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RECENT IMPROVEMENTS FOR ESTIMATION OF LONGSHORE TRANSPORT

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EXTENDED ABSTRACT

Sempre più frequentemente, la preservazione dei paesaggi costieri, di centri urbani, di infrastrutture per la viabilità o dell'industria del turismo balneare pone la necessità di ricorrere ad interventi di ripascimento delle spiagge soggette ad erosione. La longevità degli interventi talvolta non risulta adeguatamente commisurata al costo sostenuto per la loro attuazione: non è raro che interventi di ripascimento, protetti o non, si depauperino in un breve lasso di tempo seguente alla esecuzione del lavoro, vanificando così l'investimento. Pertanto, negli ultimi anni, il progettista di un intervento di difesa della spiaggia dall'erosione tende a valutare la possibilità di effettuare il ripascimento artificiale di spiagge soggette ad erosione mediante l'impiego di materiali più grossolani rispetto alla sabbia nativa; tanto al fine di ottenere una spiaggia composta da elementi dotati di una maggiore stabilità idraulica rispetto a quelli della spiaggia originaria, a parità di condizioni di moto ondoso presenti nell'area di interesse. Tra gli altri, anche le Linee Guida per la difesa delle coste basse della Regione Puglia denominate "Individuazione di strutture di mitigazione del rischio per ciascuna unità fisiografica" invitano il progettista all'utilizzo di ghiaie o ciottoli per il ripascimento di arenili, tanto allo scopo di incrementare la longevità degli assai dispendiosi interventi a mare. Tuttavia, a tale condivisibile indicazione che giunge dagli Enti regolatori non corrisponde una adeguata risposta da parte del tecnico professionista. Ed infatti, mentre per il caso delle spiagge in sabbia esiste una ragguardevole conoscenza, la comunità scientifica e professionale avverte l'assenza di criteri e metodi in grado di valutare i volumi di materiale che vengono mobilizzati dall'azione del moto ondoso che interagisce con una spiaggia, anche se questa è formata da materiali che non siano sabbia; in particolare, la necessità di poter disporre di mezzi di calcolo che non siano limitati al solo caso delle spiagge in sabbia è maggiormente avvertita per la determinazione del trasporto litoraneo di ghiaie, ciottoli e spiagge miste (sabbia, ghiaie e ciottoli).

Il presente studio intende dare un contributo al tema del calcolo del trasporto litoraneo per spiagge composte da materiali più grossolani rispetto alla sabbia. In particolare, è stata condotta la verifica delle capacità del modello GLT (Tomasicchio *et alii*, 2013) nella stima del trasporto litoraneo per spiagge in ciottoli e spiagge miste. Il modello GLT adotta un approccio del tipo a flusso di energia, combinato con una relazione di tipo empirico/statistico tra la forzante, rappresentata dal moto ondoso incidente, e il numero di elementi che subiscono lo spostamento; GLT assume l'ipotesi che gli elementi che compongono la spiaggia si muovono, durante le fasi di risalita e discesa dell'onda lungo la battigia, con obliquità pari a quella delle onde frangenti e riflesse in corrispondenza della profondità di frangimento.

Allo scopo è stata verificata la appropriatezza del modello GLT nella quantificazione del trasporto litoraneo per il caso di spiagge in ciottoli. In particolare, la verifica è stata condotta, evitando qualsiasi tipo di taratura preventiva, mediante il confronto tra i risultati del modello e i dati osservati in campo (Chadwick, 1989; Nicholls & Wright, 1991); il confronto tra il dato osservato e il dato calcolato ha mostrato che il modello GLT è in grado di predire i dati del trasporto osservati con un'approssimazione limitata ad un fattore 2. Al fine di introdurre ulteriori termini di raffronto per il modello GLT, la sua capacità di calcolo è stata verificata favorevolmente anche rispetto ad un'altra formula generale per la stima del trasporto lungo spiagge composte da ciottoli (Van Rijn, 2014). Infine, passando ad un caso non raro in natura, ma anzi assai diffuso lungo le coste della Nuova Zelanda, dell'Inghilterra, dell'Iran, della Russia o della Calabria, l'affidabilità del modello GLT è stata accertata anche per il caso delle spiagge composte da sabbie, ghiaie e ciottoli (miste); tale seconda verifica è stata resa possibile dalla disponibilità di dati di letteratura osservati in campo per spiaggia mista e spiaggia in ghiaia nella baia di Hawke's Bay, lungo la costa est della Nuova Zelanda (Komar, 2010). A seguito della verifica favorevole del modello GLT condotta per il caso di spiagge in ciottoli e miste, è possibile sostenerne la possibilità di impiego per il caso di progettazione di interventi di ripascimento per i quali si intenda utilizzare materiali più grossolani rispetto alla sabbia. E' anche possibile ipotizzare l'utilizzo del modello nello sviluppo di modelli di previsione della evoluzione nel tempo della linea di riva per spiagge composte da ciottoli o di tipo misto.

