[SQUEAKING]

[RUSTLING]

[CLICKING]

JOHN SOUTHARD: So let's start with unidirectional flow. Oh, here, I should tell you my plan of action-- my tentative plan of action. We have four hours for three to four classes. And I've made up four PowerPoints. I'm not quite finished with the fourth, but it'll come along.

And so the first one is on fluid dynamics that are relevant to sediment transport. And then there's one on sediment transport, one on bedforms and bed configurations, and finally one on sedimentary structures created by flows.

And I'm hoping to get one and maybe most of two today done, because the third and fourth are heavy. They're long and heavy and I think we need more than just one hour to do them.

So that's my point. It's been so long since I've given classes that I can't really figure out how long a presentation is going to take me because I might go off on tangents and things like that.

All right. Osborne Reynolds, famous name in fluid dynamics. And I mention him because he did a classic experiment way back in the late 1800s-- a tank with a tube coming out of it and a valve at the bottom so that he could make a flow in the tube.

And he had a little dye injection system as well, because he wanted to see what happened to the dye in the flow. These are directly from his sketches.

So A, at low flows, the dye streams along the tube without anything happening to it. Well-- come on in-- it might expand very slowly, but nothing much happens to it.

But when you increase the velocity, the dye wavers and then breaks into turbulence. And to visualize the turbulence, this is a sketch. He shows all these fluid eddies moving along. And this is a classic experiment.

So I think this is a pretty good definition of turbulence. And a little bit more about turbulence-- if you had a flow through a duct or a channel and you released little tiny buoyant markers which would float along-- neutrally buoyant markers-- every one would take a different path and a very irregular path.

So that's one element of turbulence. Every motion downstream is very irregular. And if you had your little magic velocity meter to put in the flow and you measured the time velocity, instantaneous velocity, and plotted it-- this is a bad plot.

I drew this cartoon. They shouldn't be leaning backward. They should be pretty much even. But anyway, you get the idea. So the fluctuations in velocity in a turbulent flow would be something like 5% to 10% of the mean flow. So it's substantial, but only a small part.

You could also-- if you had-- I love magic things. So if you had a magic powder and you sprinkled it into the flow, you would see integrating swirls of masses of fluid called eddies going down the flow.

If you've ever seen a river in flood, a muddy river in flood, and you look at it, at the surface, you see all these eddies at the surface. It's very impressive. I love to see that sometimes. But this is the kind of thing you can visualize.

So this is my definition of turbulent eddies. Now, if you have a question-- I didn't say, but if you have a question or comment, flag me down. I'm glad to stop and deal with things. Keep that in mind. I'd be glad to do that.

OK, so let's think about this flow through a tube. It's a good example of what we have to deal with in fluid flows. So you need four variables to account for this flow.

Obviously you need the flow velocity in the tube diameter, but also the fluid properties, fluid density and fluid viscosity. Those are four variables you need to deal with.

So if you tried to graph a four-dimensional diagram, well, that's impossible, right? You can't possibly do that. So you'd think that we're stuck in dealing with this and representing this.

But-- oh, this is an example. This is just an example I threw in of existence fields. You probably in some PCAM or thermo course, you've had to deal with the phase diagram for water, ice, vapor, water. And that's the kind of thing. But you can't do that in four dimensions very easily.

So there's a technique in mechanics called dimensional analysis. And you can get really useful information about something. You don't have a solution, but you have some idea about the physical effects.

So here's what you do. Buckingham's theorem-- Edgar Buckingham, I don't know much about him. He was an American physicist. And he was one of a few people who developed this idea of dimensional analysis.

You can look him up on YouTube-- you can google him and look him up on the internet. So here's the theorem.

Now, I went through the proof of this back maybe 60 years ago. And it's not difficult. But you're going to have to take my word for it that it works.

The number of dimensionless variables corresponding to the number n of original variables that describe the physical problem, it's equal to n minus m.

n is the number and m is the number of fundamental dimensions mass, length, and time. This is a time-honored and very useful thing to do in fluid mechanics and other mechanics.

