Pebble Origin and Beach Zone Differentation

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Abstract

Cliff erosion, mainly by toppling and/or translation at a pocket beach located at Southerndown bay, Wales, UK is *circa* 8-10cm /year and the resultant debris has given rise to a massive pebble beach. Three orthogonal beach profiles, were measured every spring tide over a whole winter period and on each occasion, 30 pebbles were measured at selected locations: the ridge top (A); the high tide position (B), slope break (C), basal sand/pebble junction (D), shore platform (E), in total 6,480. 'Sweep zone' profiles were drawn, pebble axes (a,b,c) measured, various indices obtained, Zingg diagrams drawn and statistics utilised to agree/disagree with the Null hypothesis (H_o) that there was a heterogeneous mixture of pebble shapes along the various zones in winter conditions. Under swell (summer) wave conditions, a standard zonation is expected with disc shapes predominant on the ridge top, spheres at the bottom, blades and rods in mid profile. In winter, storm waves are frequent and rearrange pebbles so that shape differentiation does not occur. Results showed that there was no statistically significant zonal differences for rod shapes; only one for disc shapes (between positions A and D); two for sphere shapes (between positions A with C and D); and three for blade shapes (between positions A and C, B and C, and C and E). H_o was proved correct.

Keywords: Pebble origin, beach zone differentiation, cliff erosion

Introduction

Within the coastal zone, erosion is globally an acute problem and in future years, this is likely to increase. Erosion, especially cliff undercutting increases the risk of failure and adds to beach sediment production, but recession is very significant for human utilisation of the coast. The erosional processes responsible for cliff failures are well known and can be found, for example, in books by Komar (1976), and Sunamura (1992). A notch, - a laterally extending hollow at the cliff base, is a clear indicator of cliff erosion, but '*available data… are surprisingly limited in number* '(Sunamura, 1992, 184) and causes instability leading to collapse with the resulting debris usually being beaches of pebbles, cobbles and occasionally boulders. Rates of cliff erosion are functions of:

- Strength of the cliff forming rock material.
- Basal wave energy.
- Amount of abrasive material available at the cliff base, i.e. a large amount forms a protective cover (a beach) and limits notching.

Compared with sand beaches, pebble and gravel beaches have been in the main poorly represented in littoral zone studies, but these beaches offer nature's best coastal protection, as they perform as a natural hydraulically engineered buffer structure to the energy inherent in the sea. Over a century ago, UK Government reports stressed the importance of more research into pebble beaches, but this report and subsequent ones, have had little effect on pebble studies (RCCEA, 1911).

Physical Background

Southerndown - a small pocket beach with a width of *circa* 150 m encompasses a massive pebble ridge at the landward edge followed by a 400m wide expanse at spring low tide of seaward extending sand. It is located along the Glamorgan Heritage Coast (GHC) on the northern shore of the Bristol Channel, UK (Fig. 1). This estuary has the second highest tidal range in the world (16.4m at Avonmouth located to the east) and the Southerndown tidal range is *circa* 8 m, but it is a high wave energy environment with a 5,000 km fetch in the direction of the prevailing and dominant south-westerly winds and 25% of these winds have speeds>50km/hr.