ABSTRACT

In the present study, the accuracy of the GLT model (Tomasicchio *et alii*, 2013) has been verified for the estimation of the Longshore Transport (LT) at shingle and mixed beaches. In order to verify the suitability of the GLT model in determining LT estimates at shingle beaches, without any further calibration, the comparison between the LT predictions and observations from two field data sets (Chadwick, 1989; Nicholls & Wright, 1991) has been considered. The comparison showed that the GLT predicted LT rates within a factor of 2 of the observed values. The predictive capability of the GLT has been also verified against an alternative general formula for the LT estimation at shingle beaches (Van Rijn, 2014). In addition, the suitability of the GLT model, even for the mixed beach case, has been assessed by means of the comparison between the LT prediction and the observation from a field experiment on a mixed sand and gravel beach at Hawke's Bay, on the east coast of New Zealand (Komar, 2010).

Keywords: *longshore transport, shingle beach, mixed beach*

INTRODUCTION

The formulation of a reliable estimate of the longshore transport (LT) rate is paramount in coastal engineering problems. Indeed, practical applications such as the design of dynamically stable reshaping or berm breakwaters, dispersion of the beach-fill and placed dredged material, beach nourishment projects, sedimentation rates in navigation channels, they all require accurate predictions of the LT. Such estimates should be based only on the use of valuable sediment transport models underpinned by reliable transport measurements (Van Wellen *et alii*, 1998).

To date, sandy beaches have received the bulk of the attention. The number of documented studies and available data on sandy beaches is, therefore, considerable and ranges from analytical/numerical models and laboratory tests to large scale field experiments. In strong contrast is the moderate attention which coarser grained (i.e. shingle) and, in particular, mixed sand and gravel beaches have received.

Presently, there is a growing interest in properly defining the morphological processes of a shingle/mixed beach due to the increased use of coarse sediments in the artificial recuperation of eroded beaches, as they are characterized by a higher hydraulic roughness and provide a better defense to the forcing processes induced during storm events (Tomasicchio *et alii*, 2010; Bramato *et alii*, 2012).

Generally cobbles roll, coarse sand moves by a series of hops or leaps (i.e. saltation) and fine sand and silt move in suspension (Dake, 1972). Longshore transport (LT) at shingle beaches is characterized by a steep beach slope, typically 1:8, which encourages waves to form rapidly plunging or surging breakers close to the shoreline; thus, most of the energy dissipation is restricted to a narrow region that includes the swash zone (Van Wellen *et alii*, 2000). Well sorted coarse sediments also exhibit a larger permeability compared to the sand; this allows larger infiltration of water during the swash run-up, which weakens the backwash and can be identified with the formation of the berm at the run-up maximum. These phenomena are rather different than on typical sandy beaches for which most popular formulae (e.g. Kamphuis, 1991; U.S. Army Corps of Engineers - USACE, 1984) have been developed.

Although several shingle beach field experiments have been conducted in the past, insufficient information has been obtained to make them useful to calibrate LT formulae; in fact, most published sources of shingle beach data failed on the lack of concurrent wave measurements and transport rates. To our knowledge, only two field data sets satisfy the criteria of available wave conditions (height, period and angle), transport rates, beach slopes and grain size: Shoreham-by-Sea (Chadwick, 1989) and Hurst Castle Spit (Nicholls & Wright, 1991), both in the UK.

The General Longshore Transport (GLT) model (Tomasicchio *et alii*, 2013) and the Van Rijn (2014) expression represent the only two general formulae in literature for the estimation of LT at sand, gravel and shingle beaches. In particular, the GLT model is based on an energy flux approach combined with an empirical relationship between the wave induced forcing and the number of moving elements. Tomasicchio *et alii* (2015) showed that GLT gives a good agreement even for the LT at dynamically stable berm reshaping breakwaters. Recently, within the START project, an extensive verification of the GLT model has been performed (Tomasicchio *et alii*, 2016; D'Alessandro *et alii*, 2016).

TWO GENERAL FORMULAE FOR THE ESTIMATION OF LT

The GLT model

A general model is defined relating LT due to oblique wave attacks to the mobility level of the units composing the coastal structure (Lamberti & Tomasicchio, 1997). The LT model is based on the assumption that movements statistics is affected by obliquity only through an appropriate mobility index and that the units move during up- and down-rush with the same obliquity of breaking and reflected waves at the breaker depth (Lamberti & Tomasicchio, 1997; Tomasicchio *et alii*, 1994). A particle will pass through a certain control section in a small time interval Δt if and only if it is removed from an updrift area of extension equal to the longitudinal component of the displacement length, $l_d \sin \theta_d$, where l_d is the displacement length and θ_d is its obliquity (Fig. 1).

This process description is particularly true when considering the wave obliquity, the up-rush and related LT at the swash zone. Assuming that the displacement obliquity is equal to the characteristic wave obliquity at breaking (θ_d=$\theta_{k,b}$), and that a number N_{od} of particles removed from a nominal diameter, D_{n50}, wide strip moves under the action of 1000 waves, then the number of units passing a given control section in one wave is:

$$S_N = \frac{l_d}{D_{n50}} \cdot \frac{N_{od}}{1000} sin\theta_{k,b} = f(N_s^{**}) \tag{1}$$

where:

$$N_s^{**} = \frac{H_k}{C_k \Delta D_{n50}} \left(\frac{s_{m,0}}{s_{m,k}}\right)^{-1/5} (cos\theta_0)^{2/5} \tag{2}$$

is the modified stability number (Lamberti & Tomasicchio, 1997) with: H_k = characteristic wave height; C_k=H_k/H_s where H_s = significant wave height; θ_0 = offshore wave obliquity; $s_{m,0}$ = mean wave steepness at offshore conditions and $s_{m,k}$ = characteristic mean wave steepness (assumed equal to 0.03). Lamberti & Tomasicchio (1997) reported that H_k is to be considered equal to $H_{1/50}$, but $H_{2\%}$ can also be adopted. In the first case: C_k = 1.55, in the second case: C_k = 1.40. The second factor in Eq. (2) is such that $N_s^{**} \cong N_s$ for $\theta_0 = 0$ if $s_{m,0}$=$s_{m,k}$. For a berm breakwater, strict threshold conditions correspond to $Ns^{**} \cong 2$.