So the way it comes out, rho UD over mu-- density, velocity, duct size, and viscosity. And it's called his number, in his honor, or Reynolds number. I say a Reynolds number. There are other Reynolds numbers coming along of the same kind of thing.

So we've collapsed four dimensional variables into just one dimensional variable. All you need to specify to describe the slope of the tube is Reynolds number. Nothing else, just the Reynolds number. It's a very powerful tool. And we're going to be using it.

So let's look at another problem which is relevant to sedimentary geology, flow past a sphere. What's the drag force? What's the drag force when it's moving in a viscous fluid?

Again, we have four variables. The same ones-- rho UD over mu. But U is now the approaching flow. D is the diameter of the sphere. So the drag force is a function of the Reynolds number-- another Reynolds number. Does that make sense to you?

But it's not quite as simple as it looks. Why? Why is that not too simple? Here you have a sphere held there and a fluid flows by it. And it's a drag force.

But there's another way it could be done. You could drop a sphere into a body of still water. And there's still a force on it. It's a gravity force. And it's moving relative to the fluid.

But what's the difference? Tell me the difference between those two cases. I'll give you a hint. It's the T word.

In the case of holding the sphere steady and letting the flow by it, the flow is likely to be turbulent. And the sphere will have to react to certain differences in the speed of the flow because of the turbulent eddies going by.

Whereas if you drop the sphere-- a negatively buoyant sphere-- into a body of water, there's no turbulence in the water. It's still. And that makes a small but non-negligible difference in how it works. Does that make sense to you?

Incidentally, we're going to get to this. I'll tell you more about this later. Now let's look at open channel flows. That's clearly an important thing to think about when we're dealing with the sediment transport, by unidirectional flows. And that's what this hour is about.

Say you're standing out there next to a river and the sun is shining and you try to look sideways at the flow downstream. What is it like?

So I have to introduce two things here. A steady flow-- this is definitions. A steady flow means no change with time. And a uniform flow means same at all cross sections downstream.

All right. So here are the forces involved. What pulls the flow down slope? Well, it's the downslope component of the weight of the fluid.

You all know about doing vectors and figuring out components of vectors, right? But there has to be a resisting force if it's a uniform flow. And that's the friction force at the base.

So these two are balanced when you have uniform flow. Make sense? So what variables do we need? Now we're going to do the same thing in dimensional analysis. What are the variables we need? Mean flow, velocity, and depth, obviously. Density and viscosity.

But there's one more-- the acceleration due to gravity. And why is that important? That's not an easy question, but you need to think about it.

Why do you need gravity here? You don't need it because of the downslope force, because that's all taken care of by the weight of the fluid. Surface waves.

Wind blows over the surface and it can create surface waves. So that's an additional thing about the flow. It turns out that waves develop on the surface not because of wind, but because of an instability that develops at high flow speeds.

And I'll say a little bit more about that because there are things called antidunes. You ever heard of-- how many people have heard of antidunes? All right, good. Anyway.

Because those are waves on the water surface that can be stationary or moving upstream, and they affect the sediment transport. So we need five.

Well, that tells us by dimensional analysis, how many dimensionless variables would we have? We had four variables in the previous and we got one dimensionless variable, three less than the number of variables. So how many would we have here? You'd have two of them. Right, OK.

So we have another Reynolds number, this one would be based on flow depth and flow velocity. There are lots of Reynolds numbers around. It's based on depth. But we need another one. It's called the Froude number.

And it has g in it, U squared over gd. Sometimes people take the square root of that and call that the Froude number. Anyway, because of certain possible surface gravity waves.

Here he is, William Froude, engineer, fluid dynamicist, naval architect. Did a lot of stuff. And I've always wondered how he pronounced his name "frood" or "frowd". And I finally recently learned that it's "frood". So it's the Froude number.

AUDIENCE: I've also heard "froid" number.

JOHN SOUTHARD: Say again.

AUDIENCE: I've also heard "froid" number.

JOHN SOUTHARD: Freud as in Sigmund Freud?