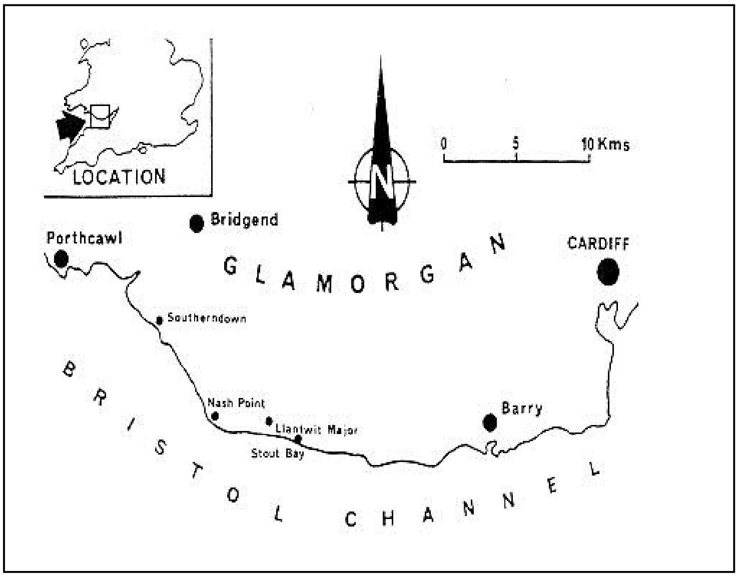

Fig. 1. Location

Wave energy densities calculated for the Pierson-Moskowitz spectrum of H_s=1.65 m. and T_z =6 seconds, were $2m^2 Hz^{-1}$ at a frequency of 0.1 Hz. The highest wave energy has typical values of the order of 68.10^5 Jm^{-1} crest width per day (Williams and Davies, 1987). The mean height of the highest one third of the waves is 3-3.5 m and in storm surge conditions, an enhanced wave height of 3.5 m for the 100 yr surge can significantly extend the altitudinal range of erosive activity (Williams and Davies, 1987). This this was greatly exceeded during 1991, 1998, and 2008 storms, when wave spray extended over the top of the 40m cliffs. The west to east trending section of the GHC lies oblique to the dominant offshore wave approach and experiences efficient longshore drift with a peak movement eastwards, but as this is a pocket beach, most of the material is trapped in the bay. Cliff collapse has produced a receding shore platform, one of the largest in the world, which has also produced well-defined pebble beaches. Pebble production is influenced by the wave contact time against the cliff face, which in the GHC has a duration of *circa* three hours per tidal cycle (Williams and Davies, 1987).

Geologically, the bay area is composed of an eastern arm of Carboniferous limestone with the main beach area being Lias Limestone/mudstone/shale rocks. The beds were sub-divided (Trueman, 1930), into the *bucklandi* (thick limestone with thin mudstone/shale layers) and *angulata* (thin limestone, thick mudrock/shale layers) series, with the latter exhibiting angled fractures and many high angle gravity faults due to tectonic horizontal shear. The Carboniferous limestone is extremely hard and erosion rates are negligible. Lias rock mass strength ratings (Selby, 1980), show variations from 78-85 for limestone to 48-54 for shale, Triaxial testing shear strength values varied from 5 to 60 MPa at $\phi 31^0$ for mudrock and at $\phi 35^0$ a shear strength of 29MPa for limestone - a Uniaxial Compression Strength value of 261 MPa is also common, but these values tend to be frequently much lower due to discontinuities with failure being common due to interlock and subsequent shear strength loss. When calculated from the Barton-Choubey equation, overall rock mass strength reduces from $123MNm^{-2}$ for intact limestone to $1.36MNm^{-2}$ for the jointed, weathered equivalent (Williams and Davies, 1980). Low Poisson ratios and values for Young’s Modulus for moderately competent shale/mudrocks could suggest that rebound aspects have occurred with small horizontal movements. Typical engineering property values for these mudrocks were: dry density $2.53g/cm^2$, plastic limit 17%, equilibrium moisture content 1.9%, slake durability 93%, linear shrinkage 5%. Many horizontal slip surfaces have been produced as a result of the mudstones anisotropic nature. Erosional and weathering effects use these inter-bedded geotechnical variations to induce cliff failure and also cave excavation.

Methodology

Testing of limestone and shale rock was carried out in the University Civil Engineering laboratory, where standard parameters were obtained. In the field, three profiles (western, central and eastern with a width of 40 m between them) were established orthogonal to the beach and measured with a Zeiss Engineer’s level. Axes (a, b, c) of 30 pebbles were measured by callipers (a ‘pebbleometer’) at pronounced slope breaks for each winter (6 months) spring tide (Fig. 2), enabling several indices (see later) to be calculated. Krumbein (1961) showed that various beach zones parallel to the shoreline should be treated as separate units. Sample size is a function of ‘purposeful sampling’ (Krumbein and Greybull, 1965) and in the literature the numbers utilised vary: Cailleux (1953) -25 pebbles; Bluck (1967) -50 and Orford (1978) -33 pebbles. Results gave information regarding pebble shape distribution over the profile, as proposed by Sneed and Folk, (1958; Fig. 3), with the end points being a prolate spheroid (one long and two short axes), an oblate spheroid (axes being two long and one short) and a sphere (all axes equal). Several thousand pebbles were measured enabling assessment of various pebble indices and shapes to be calculated, e.g. the Oblate-Prolate index (OP), Maximum Projection Sphericity index (MPS).