In the case of head-on wave attacks, under the assumption that, offshore the breaking point, the wave energy is negligible and that waves break as shallow water waves, the following relation holds:

$$F = 1/8\,\rho g H_0^2 c_{g,0}^2 = 1/8\,\rho g H_b^2 c_{g,b}^2 \tag{3}$$

where $c_{g,0}$ is the offshore wave group celerity, $c_{g,b}$ is the wave group celerity at breaking, H_0 is the offshore wave height and H_b is the wave height at breaking. Considering Eq. (3) and $c_{(g,0)}$=½ $\sqrt{g/k_0}$, where k_0 is the offshore wave number, the longshore component of F can be written as:

$$Fcos\theta \propto H_0^{5/2} s_0^{-1/2} cos\theta \tag{4}$$

and $cos\,\theta$ is present in Eq. (2) with a power *2/5*.

Eq. (3) related to $\gamma_b = H_b/h_b$ imply:

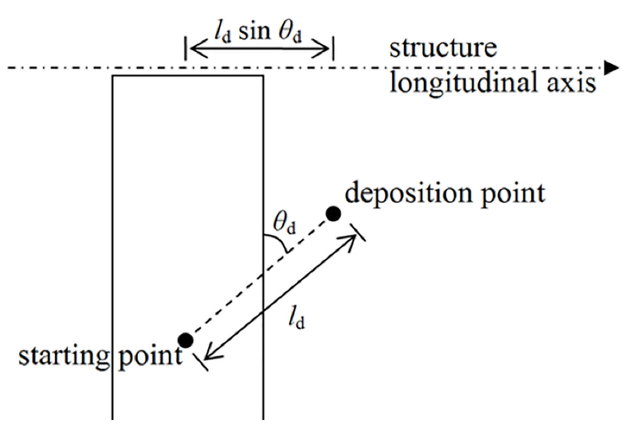

Fig. 1 - Definition sketch for the GLT model

$$H_b = H_0 \left(\frac{\gamma_b}{4k_0 H_0}\right)^{1/5} = qH_0 s_0^{-1/5} \tag{5}$$

Komar & Gaughan (1972) found the best agreement with field and laboratory data assuming $\gamma_b = 1.42$ or the proportionality constant $q = 0.56$. It follows that, considering the characteristic wave height at breaking, $H_{k,b}$, and $s_{m,0} = s_{m,k} = 0.03$, Ns^{**} can be also written as:

$$N_s^{**} \cong \frac{0.89 H_{k,b}}{C_k \Delta D_{n50}} \tag{6}$$

and it can be noticed that, according to the proposed LT model, the relevant parameter is the onshore energy flux and that the proposed model belongs to the category based on an energy flux approach.

According to the refraction theory for plane and monotonically decreasing profiles, $H_{k,b}$ and $sin\theta_{k,b}$, can be evaluated as in the following (Lamberti & Tomasicchio, 1997; Tomasicchio *et alii*, 1994):

$$H_{k,b} = \left(H_k^2 c_g cos\theta \sqrt{\gamma_b/g}\right)^{2/5} \tag{7}$$

$$sin\theta_{k,b} = \frac{c_{k,b}}{c} sin\theta \tag{8}$$

$$\boldsymbol{c_{k,b}} = \sqrt{\boldsymbol{g H_{k,b}/\gamma_b}} \tag{9}$$

where $c_{k,b}$ is the characteristic wave celerity at breaking depth.

The displacement length is calculated as (Lamberti & Tomasicchio, 1997):

$$l_d = \frac{(1.4N_s^{**} - 1.3)}{tanh^2(kh)} D_{n50} \tag{10}$$

with k = wave number.

N_{od} has been determined following a calibration procedure based on the least-squares method taking into account the full data base. In particular, two different approximating functions are considered; to accommodate the calibration procedure, N_{od} values calculated from measured data are partitioned in two subintervals. The first interval refers to $Ns^{**} \leq 23$: from berm breakwaters to gravel beaches. The second one relates to Ns** > 23: the interval for sandy beaches. For $Ns^{**} \leq 23$, a third order polynomial approximating function provides a satisfactory agreement as shown by Tomasicchio *et alii* (2007). For $Ns^{**} > 23$ a good agreement is given by a linear regression in log-log plane.

After the adopted calibration procedure N_{od} is given as:

$$N_{od} = \begin{cases} 20N_s^{**}(N_s^{**} - 2)^2 & N_s^{**} \leq 23 \\ exp[2.72 ln(N_s^{**}) + 1.12] & N_s^{**} > 23 \end{cases} \tag{11}$$

The estimated correlation coefficient results equal to 0.89 for $Ns^{**} \leq 23$, and 0.92 for $Ns^{**} > 23$, respectively.

LT rate can be also expressed in terms of [m^3/s] as in the following:

$$Q_{LT} = \frac{S_n D_{n50}^3}{(1-p)\ T_m} \tag{12}$$

with T_m = mean wave period and p = particles porosity.