AUDIENCE: Yes, pronounced that way. Yeah.

JOHN SOUTHARD: They probably mean this. They almost certainly mean the Froude number.

AUDIENCE: Yes.

JOHN SOUTHARD: Freud number. I hesitate to think about what that would describe.

[LAUGHTER]

Anyway, so let's think about the velocity structure of the flow. And we have our little magic-- here's another magic-- I love magic things. We have a little current meter that we can place at various positions above the base of the flow.

And we measure the time average velocity, just time it for a minute or two minutes or five minutes. And you get a profile. And let's talk about the profile.

What's characteristic about it is it's fairly evenly distributed in the upper part of the flow. But it rapidly goes down to 0 at the bed.

And we need to think about why that is. There's something called the no-slip condition. The fluid at the boundary has the same velocity as the boundary.

It's not like tilting up the table, putting a brick on it, and having the brick slide down the table, because there's actual a jump discontinuity in velocity. But that's not the way fluid flows are. The fluid motion is always 0 in contact with the boundary.

So now you can think about why is the profile much steeper near the base than it is higher up. Think about it. Somebody come up with an answer here. Why would-- again, I'll give you the hint-- the T word. How about the T word?

AUDIENCE: Does the surface roughness near the surface disrupt turbulence?

JOHN SOUTHARD: I'm sorry, I couldn't hear you.

AUDIENCE: Is the surface roughness near the bottom disrupt turbulence?

JOHN SOUTHARD: Well, that's relevant, but there's more to the story. And I'm going to get to that pretty soon. This is a simpler answer.

It's a turbulent flow and the turbulent eddies are doing their thing. But the closer you get to the bottom, the less possibility there is for the turbulence to exchange momentum vertically.

And that goes to 0 at the boundary, because the flow is always parallel to the boundary at the boundary. So over most of the flow, there's very effective-- I don't need to hold that, because I use my hands.

It's very effective mixing back and forth, eddies exchanging positions and evening out the flow structure, the velocity. Whereas you go down near the bottom, and the turbulence becomes imperceptible. And so the flow has a very steep gradient right near the boundary.

And it's called the viscosity-dominated layer. Now, you know about viscosity I'm going to have a slide on it pretty soon. It's basically a measure of the resistance to shearing in a continuous medium.

And so here's that profile we had. And it's turbulent up in here. But down near the base, the turbulence is almost damped out and any horizontal motions are very weak.

And so the flow here is dominated by viscous effects, not turbulence effects. And that's a basic characteristic of channel flows you need to know about.

So some terminology. It's not too important for our purposes. But there's a turbulence-dominated region. And a viscosity-dominated region is what they call a buffer layer in between.

It's just terminology. And it's not to scale, obviously. All right. So now let's see. Oh, I can't remember your name. Kuh, Kuh, Kuh-ren?

AUDIENCE: Koh Ze-Wen

JOHN SOUTHARD: Koh?

AUDIENCE: Ze-Wen

JOHN SOUTHARD: OK, you-- we have to think about not just smooth planar boundaries, but in our case, as sedimentologists, we have to think about rough boundaries.

And it seems simple, but it's not really as simple as it seems. This is a tough slide. It's in the notes. So we have something called dynamically smooth flow and dynamically rough flow.

And dynamically smooth flow is like what I showed you. It's a viscosity-dominated layer. And the surface grains or particles are immersed in this viscosity-dominated layer.

And it's as if it was a planar boundary. As far as the flow is concerned, it's as if it's over a planar boundary. But for stronger flows, the particles stick up above the viscosity-dominated layer.

There basically is no viscosity-dominated layer. And the particles are shedding turbulence. And the turbulence extends right down near the grains. So that's worth keeping in mind.

So this may help you. We'll see. A boundary can be physically smooth and with all viscous drag and no roughness. It's dynamically smooth. But it can be physically rough. And when it's physically rough, it can be dynamically smooth because it's all viscous drag and pressure drag, which I'm going to talk about soon.