Cliff Recession

Mathematical modelling helps forecasting coastal cliff retreat and most retreat occurs during storms when increasingly strong wave action produces large hydraulic forces enhanced by the abrasive force of rock fragments hurled at the cliff. The latter set up, ‘*impact stresses on the rock surface, the stress increasing as the mass and/or angle of velocity of the impacting particles are increased’*, (Sunamura, 1992, 78).The major factors of basal erosion has been summarized by Sunamura‘s (1992) equation, which relates erosion distance as a function of the wave action, material resistance for uniform strata and the process duration:

$$x = f(F_w, s_r, t) \tag{1}$$

where: x is the basal cliff erosion distance, F_w is the wave induced force, s_r is the cliff material resistance and t is time.

Under marine influences, a 2-D cliff profile evolution involves a plethora of different mechanisms, all of which have diverse time/space scales and process intensities, but can take the general form of:

$$\left(\frac{\partial f}{\partial t}\right)^2 = k(z,t)\left\{\left(\frac{\partial f}{\partial y}\right)^2 + \left(\frac{\partial f}{\partial z}\right)^2\right\} \tag{2}$$

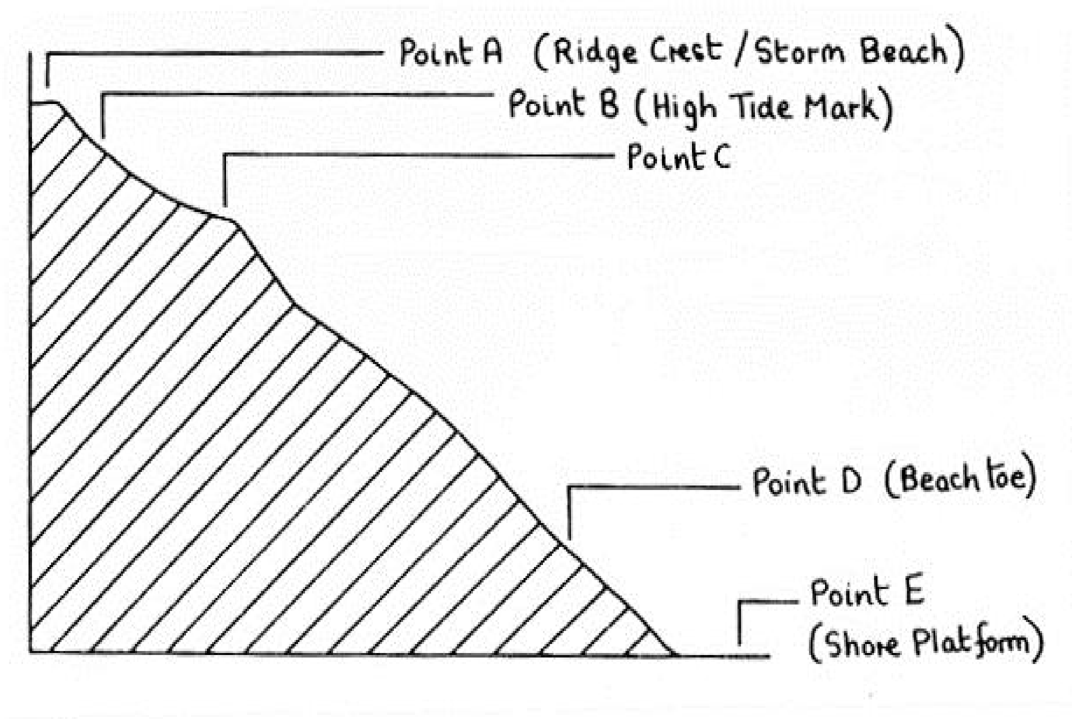

Fig. 2 Sampling zones along a profile

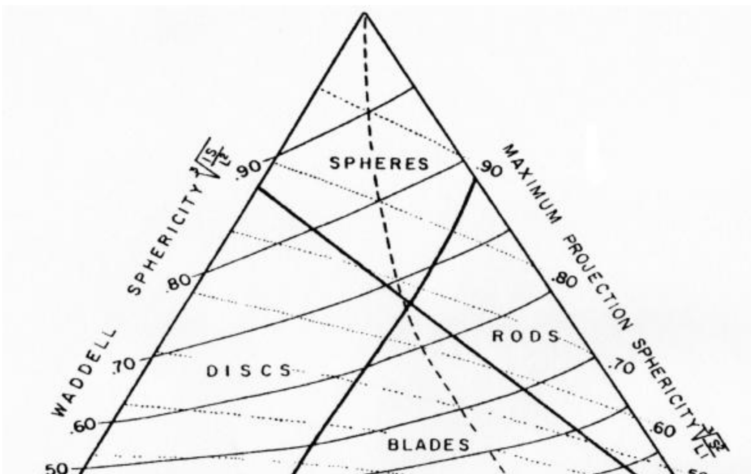

Fig. 3 Pebble shape differentiation (after Sneed and Folk, 1958)

Where: $f(y,z,t) = 0$ is the cliff profile function which describes the interface between rock and air. Solving for z the vertical co-ordinate, $z = z(y,t)$, where t is the time, y is the long-shore distance, $k(z,t)$ is the erosion function representing the vertical distribution of erosion intensity and also the temporal variation in storm-tide periodicity which modulates the impact amplitude and accounts both for cliff strength properties and the destructive forces which cause rock surface deterioration.

Equation 2 (the Belov Davies Williams – BDW - governing equation; Belov *et al.,* 1999), describes cliff profile recession for various types of marine erosion for an initial linear cliff profile and explicitly solves for the vertical distribution of erosion intensity of storm/tidal sequences. The BDW equation models cliff erosion, as described in laboratory experimental papers and field/numerical modelling studies of the cliff notching/undercutting process (Sunamura, 1992; Williams *et al.,* 1993, 1996).

