0.10 - 0.19* *0.066 - 0.4*

2.2 Runs

The beach face slope (tan β) response is analysed for four different wave climates defined by their wave conditions and the offshore Dean number (Ω_0). A summary of the initial morphology, wave climates and experiments run is given in Table 2.

Table 2. Morphology and wave climate parameters used in this study. Related dimensionless number estimated from Dean equation $\Omega 0 = H_0 / (T_0\ W_S)$, where the sediment fall velocity (W_S) is calculated using Stokes law.

Wave climates					*Morphological initial conditions*			
Type	H_0 *(cm)*	T_0 *(s)*	λ_0 *(cm)*	Ω_0	*Number of runs*	$tan(\beta_i)$	L_i *(cm)*	L_i / λ_0
A	*4.70*	*0.74*	*75*	*10.7*	*15*	*0.06 - 0.40*	*10 - 115*	*0.70 - 1.50*
B	*2.45*	*1.28*	*150*	*3.26*	*16*	*0.06 - 0.40*	*8 - 140*	*0.05 - 0.90*
C	*2.40*	*1.69*	*203*	*2.26*	*7*	*0.04 - 0.25*	*12 - 100*	*0.06 - 0.50*
D	*2.20*	*2.51*	*310*	*1.50*	*7*	*0.07 - 0.28*	*15 - 127*	*0.04 - 0.040*

One run consists to submit an initial beach face profile, characterized by its initial slope β_i and its initial distance to the breaker point L_i, to a constant wave climate for 2 hours duration, corresponding to a tidal cycle in nature. It was observed from preliminary results from this laboratory device, that the beach face would quickly adapt its slope in less than 2 hours. After this time the beach profile would be in constant erosion (as there is no sediment addition), while maintaining this stable slope until the shoreline would reach a stable position. This state of constant erosion of the shoreline while maintaining a stable slope, is called a quasi-equilibrium of the beach-face slope (β_{eq}) to that wave climate. Such β_{eq} is believed to be observable in the field as it shall correspond to the transient from state to state when climate forcing changes. In total, 15 runs were done for wave climate A varying the initial beach face slope (β_i) and shorelines position (L_i), 16 runs for wave climate B and 7 runs for wave climates C and D.

2.3 Experimental measurements

High resolution sCMOS cameras are used to obtain a high-quality time-series images of the beach face profiles and waves evolution. Using optical shadow-graph techniques, the free surface $H_b(x)$, evolving beach face slope $\beta(t)$ and shoreline position $L_t(t)$ are extracted from collected images. A post-processor programming code is developed to automatically analyse the collected images. For the morphological analysis of the beach face evolution ($\beta(t)$ & $L_t(t)$) the image frequency acquisition is 2Hz and for the hydrodynamics analysis of the free surface $H_b(x,t)$ the image frequency acquisition is 40Hz.

3. Experimental results

3.1 Hydrodynamics: Wave dissipation in the modelled-rigid surf zone.

To characterize the four wave climates that are used as a control parameter of the beach-face slope reaction, preliminary experiments were performed without the sandy-beach. The objective is to characterise the transformation and dissipation of the wave after the breaking point, focusing on the relationship between the offshore wave forcing (here four wave climate A, B, C and D) and their associated wave forcing in the surf zone (see figure 2 for a sketch). Based on this analysis, a Swash Dean number can be calculated on local wave conditions on the terrace (surf zone), defined as $\Omega_{SW} = H_b(x) / (T_0\ W_S)$. $H_b(x)$ corresponds to the water height following the bore maximal height. As noted here, the local Swash Dean then depends on the position on the terrace. These results are illustrated in figure 2.

It is shown in figure 2b that as from 50 cm to breaking point the amplitude of the bore (Hb) remains rather constant for all wave climates. The dissipation of the bore can be represented by the following exponential law: where a, b and c are fit constants: Bore amplitude is similar for the four wave climates, and the same dissipation law can be attributed, thus the variation of Ω_{SW} depends mainly on wave period. Figure 2c illustrates the evolution of Ω_{SW} on the terrace as a function of the distance from the beach-face to the breaker point (x) divided by offshore wavelength (x/λ_0). Its observed that Ω_{SW} varies significantly on a small part of the terrace close to the breaker point when the wave moves away from it, while it remains nearly constant when the wave moves further away from the breaker (shown by dash-dot lines in figure 2c).