And on the other hand, at higher velocities, it can be dynamically rough. So that's the difference between them. I haven't told you what Re* is, but I'm going to get there eventually.

Boundary Reynolds number-- there's another Reynolds number. Boundary Reynolds number, roughness Reynolds number, it's a kind of dimensionless boundary shear stress. And it's useful. Rho to the 1/2 tau 0 is the boundary shear stress to the 1/2 D divided by mu. So this is a useful little Reynolds number that you have to deal with.

So now to change the pace here, there's something called the Navier-Stokes equation. It's a long partial differential equation that accounts for all of fluid flow. The trouble is, it's very hard to solve. You can't solve it analytically, for most problems.

And I'm not going to tell you about the Navier-Stokes equation, except to show you the two people who developed it, Claude-Louis Navier, who was a French physicist and civil engineer, and Sir George Gabriel Stokes, mathematician, physicist, fellow of the Royal Society. Big deal, right?

So there's something called creeping flow. What you do is forget about turbulence and just look at the viscous fluid flow at very low Reynolds numbers, which I told you about. And it's called creeping flow.

This is what it looks like past a sphere. The streamlines diverge, go around the particle, converge again. But I didn't draw it quite right. I didn't emphasize it enough. They come together slower than they went apart, which means there's a force on the particle. So this is useful for small particles in slow flows.

Stokes solved the Navier-Stokes equations by ignoring viscous effects. You throw out viscosity and you have a solvable equation. No details here.

But the thing about it is that turbulence is not an issue here. Fluid density is not in that because there's no fluid accelerations, or very, very weak accelerations, very slow change in the direction of the flow.

And this has a practical application. You can measure settling. You can measure the settling velocities of particles, so long as the Reynolds number is low.

If you have a tank of water, you add a little fine sand, silt-sized particle, and you drop it until it settles, according to Stokes' law-- and you measure the settling time, rate of settling, and you can figure out the size. Back out the size from-- that r is a radius. If you put diameter in, you change the coefficient.

And this is done. This is a common thing in studying fine sediments is to measure the settling velocity and figuring out the size. It's very useful. There are devices to do that.

OK, now let's look at higher Reynolds numbers. So here's a solid surface that breaks away from the main flow. And what happens is that the flow has so much inertia that it keeps on going.

It separates from the solid surface where it breaks away and falls away from the flow. And so you get very strong shear. And that shear develops turbulence on it. And you have an expanding turbulent shear layer.

And you get a lot of mixing, a lot of entrainment. And down here, you get a counter-rotating, irregular turbulent vortex. And we're going to see a lot of this when we talk about bedforms, ripples, dunes, et cetera, because this is a classic kind of thing that goes on.

And although I didn't mention it in the slide, it takes a long way down past the point of separation for the flow to adjust itself to conditions that are-- as if there had been no direction.

That's a very complicated sense, but you see what I mean. You have to go a long way before the flow comes back to what it was before it approached this breaking away point.

And that's painful for people studying flows around things in open channels, because the channel has to be very long before the effect of the thing that's there disappears. But you have to live with that.

So this is what it would look like around a sphere. Now, this separation is not a line. It's a circle that goes around the flow transverse cross-section particle.

And that's where flow-- there's a flow separation ring that goes away, goes downstream of the flow, with the kind of thing I described-- turbulent shear layer developing all around as is a-- with this blobby mass wake right behind the sphere.

I want to introduce two terms here, skin friction and form drag. I used the term form drag in an earlier figure and I didn't think to define it for you. Skin friction is a viscous force that's on a solid boundary. And I've told you about viscosity.

Form drag is the front and back pressure forces because of flow separation. It turns out that-- and I should go back to this slide. It turns out that the pressure is high is-- I'm sorry.

It's high at the front. And then in the back, the low pressure above and all around that circle means low pressure. And so that creates a drag force just because of the structure of the flow. And I have another slide here to show you.

Wait a minute. I have to go. OK. So things like the sphere or a sediment particle can be called a bluff body or a roughness element. Bluff bodies, your house is a bluff body in the wind.