Cliff safety factors are functions of the potential thrust force values and cliff failure risk rate is high when the potential thrust force critical value is low - easily attained during GHC environmental conditions where forces have varied from zero to > 4 MNm^{-2}. If P_{max} is the potential thrust force highest possible value, a thrust force hazard index can be obtained for toppling (P_1) and translation (P^*_1) failures defined by:

¦ $= 1-P^*_I / P_{max}$ for translation failure (3)

¯ $= 1-P_1 / P_{max}$ for toppling failures (4)

The higher this index, the higher becomes the failure probability (Williams *et al.*, 1993). A numerical model incorporating 12 morphological, structural and mechanical parameters has been produced with respect to dominant failure modes (Williams *et. al.,* 1993). Here the factor of safety reduces as the ratio of undercutting depth to tension fracture distance from the cliff face is increased; together with raised thrust forces within cliff joint systems due to water infill by wave and tide factors, freeze-thaw, clay infill expansion and contraction.

The commonly observed failure modes are translation and toppling (Fig. 4), the former being common where *angulata* mudstone dominates basal strata. Weathering and erosion processes can weaken and remove the mudstones and pressure release opens discontinuities in the overlying limestone, all reducing interlock and discontinuity shear strength. Reduction is progressive, as soil material from the weathered mantle gravitates into any opening discontinuity. At limiting equilibrium, resisting forces are mobilised along a critical shear plane within the reduced basal support. Translation of the unstable block is associated to shearing in the basally supported mudstone. Failure takes place along minimum energy paths, *i.e*. where work to overcome resistance of the interlocking blocks and discontinuity shear strength is at a minimum. As disturbing forces increase, the low elasticity moduli mudstone response is production of small scale articulation within the rock mass, facilitating dilation associated with low normal stress discontinuity shearing. The elastic response in mudstones, increases stress levels in intact limestone blocks proffering high restraint by virtue of the degree of interlock with shear fracturing preceding translation. Dilation is enhanced by lateral pressure of any infilling colluvium material. Toppling can occur if load eccentricity exists, which during rock mass translation establishes a fulcrum, e.g. from a protruding competent limestone ledge.