Van Rijn (2014) formula

The process-based CROSMOR-2013 model has been used to determine the effects of wave period, grain size, beach/surf zone slope and type of waves (wind waves or swell waves). The CROSMOR-2013 model is an updated version of the CROSMOR-2004 model (Van Rijn, 2006/2012, 2007) and computes both the cross-shore and longshore transport rates. The model has been extensively validated by Van Rijn *et alii* (2003) and (2011).

The LT has been found to be proportional to wave height to the power 3.1 ($\approx H^{3.1}$), to grain size to the power -0.6 ($\approx D_{n50}^{-0.6}$) and to beach slope to the power 0.4 ($\approx tan\beta^{0.4}$). Based on the CROSMOR-2013 results, it is assumed that the longshore transport rate ($Q_{t,mass}$ in kg/s) can be represented by the following (dimensionally correct) expression:

$$Q_{(t,mass)} = \alpha M \tag{13}$$

with M is mobility parameter (in kg/s)

$$M = \rho_s g^{0.5} (tan\ \beta)^{0.4} (D_{n50})^{-0.6} (H_{s,br})^{3.1} sin(2\theta_{br})$$

ρ_s = sediment density (kg/m^3), g = acceleration due to gravity (m/s^2), $tan\ \beta$ = slope of beach/surf zone, D_{n50} = median grain size (m), $H_{s,br}$ = significant wave height at breaker line (m), θ_{br} = wave angle to shore normal at breaker line (degrees), α = calibration coefficient = 0.00018. Thus:

$$Q_{t,mass} = 0.00018\ \rho_s\ g^{0.5}\ (tan\ \beta)^{0.4}\ (D_{n50})^{-0.6}\ (H_{s,br})^{3.1}\ sin\ (2\ \theta_{br}) \tag{14}$$

Eq. (14) does not account for the effect of the wave period on the longshore transport rate.

SHINGLE BEACHES DATA

Several field investigations on LT at shingle beaches have been conducted along the UK coastline. In the present paper, two field data sets have been adopted: Shoreham-by-Sea (Chadwick, 1989) measured by traps and Hurst Castle Spit (Nicholls & Wright, 1991) measured by tracers. In Chadwick (1989) and Nicholls & Wright (1991) LT rates are given as mass transport rate per unit time ($Q_{LT,m}$ in kg/s). These values have been converted to the LT rates in volume per unit time (Q_{LT} in m^3/s) by using $Q_{LT} = Q_{LT,m} /(1-p)\rho_s$ with p = porosity factor (0.45 for shingle). Table 1 lists the observed data (n=6 data points; T_p = peak wave period; $Q_{LT,o}$=LT rate in volume per unit time, observed).

Van Hijum & Pilarczyk (1982) conducted a limited number of laboratory 3D experiments on gravel sized beaches at the Delft Hydraulics laboratory. LT has been measured from beach profile surveys using the principle of continuity of sediments in the longshore direction. In Van Hijum & Pilarczyk (1982)

Location	n (-)	D_{n50} (mm)	ρ_s (kg/m^3)	tanβ	$H_{s,br}$ (m)	θ_{br} (°)	T_p (s)	$Q_{LT,o}$ (m^3/s)
Shoream, UK	4	20	2650	0.1	0.30	15	3	3.1E-05
		20	2650	0.1	0.35	15	3	1.1E-04
		20	2650	0.1	0.40	15	3	1.9E-04
		20	2650	0.1	0.70	15	4	3.1E-04
Hurst Castle Spit, UK	2	32	2650	0.1	0.75	15	6	3.1E-04
		32	2650	0.1	1.00	15	6	9.4E-04

Tab. 1 - Longshore transport field data (Chadwick, 1989; Nicholls & Wright, 1991)

n (-)	D_{n50} (mm)	ρ_s (kg/m^3)	tanβ	$H_{s,0}$ (m)	θ_0 (°)	T_p (s)	$Q_{LT,o}$ (m^3/s)
10	4	2570	0.2	0.076	30	1.18	1.1E-05
	4	2570	0.2	0.088	30	1.00	1.0E-05
	4	2570	0.2	0.080	30	1.44	2.1E-05
	4	2570	0.2	0.129	30	1.46	8.7E-05
	4	2570	0.2	0.090	30	1.43	2.3E-05
	4	2570	0.2	0.124	30	1.45	5.6E-05
	4	2570	0.2	0.085	30	1.80	2.8E-05
	4	2570	0.2	0.124	30	1.81	8.0E-05
	4	2570	0.2	0.119	30	2.05	7.1E-05
	4	2570	0.2	0.165	30	2.06	2.0E-04

Tab. 2 - Longshore transport laboratory data (Van Hijum & Pilarczyk, 1982)

LT rates are given as the ratio S(x)/gD_90^2 T_s where: S(x) = component of resulting material transport, S, parallel to the beach (m^3/s); D_{90}=90% representative grain diameter (D90 =1,2D_{n50}); Ts =significant wave period. Information on wave characteristics are given offshore the breaker line (Tab. 2).

For the shingle beach case, calibration of the Van Rijn (2014) formula made use of data from Chadwick (1989) and Nicholls & Wright (1991).