A semi-trailer. You come up behind a semi-trailer, it's a bluff body. And you're tailing him in the wake and you're feeling it like this. Then you go to pass him and you're hit with the flow.

And we are bluff bodies. We are rough elements. Did you ever think of yourself as a bluff body and a rough element? Probably not. But we are.

So for a low Reynolds number and not bluff body, smooth boundary, skin friction-- that is, the friction right at the boundary between the flow and the solid surface-- is much greater than this form drag that I mentioned on the last slide about the flow around a sphere.

Big pressure difference. And you get a lot of pressure, a lot of force on the particle. But relatively high Reynolds number around bluff bodies. Form drag is far greater than skin friction. So just keep that in mind.

Now, there's something called an inviscid fluid. And there's no such thing as an inviscid fluid. But it's also called an ideal fluid.

No viscosity, only pressure and velocity. That's all that's involved. And it turns out that for large Reynolds numbers, outside that thin, viscosity-dominated layer, the nature of the flow is pretty much like it is in an inviscid fluid. It's a good approximation.

And that helps us because there's a relationship between pressure and velocity. That v is a velocity there, as the flow moves around an object. So there's an inverse relationship between velocity and pressure. And I'll show you why that could be useful by looking at an airfoil of an airplane wing.

You're probably familiar with this. The shape is such that when the flow goes around, because of the stronger arching on the upper surface, the streamlines are crowded, velocity is higher, pressure is lower, so you get a lift.

Maybe you knew that about how airplane wings work. The Wright brothers discovered this without knowing why back in 1900 or something like that.

This is a complicated slide. And I'm going to show it in two parts, fluid forces on a sphere at low Reynolds numbers and at high Reynolds numbers, A and B.

And just so you can read it more easily, I'll show you first the one at small Reynolds numbers. This is the one I defined for you, the boundary Reynolds number.

And so there's some lift, but there's a lot of drag. And so the total fluid force is at a moderate sort of shallow angle. And the line of action is it is fairly high up on the particle.

Those pluses and little arrows are-- the pluses and minuses are pressure differences. And the little single barbed arrows are some friction.

But then I'll show you the other one. For large Reynolds numbers, this would be anything coarser than coarse sand up into the gravel range. And you can see there's a difference. It's rough flow. There's flow separation and a big pressure difference from front to back. Still some skin friction.

So it's mainly dominated by form drag. And the lift-- lift is substantial. I mean, it's almost equal to the horizontal component of the flow. So very different, depending on the Reynolds number. And this is relevant to if we're looking at a bed of silt or fine sand at relatively slow flows.

That would be the first case. If we're looking at coarser sediment, like medium to coarse sand up in the gravel range, and then strong and large Reynolds numbers-- strong flows-- we'd draw it like this. You get a lot of lift, which is important. We'll see that as time goes on.

All right. That's my pitch on oscillatory flow. Now I have to stop for a minute and you in the back will have to readjust because I want to take my sweater off.

This is the other main topic we have to deal with. We've looked at unidirectional flows-- down a channel. It could be a river. It could be a tidal current, tidal flow, a longshore current in the shallow ocean.

But there's also oscillatory flow, back and forth flow. And it's another important thing to deal with. The approach is going to be a little different from what I just gave you, but bear with me and see what you think.

All right, so you probably know that that's a wave with a crest and a trough, a wave height and a wavelength. That's a typical wave that we would deal with. And this is a problem with this slide here. This is supposed to be a circle.

And I know why it happened. I was resizing it, trying to make it bigger, and go up and down. And I don't know how on PowerPoint you can expand something without changing the dimensions. There must be a way of doing it.

But I had to relearn PowerPoint. It's been 15 years since I made a PowerPoint. Literally, yes. I had to relearn. But anyway, so that's what we see when the wave goes by.

But there's an important difference between the deep water waves and shallow water waves. And deep water waves, the sea bed is so far down that the orbits die out slowly with depth till you get to-- they disappear before you reach the bottom.

And that's not relevant to our business here. But the shallow water waves, the orbits are ellipses. And I can't tell you why, but they're ellipses. And ellipses die back.