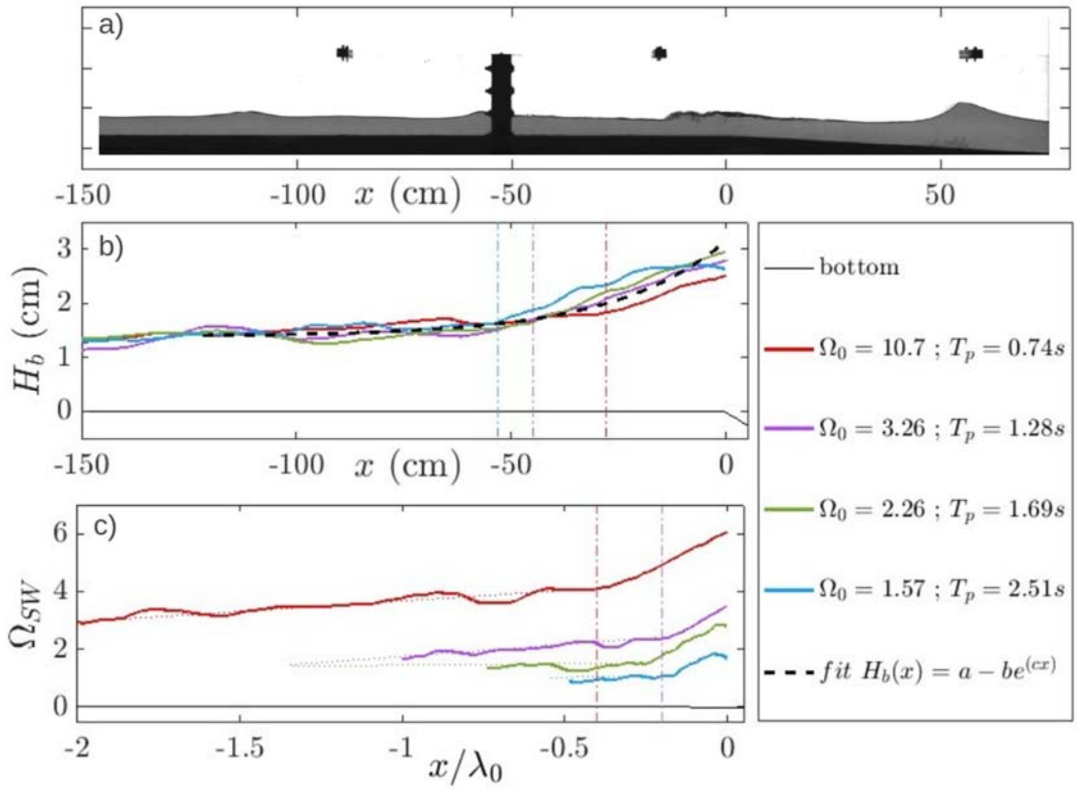

Figure 2. a) Illustration of the wave transformation in the rigid bottom. b) Free surface of the bore maximal height evolution on the terrace, $H_b(x,t)$. c) Evolution of Ω_{SW} on the terrace as a function of the distance from the breaking point to the beach-face divided by offshore wavelength (x/λ_0).

3.2 <u>Morphodynamics</u>

For each 2 hours run the trajectory of the beach-face slope can be captured (β(t) & X_0(t)). It has been observed for nearly all experiments that after 1000 waves impacting the beach-face a stable slope was reached. For some experiments it could take more time depending on the initial conditions of the beach-face (L_i & β_i). A stable beach-face slope is associated to Ω_0 and Ω_{SW}, calculated for each run between 1500 and 3000 waves acting on the beach-face. In this time range if the slope is active, meaning that it reacts to the wave climate, we ensure that it has reached its quasi-equilibrium value (β_{eq}). These equilibrium slopes (β_{eq}) are plotted with their associated Ω_0 and Ω_{SW} in figure 3. For wave climate A, a big dispersion of β_{eq} is observed (see figure 3a). This β_{eq} dispersion increases for increasing values of Ω_0. It is found that for $\Omega_0 > 2.5$ surf zone processes controls the beach face slope dynamics, different states of β_{eq} become dependent on initial shoreline position L_i, i.e. the distance to the breaker point. In order to highlight the influence of this surf length, and the associated dissipation of the wave energy, all quasi-equilibrium beach face slopes (β_{eq}) obtained for each individual initial condition and wave climate are plotted as a function of the local Ω_{sw} in figure 3b. There is a good correlation with field observations.

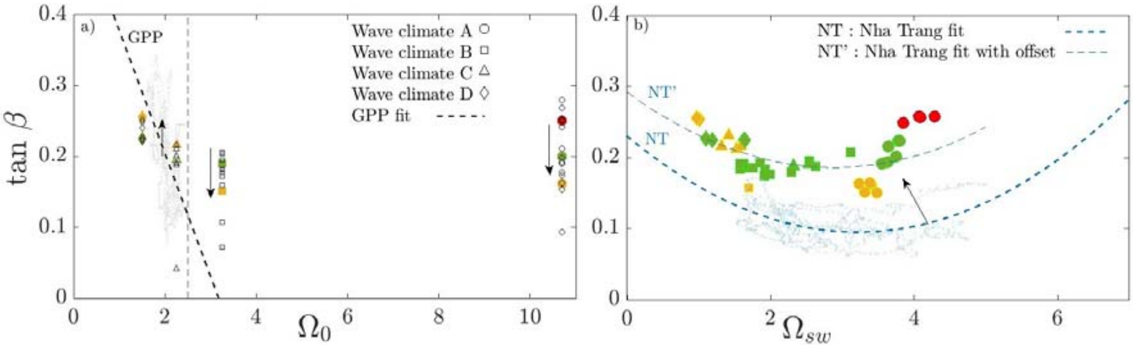

Figure 3. (a) Dean number vs quasi-equilibrium value of the beach-face slope (Ω_0 vs β_{eq}). Grey dots correspond to field data observations obtained at Grand Popo, Benin. (b): Swash Dean number vs quasi-equilibrium value of the beach-face slope (Ω_{sw} vs β_{eq}). Light blue dots correspond to field observations values obtained at Nha Trang, Vietnam.