Calibration of the GLT model (Tomasicchio *et alii*, 2013) made use of different field and laboratory data ranging from sandy beaches till reshaping berm breakwaters; in particular, for the shingle beaches case, laboratory data from Van Hijum & Pilarczyk (1982) have been adopted.

GLT VERIFICATION

Although the GLT model has been proposed and verified for an extensive range of conditions, from sandy beaches till reshaping or berm breakwaters, its verification, without any further calibration, is now particularly focused to the case of shingle beaches: for this purpose, the Chadwick (1989) and Nicholls & Wright (1991) field data have been considered. Fig. 2 shows the relationship between the calculated *SN/sinθ*$_{k,b}$ versus *Ns*** (Lamberti & Tomasicchio, 1997). With reference to the range of variation of *Ns***, the second region refers to the shingle beaches (cobbles and gravel, 6 <Ns**< 23); this region is now reporting a larger number of data (Chadwick, 1989; Nicholls & Wright, 1991) which allows to confirm that the GLT model gives reliable estimates of the longshore transport

Data set	n	d_r (%) – data with $Q_{LT,c}/Q_{LT,o}$ in the range [0.5, 2]	d_r (%) – data with $Q_{LT,c}/Q_{LT,o}$ in the range [0.25, 4]
[a]Shoream, UK	4	25	25
[a]Hurst Castle Spit, UK	2	50	0
[b]Van Hijum and Pilarczyk (1982)	10	20	0
Total	16	25	6.25

Tab. 3 - Capability of the GLT model ([a]data adopted for verification of the GLT model, [b]data adopted for calibration of the GLT model)

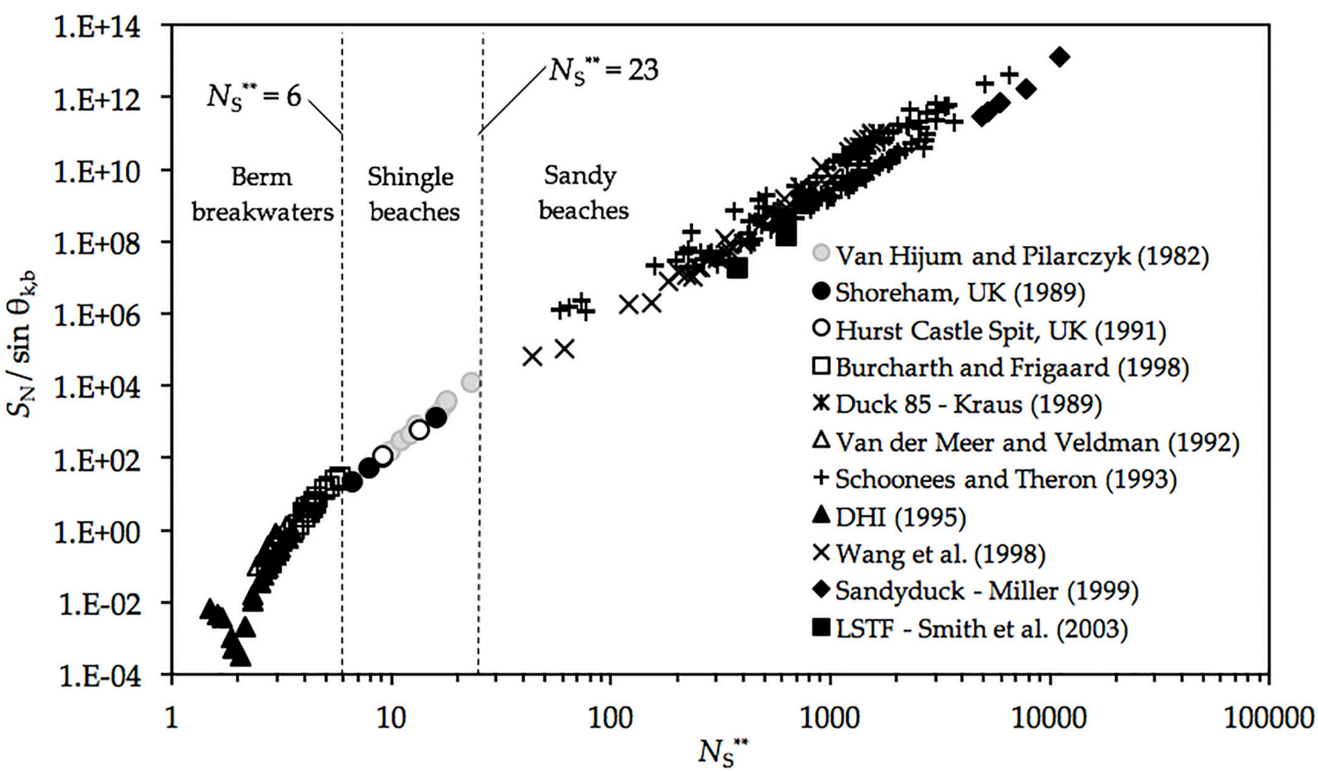

*Fig. 2 - Calculated SN/sinθk,b versus Ns***

Data set	n	d_r (%) – data with $Q_{LT,c}/Q_{LT,o}$ in the range [0.5, 2]	d_r (%) – data with $Q_{LT,c}/Q_{LT,o}$ in the range [0.25, 4]
[a]Shoream, UK	4	0	0
[a]Hurst Castle Spit, UK	2	0	0
[b]Van Hijum and Pilarczyk (1982)	10	90	60
Total	16	56.25	37.5

Tab. 4 - Capability of the Van Rijn (2014) formula (adata adopted for calibration of the Van Rijn (2014) formula, bdata adopted for verification of the Van Rijn (2014) formula)

at shingle beaches.