But there's still back and forth motion right at the boundary-- even at the solid boundary, at the seabed. And so that's relevant to us. We're going to think about how sediment is moved by oscillatory flows.

It's getting late. Boy. It's getting late. So what is the flow like at the bed? Well, again, we'll think about variables. Wave period, max orbital velocity-- the wave period, you know it.

And orbital velocity, it moves this way and this way. And that's an orbital diameter, how far the it moves back and forth. And the maximum orbital-- in the middle of the orbit, that's the maximum velocity. So there's three variables.

And actually, only two are needed. Now, I'm not going to prove this, but it's well-known that the velocity equals pi times the orbital diameter divided by the period. You just have to accept that. Only two of these are-- but it's U, m, and T that I and we as sedimentologists are mostly interested in.

So we have four variables, U, m, T, rho, and mu. And of course, we get a dimensionless variable. But it turns out that this doesn't help us much. I just mentioned that you can do that. It holds for a smooth bed with no sediment, but we're dealing with the mobile bed case pretty soon for sediment transport.

So here's an important point for shallow water waves with very small amplitude, the time history velocity is symmetrical. The forward velocity is equal to the back velocity.

But for large amplitude waves-- and that's pretty typical of large waves, when the troughs are broad and the crests are sharp-- it turns out that when the wave crests are sharper and the troughs are broader, it's not symmetrical, it's asymmetrical.

We just did that. OK. So the thing is, if you look at the maximum velocity when the crest is passing over you forward, the velocity is higher, but the time of passage is smaller.

And it's the opposite for when the trough is over you and it's moving backward. So there's no net movement of sediment. But it goes this way fast and this way back slow.

And so because-- and I'm not going to tell you too much about it, but the sediment transport rate, how much sediment gets moved, is a very steeply-increasing function of the flow velocity.

And so the consequence is that there's some net sediment movement under a purely oscillatory flow, which seems counterintuitive. But that's the way it works.

And as you know, the waves come from the deep ocean, and they shoal. And when the depth gets to be less than about a half a wavelength of the wave, it begins-- the wave scrunch up.

It's a technical term. The waves scrunch up and finally break, of course. But in this range from here to here, even in purely oscillatory flow, there is some net transport toward the shore.

And this is a business about shoaling waves that I just mentioned.

We're talking about a single oscillation. A single wave goes in, water moves back and forth. But you can have more than one oscillatory component. There can be-- let me get rid of this-- there can be waves running this way and waves running this way or maybe this way.

And they superimpose on one another. They add to the effect. But they act at the same time, and it makes for very complicated water movements at the bottom, as you can imagine.

So when the sea is fully developed under a storm, under a wind, how big the waves get depends on both wind strength, but also how far-- what greater distance that the wind has the chance to operate on the surface.

And in a storm, if you've ever been out on a ship during a storm, there's pretty good size waves running. They're very complicated. So there's a spectrum of waves running in different directions and with different characteristics, and they all add together.

But they're self-sorting. Because when the waves move out away from the storm, they sort themselves out by direction, obviously. But also, there's a low-pass filter effect.

The bigger waves die out slower than the smaller waves. And so when you get well away from the storm, it gets simpler, because there's only usually one dominant oscillation component, unless there were a couple of subequal ones in different directions, which can happen in major storms.

I just talked about this. But we have to think about the bottom water motions, because when we talk about the sediment movement by these oscillatory flows, that's an important consideration.

So they can be at right angles, which is a fairly simple kind of thing. The ellipses would be-- the orbits would be ellipses rather than straight lines. And if you had two oscillations not at right angles, it gets a very complicated pattern which is infinitely repeating.

Have you ever heard of Lissajous figures? How many people have heard of Lissajous figures? There's a nice Wikipedia entry on Lissajous figures. And to go and look at it sometime. It's clever.

Some guy named Lissajous developed this. And I don't know who he is or when he lived or anything like that. Anyway, now we have to deal with combined flows.

