MS698–3: Sediment transport processes in coastal environments
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Lecture 4: Bottom Roughness in Coastal Environments

- Hydraulic roughness (z_0) vs. Physical roughness (k_b).
- Roughness elements: Nikuradse, ripples, biogenic, saltation.
- Predicting roughness.

Class business

- Reading list; revised syllabus on web-site.
- Term paper topics due in next two weeks.
- First problem set will be handed out next week.

Bottom Roughness

The roughness of the sea floor varies over several orders of magnitude, from the diameter of a sediment grain to the size of large sand waves. The sediment bed is usually mobile and responds to energetic flows, and its roughness in turn impacts the flow. Hydrodynamics over mobile beds therefore involves feedbacks between the sea floor and overlying flows.

In the literature, you will see references to both the "physical roughness" (often called k_b) and they "hydrodynamic roughness", z_0. Both have units of length (m, cm, etc.). The "physical roughness" is a physically meaningful quantity- such as sediment grain size, ripple dimension, etc. Hydrodynamic roughness, z_0, is related to physical roughness, and to flow structure, but it is really a mathematical construct. It is the height, z, at which a velocity profile, u(z), would go to zero if it were extrapolated towards the boundary.

Roughness elements

Sea-bed roughness forms a hierarchy from smallest-to-largest that can include:

1. **Nikuradse roughness:** The smallest form of roughness is that of the sediment grains themselves, called "grain roughness" or "Nikuradse roughness". This is usually not the dominant form of roughness in coastal waters- but is used as a lower limit for physical roughness estimates. It is also needed as a roughness length scale for an inner boundary layer when bedforms are present (to be covered in a later lecture). Nikuradse (1933) found an expression for this roughness scale using laboratory measurements of flow through smooth and roughened pipes. The physical grain roughness is often taken to be a "larger-than-mean" grain size, $k_b = D_{84}$,

e.g. Under rough turbulent flows, the hydrodynamic roughness due to sediment grains is $z_{0gr} = k_b/30$ (Nikuradse, 1933).

2. **Biogenic roughness:** Sea-bed roughness is also generated by biology. Benthic organisms build mounds and dig burrows that roughen the sea floor. Organisms that extend into the flow (worm tubes, grasses) act as roughness elements themselves. It is very difficult to predict length scales associated with biogenic roughness, but it often dominates in muddy environments. In such cases, photographs of the sea-bed, intuition, and parameter fitting are ways to estimate biogenic roughness. Wheatcroft (1994) used stereographic photos of the sediment bed to constrain the heights and mobility of mounds and burrows built by benthic organisms.

   Roughness generated by biology also responds to energetic flows and can exhibit feedback between the benthos and flow. Energetic flows can degrade biogenic structures, encourage benthic organisms to burrow into the sediment, or collapse grass beds. For the case of roughness in the forms of biogenically-formed mounds and burrows, Harris and Wiberg (1997) included an estimate of biogenic roughness based on initial topography and bed shear stress to model a muddy site on the continental shelf of Northern California.

3. **Saltation roughness:** Once sediment begins to move, it saltates (hops) along the sea-bed, and that raises the roughness of the bed. Wiberg and Rubin (1989) performed lab experiments and revisited existing relationships to develop an expression that relates saltation roughness to sediment size and bed shear stress:

$$\begin{aligned} z_{0st} &= \alpha D \frac{a_1 T_*}{1 + a_2 T_*}; \qquad (1)\\ \alpha &= 0.056; a_1 = 0.68;\\ a_2 &= 0.0204\,(logD)^2 + 0.0220\,(logD) + 0.0709;\\ T_* &= \frac{\tau_b}{\tau_{cr}}. \end{aligned}$$

   Muddy sediments don't travel as bedload, and so saltation roughness is a factor only in sandy substrates. Saltation roughness ($z_{0st} \sim 0.1$ cm) often dominates on sandy coastal areas during energetic transport, unless bedforms are present.