Toppling failures tend to occur where limestone dominated strata are exposed and where mudrocks increase in density towards the cliff base. Erosive forces exploit low durability mudstone horizons creating basal notches followed by discontinuous rock mass quarrying, all reducing effective basal support. The process increases the overturning moment and when limiting equilibrium is reached toppling occurs. The discontinuity set, which has minimum shear strength, strikes orthogonally to the cliff line. Some resistance *via* toppling is provided by interlock with the rock mass behind, but the largest proportion of resistance forces are contributed by the torsional shear strength mobilised along the discontinuity striking at right angles to the cliff. A prerequisite is establishment of a competent fulcrum point and where the discontinuity dip direction is vertical/sub vertical, rather than dipping back into the rock base.

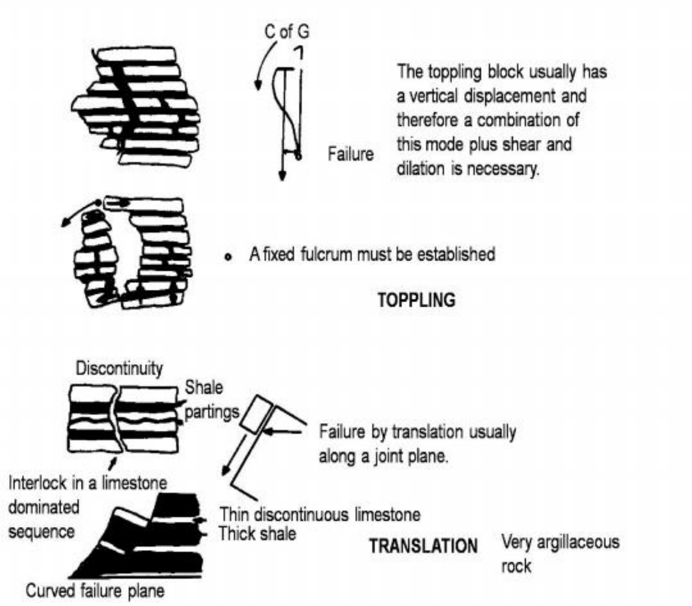

Fig. 4 Toppling and Translation mechanisms

In essence, at limiting equilibrium, resisting forces are mobilised along a critical shear plane within the reduced basal support. Shearing in the basally supported mudstone causes translation of the unstable block, failure occurring along minimum energy paths As disturbing forces increase, the low elasticity moduli mudstones induce small scale articulation within the rock mass, facilitating dilation, enhanced by lateral pressure of infilling colluvium material. If load eccentricity exists and during translation the rock mass establishes a fulcrum, e.g. from a protruding competent limestone ledge, toppling can occur. Fulcrum establishment is mandatory for toppling, consequently toppling failures are more likely to occur where limestone dominated strata are exposed especially where undercutting occurs.

Facies Changes

a) The standard pebble beach model,

This is one first proposed some 50 years ago by Bluck (1967) at a beach, some 20 km to the east of Southerndown. He divided pebble beaches into two distinct types (Sker and Newton ; high and low energy areas respectively) based upon sequential and aerial extent of the pebble zones, all based on Zingg shapes and the b axis – latter workers have cast doubt on the b axis efficiency, but in this locality it was proved to be a sound choice. However, the maximum b axis size recorded by Bluck (1967) was 95 mm and much higher values were found at Southerndown. The model had no time frame but envisaged that initially in a storm, a loose poorly sorted mass of pebbles is thrown creating a bank and subsequent post storm wave activity is responsible for shape sorting. The system was split into four zones (Fig. 5).

- Large disc. Found near the ridge top and containing many discs shapes of larger sizes, with spherical and rod shapes having lower size ranges.
- Imbricate. Immediately seaward of the above, characterized by a high proportion of discs of all sizes.
- Infill. Seaward of the above and more complex with a larger proportion of spherical and rod shapes. Frequently (not in the case of Southerndown) a sand sheet bordered the zone over

which pebbles moved quickly.

õ Outer frame. Located on the seaward edge of the pebble beach, with cobbles and boulder sized particles and usually laid on sand/rock.