We've talked about unidirectional flows, various things about the forces and motions. And we've talked about oscillatory flows. But it's natural to think that there can be oscillatory flow with a superimposed unidirectional flow-- their combined flows.

And in terms of sediment transport, it's a jungle. It's amazingly difficult to deal with all this. John Grotzinger, my long time colleague, would call it a dog's breakfast. He loved that expression, it's a dog's breakfast.

Anyway, it's really complicated. And we're going to get to that when we talk about sediment transport and bed forms. But you have to live with that. The simplest case is they're collinear.

And that's easy to do in the lab because you have a channel with a flow in it at the same time you're making waves. And you can look at the effects when they're collinear.

And in this case, you can see that this is a steady-- this is a spectrum. Steady unidirectional flow, time and varying velocity. But it can be pulsing unidirectional.

If you have a minor oscillatory component, the flow pulses-- slow fast, slow fast, slow. And then there's a middle thing, stop start. It flows and stops. It flows and stops. But in terms of sediment transport, it's not much different from-- the case of steady unidirectional is not much different from pulsing unidirectional stop and start.

But if the oscillatory component dominates over the unidirectional component, you get an asymmetrical oscillatory flow until finally, you get to a symmetrical oscillatory flow. And any one of these unidirectional components and oscillatory components can be combined with each other because we have combined flow.

Now, if they're at right angles to each other, that's a little more complicated. And I don't know of anybody who's done this in the laboratory, but I had an idea long ago-- and I thought about doing a research proposal on it-- have a channel flow flowing down it.

But on the sides of the channel, all along the sides of the channel, there are reservoirs with entrances into the channel. So you tilt the channel back and forth, slosh the water sideways while it's flowing down that way.

I never did it maybe I should have done it sometime. But I never got into actually writing a proposal for it. So that's pretty easy to deal with.

The most difficult case is when there are currents plus multi-directional waves. And the only thing I can think of, if you want to do experiments, you'd have to build a very large wave tank with wave makers at various angles.

Plus you pump water in at one end and you pull it out of the other end. And I don't think anybody has done that. But an experimentalist like me thinks in terms of doing something like this.

And you could instrument the seabed. People do that and look at sediment transport and bed configurations, ripples on the seabed. But it's difficult and expensive. And it's especially difficult in major storms where much of the action takes place. So it's difficult.

And that's it. So now I have to go to-- let's deal with sediment transport. Now that all about fluid flow, let's deal with sediment transport.

And the obvious place to start is initiation of motion. How strong does the flow have to be before the sediment starts to move? It's an important thing to deal with. It's a classic problem. Much has been written about it over the many, many decades.

So here's a thought experiment for you, an imaginary field trip. You can shrink yourself down to microscopic size. You're a micro person.

And if you're doing it in water, you have to have scuba gear, obviously. And you have shoes that are equipped so that you can grab onto any surface down there. We're dealing with sediment particles on a sediment bed. You want to be able to get your feet onto it.

And so you go down among the particles sitting there on the bed and below the bed as the flow is flowing. What would you see? What would you feel?

Well, clearly there'd be flow around the surface particles, but there'd also be slower flow around some of the particles, fairly well down in the sediment. And it would be viscosity-dominated flow.

But there would be irregularities, because overhead, above the sedimentary bed, there'd be turbulent flow. And so there'd be velocity fluctuations that would be transmitted down into the subsurface. That's my field trip.

But there's more to it than that because if you-- now I'll turn into a fluvial geomorphologist. Do you know about effluent streams and effluent streams? Maybe not.

OK, so look at the stream. And the groundwater table comes down to the surface of the stream. And so if the groundwater table slopes up from the channel, water is coming in from the subsurface up into the channel.

And it's not a small-- it's a small effect, but it's not negligible, because that would tend to move the particles upward and entrain them. An effluent stream, the groundwater table slopes away from the channel and you're losing water.

And so there's a downward flow. And that would tend to inhibit the particle transport. I don't think it's a big deal. I should talk with Taylor Perron about that sometime.