In order to have a measure of the scatter, according to Bayram *et alii* (2007), a mean discrepancy ratio, dr, has been assigned to the GLT model given by the percentage of the calculated LT, $Q_{LT,c}$, within an interval of confidence in the range between 0.5 and 2 of the observed LT, $Q_{LT,o}$; the resulting value of dr is subtracted from 100% to yield a small number for good agreement. An extended interval of confidence in the range between 0.25 and 4 of the observation points has been also considered in the analysis. Table 3 summarizes the values of dr for the different adopted field and laboratory data sets. A low discrepancy is obtained within the extended interval of confidence between 0.25 and 4, where most of the data points are included.

GLT COMPARISON WITH VAN RIJN (2014) FORMULA

The predictive capability of the GLT model has been verified against an alternative general formula for the LT estimation at shingle beaches (Van Rijn, 2014).

Figure 3 shows the calculated and observed values of Q_{LT} together with the two considered intervals of confidence for GLT and Van Rijn (2014) formulae.

The estimated dr values for the investigated Van Rijn (2014) formula are shown in Table 4.

Comparison of the results in Fig. 3 and summarized in Tables 3 and 4 reveals that the proposed GLT model exhibits the smallest dr compared to the Van Rijn (2014) formula.

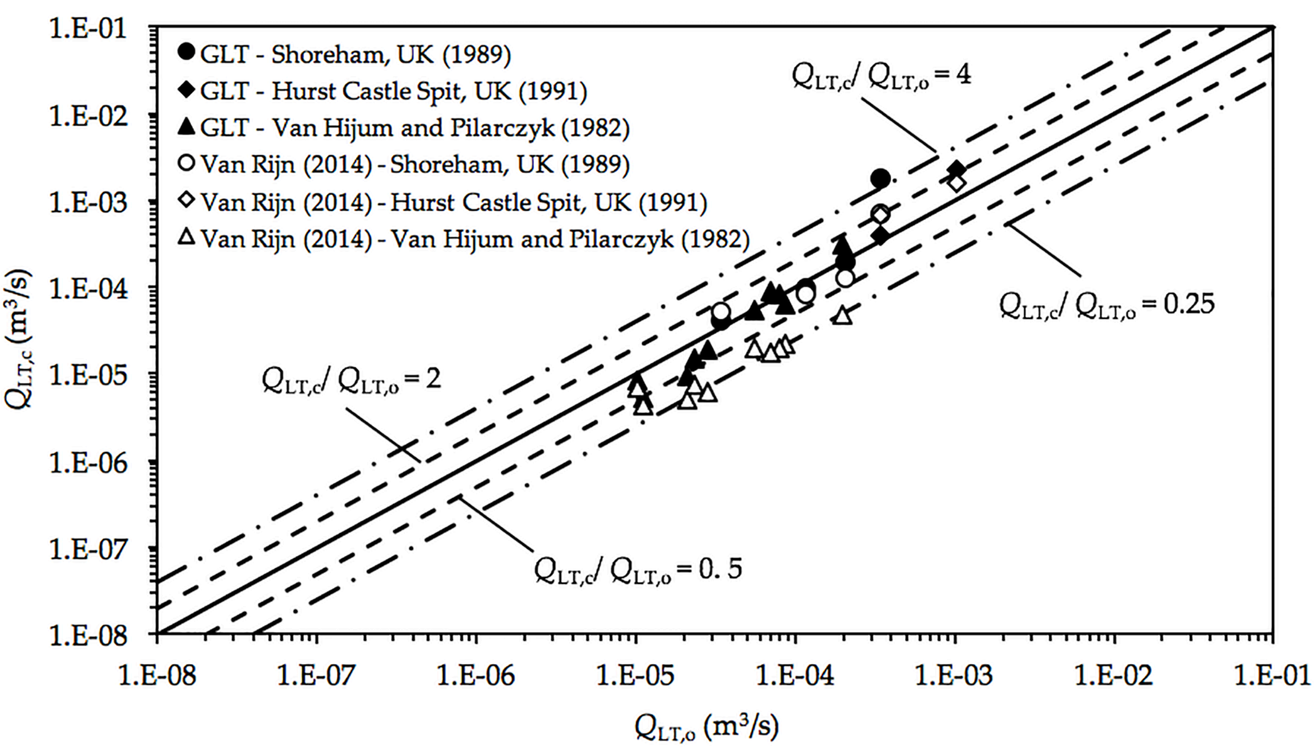

Fig. 3 - Calculated versus observed LT (m³/s)

LT AT A MIXED SAND AND GRAVEL BEACH

Mixed sand and gravel beaches are beaches consisting of high proportions of both coarse particles and sand, with there being an intimate mixing of the two size fractions in the beach deposit.

Mixed beach, with poorly sorted grains of multiple sizes, are a common and globally distributed shoreline type. Despite this, rates and mechanisms of sediment transport on mixed beaches are poorly understood.

Mixed sand and gravel beaches are similar in form to gravel beaches, but the morphodynamics of the mixed beaches are distinct and potentially more complex than either sand or gravel beaches (Pontee *et alii*, 2004; Ivamy & Kench, 2006).