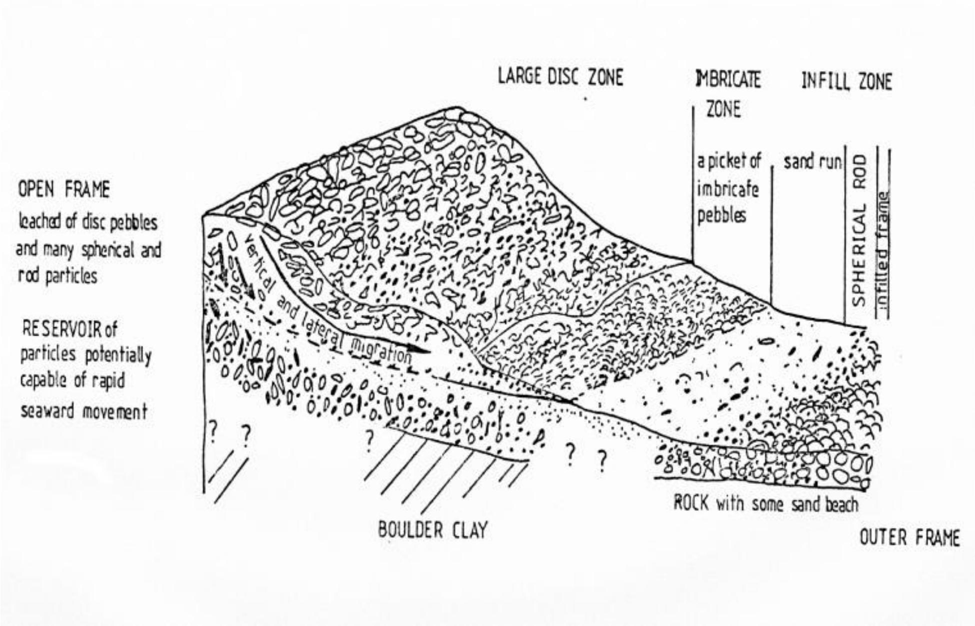

Fig. 5 Storm beach zones (after Bluck, (1967)

Material in the upper beach acted as a sieve by filtering particles from the backwash through gaps in the porous frame. In traction mode, spheres and rods travel faster than discs and the juxtaposition of cobbles and infill material do not impede their simultaneous deposition. Bluck (1967) called this the 'Sker' type based on incident high wave energy. Transportation processes undoubtedly occur but are only part of a number of sedimentological phenomena taking place under swash and backwash processes. Pebble size is also a key parameter with respect to the energy in the system. When swash/backwash produce entrainment forces at a critical threshold for transport of certain particle sizes, the more easily suspended oblate material is thrown forward during the short-lived swash period. The longer backwash duration possesses a lower initial energy level, which produces down beach winnowing of spherical and prolate material, *i.e.* shape sorting is dominant in a low energy environment. With no longer marginal entrainment forces *i.e.* higher energy levels, pebble mass becomes the dominant factor. Southerndown sweep zone profiles indicated large height fluctuations, *i.e*. instability due to higher wave energy levels, which is to be expected for winter field work,

b) Zingg shapes.

The main finding was the abundance of discs and spheres compared with rods and blades (Fig. 6), which compares well with earlier work carried out on GHC beaches by Bluck (1967) and Williams and Caldwell (1988). Labile sub-greywacke bedrock splits easily along bedding planes and produces 'platey' disc shaped fragments. The more massive anisotropic limestone tends to break into blocky fragments, which undergo weathering, rolling, etc. giving rise to sphere shapes and statistical testing indicated few differences between discs and spheres down beach. The main difference was between ridge top discs (A) and the bottom (D). A greater number of discs were found at point A because this shape tends to ride a wave as a ‘surf board,’ and once deposited at the ridge top they are not easily removed. Spheres on the other hand can easily roll down a beach, especially when augmented by backwash. Results showed that:

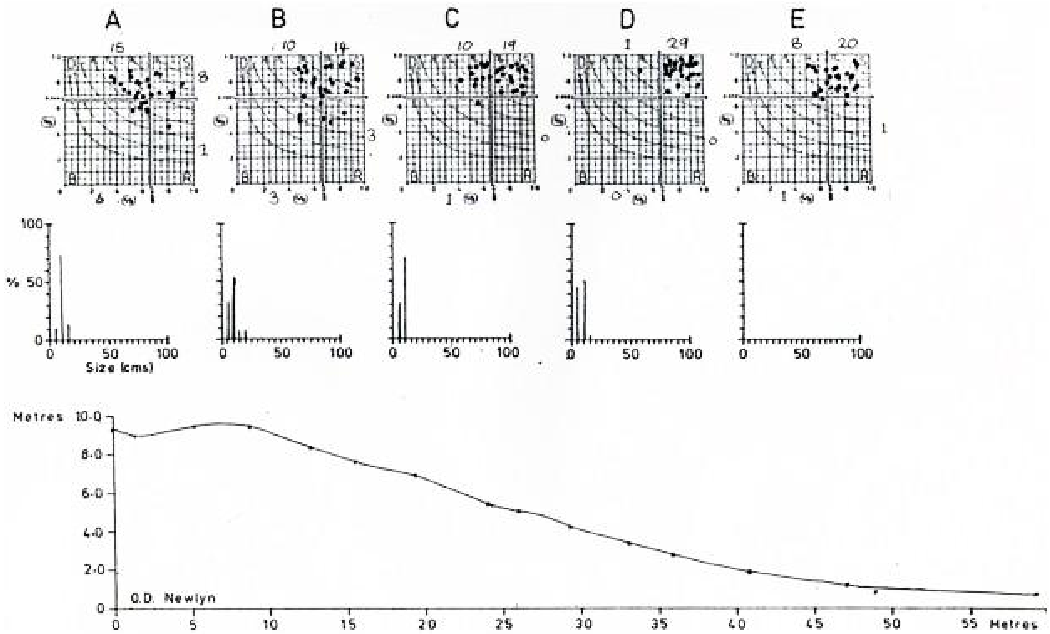

Fig. 6. Zingg diagrams, profile and pebble size of the eastward profile, Dec. 2012.

- Disc zones: No significance differences except between zones A and D (at the 0.05 statistical significance level).
- Spheres: No significance differences except between points A and C; A and D (all at the 0.05 statistical significance level).
- Rods: No significance difference between any zone.
- Blades: No significance except between points, A and C; A and D; B and C; C and E (all at the 0.05 statistical significance level).

c) The c axis.

This is the most sensitive and probably the key axis with respect to pebble hydraulics (Carr, 1974). No down beach differences were found at sampling points A, B and C for all profiles, but on four occasions differences at the 0.05 statistical significance level were found between the western and eastern profiles at the lower extremities of the beach (D and E), attributed to the fact that these areas are under hydraulic influence for most tidal cycles.

d) Oblate-Prolate index (OPI).

This is calculated from values obtained again by measurements of the, a, b, c axes, which defines whether the intermediate b axis is closer in size to the short c or long a axis. If the b axis is half way, the OPI value is 0.5.the ratio is:

$$OPI = \frac{[\,(a-b/a-c) - 0.05]}{c/a}$$

Thick discs and thin rods can have the same sphericity. In this research, there was a distinct lack of these shapes, but for the ones collected, all discs had negative values and rods positive ones and in only one case, between points D and E on the eastern profile was any difference found,

e) Maximum Sphericity Projection (MPS)

This indicates the dynamic behaviour of a particle during transport, as these settle with the planes of the a and b axes perpendicular to the motion direction, therefore resisting movement. It is:

$$\gamma p = s\sqrt{c^2/ab}$$

A significant statistical difference was found between all positions between all profile points D and E, which could be due to the fact that this zone is under water at every tidal cycle as distinct from zones A and B, where wave energy is much less. Profile analyses showed that moving along the beach from the west to east, *i.e.* the longshore drift direction, so did differences appear between zones C D and E.

Conclusions

Over a 6 month winter period, at each spring tide, three profiles were measured along Southerndown bay, Wales, UK and 30 pebbles measured at five distinctive slope positions along each profile – in total 6480 pebbles over the work period. The pebble shape categories obtained were classified into discs, rods, blades and spheres. Winter is a time when this region experiences high-energy waves and statistical testing showed that in essence, there was extremely little shape differentiation on the beach. Shape distinctiveness; be it, Zingg, OPI, MPS, the c axis, is a result of constructive summer wave impingement upon the pebble ridge.

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