4. Discussion and conclusions

The present laboratory model allows us to capture a quasi-equilibrium beach face slope (β_{eq}) for a constant wave forcing. Since there is no sediment input into the system, the beach profile is always in constant erosion until it reaches a stable point. It is observed that for a same grain size (D_{50}) and wave climate, different values of beach-face slope in quasi-equilibrium can be reached. These values fluctuate between tan β=0.15 and tan β=0.25. This dispersion is highly dependent on the initial conditions of the beach-face profile (L_i and β_i) and is more pronounced for increasing values of Ω_0. This means that the beach-face behaviour is highly controlled by the surf zone dynamics. Thus, it becomes necessary to analyse the dissipative beaches with the Swash Dean number (Ω_{sw}) that considers the dissipation of the wave in the surf zone. A parabolic trend of the mean beach-face slope with Ω_{sw} is shown in figure 3b.

These experimental results allow to describe quite nicely field data (see figure 3). Based on relative comparison between experiments and field data, a critical value of the offshore Dean number (Ω_0) close to 2.5 is highlighted, as the beach face slope trend changes its behaviour. For $\Omega_0<2.5$ there is an increasing trend of the beach face slope with the decreasing of Ω_0 and for $\Omega_0>2.5$ it's the opposite. Moreover, this experimental model allows to highlight the variability of quasi-equilibrium states with a terrace (or surf) length. This has been associated with a slope function of a local Dean number Ω_{sw} (see figure 3b). Again, this observed trend describes nicely field observations. This is a starting point to explain variability of beach-face states in quasi-equilibrium, observed in the field.

5. References

BAGNOLD R.A. (1940). *Beach formation by waves: some model experiments in a wave tank*. Journal of the Institution of Civil Engineers, vol 15 (1), pp. 27–52. https://doi.org/10.1680/ijoti.1940.14279

BASCOM W.N. (1951). *The relationship between sand size and beach face slope*. Trans. Am. Geophys. Un., vol 32, pp. 866–874. https://doi.org/10.1029/TR032i006p00866

BUJAN N., RONADH C., MASSELINK G. (2019). *From fine sand to boulders: Examining the relationship between beach-face slope and sediment size*. Marine Geology, vol 417, 106012. doi :10.1016/j.margeo.2019.106012

KEMP P.H. (1975). *Wave asymmetry in the nearshore zone and breaker area*. In: Hails J, A Carr (ed) Nearshore sediment dynamics and sedimentation, Wiley, pp 47–65. https://doi.org/10.1002/esp.3290010311

KIKKERT G.A., POKRAJAC D., O'DONOGUE T., STEENHAUER K. (2013). *Experimental study of bore-driven swash hydrodynamics on permeable rough slopes*, Coastal Engineering, vol. 79, pp. 42-56. https://doi.org/10.1016/j.coastaleng.2013.04.008

MASSELINK G., HUGHES M. (1998). *Field investigation of sediment transport in the swash zone*. Continental Shelf Research, vol. 18, pp. 1179–1199. doi:10.1016/S0278-4343(98)00027-2

MASSELINK G., LING L. (2001). *The role of swash infiltration in determining the beachface gradient: a numerical study*. Marine Geology, vol. 176 (1-4), pp. 137-156. https://doi.org/10.1016/S0025-3227(01)00161-X

MASSELINK G., PULEO G. (2006). *Swash-zone morphodynamics*, Cont. Shelf Res. Vol. 26 (5), pp. 661– 680. https://doi.org/10.1016/j.csr.2006.01.015

MINGO I.M., ALMAR R., LACAZE L. (2021). *Surf and swash dynamics on low tide terrace beaches*. Coasts 2021,vol. 1, pp. 73-89. https://doi.org/10.3390/coasts1010005

PULEO J.A., BEACH R.A., HOLMAN R.A., ALLEN J.S. (2000). *Swash zone sediment suspension and transport and the importance of bore-generated turbulence*. Journal of Geo- physical Research C: Oceans. Vol. 105, pp. 17021–17044. https://doi.org/10.1029/2000JC900024

THUAN D.H., ALMAR R., MARCHESIELLO P., TRUNG VIET N. (2019). *Video sensing of nearshore bathymetry evolution with error estimate*. Journal of Marine Science and Engineering. Vol 7 (7), 233. https://doi.org/10.3390/jmse7070233

TURNER I.L. (1995). *Simulating the influence of groundwater seepage on sediment transported by the sweep of the swash zone across macro-tidal beaches*. Marine Geology. Vol. 125 (1-2), pp. 153–174. https://doi.org/10.1016/0025-3227(95)00026-U