In the present paper, the suitability of the GLT model, even for the mixed beach case, has been assessed by means of the comparison between the LT prediction and the observation from a field experiment on a mixed sand and gravel beach at Hawke's Bay, on the east coast of New Zealand (Komar, 2010; Dickson *et alii*, 2011).

Figure 4 compares the orientations of two littoral cells, Bay View and Haumoana, respectively, with the dominant southeast waves (shown by the wave rays).

The sediment composition varies from fine sand to very coarse elements with diameters ranging between 0.17 mm and 64 mm.

Multiple factors have affected the Hawke's Bay shore and the locally induced beach and property erosion. An examination of the credits and debits in the sediment budget for the Haumoana cell, shown in Table 5, reveals that the debits are substantially greater than credits, with the net balance being -45,000 m^3/yr. Specifically, the net balance of -45,000 m^3/yr has been obtained directly from the beach profiles collected over the years by the monitoring program, and, as a result, this value is one of the more confident assessments in the budget (Tonkin & Taylor, 2005).

The estimated mean sediment volume by GLT model was about 23,000 m^3/yr for a mean annual value of H_s when D_{n50} = 32 mm. Possible reasons for disagreement can be found in (i) defining of the mound material in the GLT: i.e. sorting, porosity; (ii) a missing extensive information on wave climate and (iii) considered field data limitations (large influence from human activities). According to the latest point, sediment budget was affected by environmental impacts of human interventions.

CONCLUSIONS

The GLT model and the Van Rijn (2014) expression represent the only two available general formulae in literature for the estimation of LT at sand, gravel and shingle beaches.

The GLT model belongs to the category based on an energy flux approach: in fact, the relevant wave parameter is the onshore energy flux giving the dependency of the longshore transport phenomena from the wave period (Tomasicchio *et alii*, 2013).

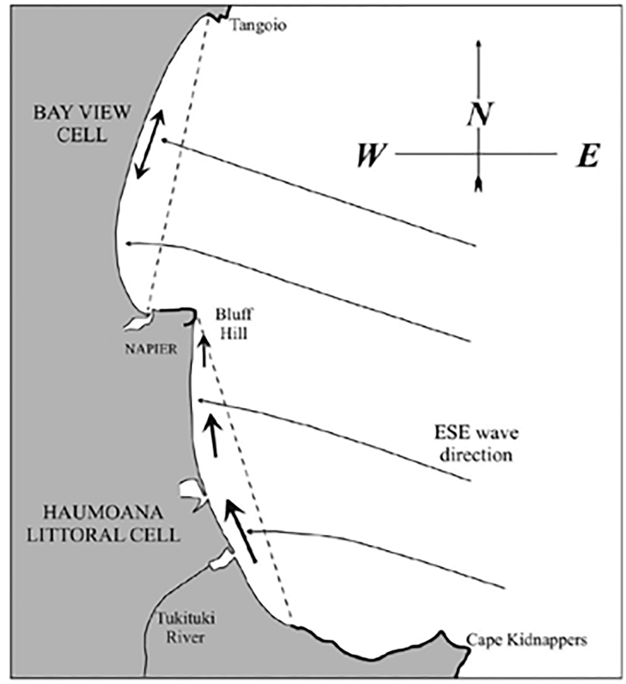

Fig. 4 - Orientations of the shores of the Bay View and Haumoana littoral cells, compared with the directions (wave rays) of the prevailing waves. The arrows denote the patterns of the longshore sediment transport (Komar, 2010)

Budget components	Estimated annual rates (m^3/yr)
Sources (credits)	
Tukituki River	28,000
Cape Kidnappers erosion	18,000
Total	46,000
Losses (debits)	
Awatoto extraction	-47,800
Pacific Beach extraction	-12,800
Gravel abrasion	-30,400
Total	-91,000
Net balance of beach sediments	-45,000

Tab. 5 - The sediment budget for the Haumoana littoral cell (modified from Tonkin & Taylor, 2005)

Similarly to the CERC formula (U.S. Army Corps of Engineers - USACE, 1984), the GLT model does not depend on the slope of the beach profile; this absence eliminates a source of uncertainty.

Van Rijn (2014) formula does not take into account the influence of the wave period of irregular wind waves; influence of wave period is taken into account for regular swell waves solely by means of a swell correction factor. Moreover, the author indicates a significant underprediction of LT in the case of very low waves at shingle beaches which is justified by neglecting the longshore transport at the swash zone above the mean waterline.

The verification of the two procedures, without any further calibration, has been conducted against two field and one laboratory data sets. In most cases the GLT predicted LT rates within a factor of 2 of the observed values. Van Rijn (2014) formula gave results which are slightly smaller than the laboratory observations (Van Hijum & Pilarczyk, 1982). The estimated dr values showed that the GLT model gives a better agreement with the observed data with respect to the other investigated formula.

In addition, the suitability of the GLT model, even for the mixed beach case, has been assessed by means of the comparison between the LT prediction and the observation from a field experiment on a mixed sand and gravel beach at Hawke's Bay, on the east coast of New Zealand.

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REFERENCES

Bayram A., Larson M. & Hanson H. (2007) - *A new formula for the total longshore sediment transport rate*. Coastal Engineering, **54** (9): 700-710.

Bramato S., Ortega-Sanchez M., Mans C. & Losada M.A. (2012) - *Natural recovery of a mixed sand and gravel beach after a sequence of a short duration storm and moderate sea states.* Journal of Coastal Research, **28**: 89-101.