4. **Bedform roughness:** A great deal of work has gone into predicting the height (η), wavelength (λ), and roughness of ripples in both wave- and current-dominated coastal areas. If the dimensions of the ripple are known, the physical roughness has been defined to be

$$k_b = 27.7\eta^2/\lambda \qquad (2)$$

   (Grant and Madsen, 1982). Under rough turbulent flow, this results in a

> hydrodynamic roughness equal to
>
> $$z_{0bf} = \frac{k_b}{30} \approx \eta^2/\lambda. \quad (3)$$
>
> The orientation of the ripples relative to flow is important in many sandy environments (off-shore of the eastern U.S., for example). Many other relationships exist for ripple roughness than the one in equations 2 and 3, some include the angle between overlying currents and the ripple crest in the estimate of z_{0bf} (see, e.g. work by Madsen).

In many locations, a hierarchy of roughness elements exist. For example, you might have saltating sediment over ripples. Some investigators add all contributions together to get total roughness ($k_b = k_{b,gr} + k_{b,rip} + k_{b,st}$), and others just use the maximum of the roughness scales. Because the roughness scales often vary by orders of magnitude- calculations usually are more sensitive to the classification of the dominant form of roughness than to details in the estimate of roughness scale.

Predicting bedform type

For hydrodynamic and sediment transport models it is important to be able to estimate the hydraulic roughness of the seafloor, at least to within an order of magnitude. The feedbacks between a movable bed and energetic flow involve modifications to seafloor roughness (either physically built or biogenic), and the drag imparted on the flow by the seafloor. Relating seafloor morphology to flow properties is also a problem central to stratigraphic reconstruction.

Myrow and Southard (1991) present a predictive relationship between oscillatory wave energy (as quantified by near-bed orbital velocity), current velocity, and bedform type. They classify a fine sand bed according to dominant expected bedform type, based on laboratory work. At the most energetic end is *upper plane bed*; where bedforms are not present because they've been eroded. At the lower end is *no movement*, where shear stresses are not energetic enough to transport sediment. Intermediate energies set up rippled beds that can be assymetric (dominated by currents) or symmetric (dominated by waves). Ripples can also be small or large; and 3-Dimensional (structure along the ripple crest) or 2-Dimensional (linear ripple crests).

Wave Ripple dimensions

Other researchers have put substantial effort into predicting the actual dimensions (height= η, wavelength=λ, and steepness= η/λ). For the case of wave-dominated environments, where ripples are symmetrical, relationships derived by Grant and Madsen (1982); Nielsen (1981) and Wiberg and Harris (1994) are often used. Clifton and Dingler (1984) noted that wave-dominated ripples fell into three categories; one where ripple dimension seemed proportional to wave orbital velocities (*orbital ripples*); and another where dimensions seemed proportional to grain size (*anorbital ripples*), and a third, transitional region (*suborbital ripples*). Most lab data fell into the orbital – to – suborbital range; whereas field data seemed to fall into anorbital – to – suborbital range.

The contribution of Wiberg and Harris (1994) was to lump all available ripple data (from field and laboratory measurements) into one set of relationships; but noting that ripple morphology might depend on the relative scale of ripple height (η) compared to wave boundary layer height (δ_w), instead of being dependent on whether the measurements were from a field or lab setting. The Traykovski et al. (1999) paper that we will read for Thursday has data of a type unavailable 10 years ago when we worked on Wiberg and Harris (1994).

Ripple dimensions: combined flows

Ripples formed under unidirectional flow tend to have dimensions proportional to a characteristic grain size of the bed; but then degrade when flows get very energetic as ripple crests are eroded. Li and Amos (1998) develop a series of relationships that predict ripple height and steepness for flows that have significant steady (current) and oscillatory (wave) components. Their results were derived from data from the Scotian Shelf; where tidal currents often overwhelm wave orbital motions.

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