Chadwick A.J. (1989) - *Field measurements and numerical model verification of coastal shingle transport.* BHRA, The Fluid Engineering Centre, UK, pp. 381-402 (Chapter 27).

Dake J.M.K. (1972) - *Essential engineering hydraulics*. MacMillan Intern. College Edition.

D'Alessandro F., Tomasicchio G.R., Coppini G. & Federico I. (2016) - *Climate change adaptation and coastal management.* Proceedings of the IV Annual Conference of the Italian Society for Climate Sciences, Cagliari, printed on-line.

Dickson M.E., Kench P.S. & Kantor M.S. (2011) - *Longshore transport of cobbles on a mixed sand and gravel beach, southern Hawke Bay, New Zealand.* Marine Geology, **287**: 31-42.

Ivamy M.C. & Kench P.S. (2006) - *Hydrodynamics and morphological adjustment of a mixed sand and gravel beach, Torere, Bay of Plenty, New Zealand.* Marine Geology, **228**: 137-152.

Kamphuis J.W. (1991) - *A longshore sediment transport rate*. Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, **117**: 624-640.

Komar P.D. (2010) - *Shoreline evolution and management of Hawke's Bay, New Zeland: tectonics, coastal processes and human impacts.* Journal of Coastal Research, **26** (1): 143-156.

Komar P.D. & Gaughan M.K. (1972) - *Airy wave theory and breaker height prediction.* Proceedings of the 13th International Conference on Coastal Engineering, ASCE, Vancouver, 405-418.

Lamberti A. & Tomasicchio G.R. (1997) - *Stone mobility and longshore transport at reshaping breakwaters.* Coastal Engineering, **29** (3): 263-289.

Nicholls R.J. & Wright P. (1991) - *Longshore transport of pebbles: experimental estimates of K*. Proceedings of Coastal Sediments '91, ASCE, 920-933.

Pontee N.I., Pye K. & Blott S.J. (2004) - *Morphodynamic behaviour and sedimentary variation of mixed sand and gravel beaches, Suffolk, UK*. Journal of Coastal Research, **20**: 256-276.

Tomasicchio G.R., Lamberti A. & Guiducci F. (1994) - *Stone movement on a reshaped profile.* Proceedings of the 24th International Conference on Coastal Engineering, ASCE, Kobe, 1625-1640.

Tomasicchio G.R., Archetti R., D'Alessandro F. & P. Sloth P. (2007) - *Long-shore transport at berm breakwaters and gravel beaches.* Proceedings of the International Conference Coastal Structures '07, World Scientific, Venice, 65-76.

Tomasicchio G.R., D'Alessandro F. & Musci F. (2010) - *A multi-layer capping of a coastal area contaminated with materials dangerous to health.* Chemistry and Ecology, **26** (1): 155-168.

Tomasicchio G.R., D'Alessandro F., Barbaro G. & Malara G. (2013) - *General longshore transport model.* Coastal Engineering, **71** (1): 28-36.

Tomasicchio G.R., D'Alessandro F., Barbaro G., Musci E. & De Giosa T.M. (2015) - *General longshore transport model at shingle beaches: an independent verification.* Coastal Engineering, **104**: 69-75.

Tomasicchio G.R., D'Alessandro F., Barbaro G., Ciardulli F., Francone A. & Kurdistani S.M. (2016) - *General model for estimation of longshore transport at shingle/mixed beaches.* Proceedings of the 3rd International Conference on Coastal Zone Engineering and Management in the Middle East, Arabian Coast 2016, Dubai, (https://journals.tdl.org/icce/index.php/icce/article/view/8250).

Tonkin & Taylor (2005) - Shoreline modelling report. Report to the Hawke's Bay Regional Council, Christchurch, New Zealand. Tonkin & Taylor.

U.S. Army Corps of Engineers - USACE (1984) - *Shore protection manual.* U.S. Army Corps of Engineers Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg.

Van Hijum E. & Pilarczyk K.W. (1982) - *Equilibrium profile and longshore transport of coarse mate-rial under regular and irregular wave attack.* Delft Hydraulics Laboratory, Netherlands, Publication n. 274.

Van Rijn L.C. (2007) - *Unified view of sediment transport by currents and waves, IV: application of morphodynamic model.* Journal of Hydraulic Engineering, ASCE **133** (7): 776-793.

Van Rijn L.C. (2012) - *Principles of sedimentation and erosion engineering in rivers, estuaries and coastal seas*. Aqua Publications, The Netherlands (www.aquapublications.nl).

Van Rijn L.C. (2014) - *A simple general expression for longshore transport of sand, gravel and shingle*. Coastal Engineering, **90**: 23-39.

Van Rijn L.C., Walstra D.J.R., Grasmeijer B., Sutherland J., Pan S. & Sierra J.P. (2003) - *The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based models*. Coastal Engineering, **47**: 295-327.

Van Rijn L.C., Tonnon P.K. & Walstra D.J.R. (2011) - *Numerical modelling of erosion and accretion of plane sloping beaches at different scales.* Coastal Engineering, **58**: 637-655.

Van Wellen E., Chadwick A.J. & Mason T. (2000) - *A review and assessment of longshore sediment transport equations for coarse-grained beaches*. Coastal Engineering, **40** (3): 243-275.

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