So I told you about the boundary shear stress. Averaged over time and space. Skin friction formed lift. We did this in the previous part.

But you can look at things a little more closely and look at a sediment bed as a flow over the sediment bed. And here are particles. They have contact points, usually three contact points.

They're sitting there. And they have a weight. And there's a fluid force of the kind I just talked about. And so that's what we have to think about.

If we're thinking about making the move start happen, this is the kind of picture we have to think about. And in more detail, we could say there's this particle maybe ready to move.

And so there are skin friction forces. There are front-to-back pressure forces. And that's what actually moves the particle. And which are more important, the viscous forces or the pressure forces? Depends on a Reynolds number, as you might guess, because that's what Reynolds numbers are all about.

So this is from what I gave you before. You've seen this. And just to remind you that the nature of forces on a particle that might be ready to move is very strongly a function of this Reynolds number Re*, boundary Reynolds number.

So let's do more. I am a lover of dimensional analysis. I guess you can see that. So here's a flow over a loose granular bed. And what do we need to worry about?

We need the boundary shear stress. That's what moves the sediment. We need the particle size. You also need rho and mu, the field properties. But we also need the specific weight, the weight per unit volume of the sediment.

Now, you might be saying to yourself, why do we have to have the fluid density rho and the specific weight? And I'm going to run through a little thing with you. It'll probably be the last thing I can do.

Let's think about the threshold as a function of fluid properties, specific weight of the particles, size, and shear stress. And so as before, we have four of them. We have two dimensionless variables.

This is a kind of a dimensionless shear stress. And the other is another kind of Reynolds number. This is called the shields parameter. And I'm going to tell you about Albert F. Shields in a minute.

And u* is a kind of a fake velocity. It's a tau 0 divided by rho to the 1/2. And if you figured out, that sets the dimensions of velocity. So it's not really velocity. It's a shear stress in disguise. But anyway, that's the basic thing.

Now, suppose you have a smooth granular bed and you slowly increase the flow velocity. A few grains start to move, rolling, sliding. And they find new pockets here and there.

But you know what that is? That's called a printer's fist. Did you know that? It's a printer's fist. I love those printer's fists. It's to emphasize something this important. It's a printer's fist.

The cutoff between no movement and established movement, there's no well-defined point. It's first a few grains start to move, and then some more grains start to move, and more and more, and pretty soon a lot of them are moving. Oh, well, it's past the threshold. But there's no way to actually put a value on the particular threshold.

This is probably the last thing I can do. But here's a nice graphic way of thinking about how it works. This distribution is a distribution of instantaneous shear stress on the bed.

And it ranges from small to large, depending on the turbulent eddies. Over the bed, that's the size distribution of the particles in the bed. So when there's no movement, clearly even the strongest flow doesn't move the most easily-moved sediments.

But you finally get to a point-- as you increase the flow velocity, the bed size distribution stays the same and the flow distribution shifts to the right. And it starts to overlap.

And that's what we'd call incipient motion. And then eventually, it gets to the point where the flow overlaps the bed quite a bit and we have general motion.

So there's a famous diagram called the Shields diagram. I don't have a slide about Shields, but there's a nice interesting Wikipedia entry for Albert F. Shields. Read it sometime. He had an interesting and varied career and I won't spend time talking about it.

But anyway, this is a plot, basically dimensionless boundary shear stress versus the boundary Reynolds number, which I told you about before. And he plotted a number of data points from the literature.

Ignore these diagonal lines. And he fitted a curve through it. And it looks pretty reasonable. But he extended the curve up to very small boundary Reynolds. That is small particles. And it climbs without any data in there. And the last thing I want to do is talk about that.

Fine particles tend to be cohesive, because large particles-- any cohesive forces between electrostatic cohesive forces are negligible. But when you get down to really fine sizes, they dominate the situation and the particles tend to clump together.

And so that makes it more difficult for the flow to move. And although there's no data here, that's a reasonable way of looking at what happens. In fine sediments, you have to really have a strong flow to overcome those interparticle forces.

And I think-- oh, one more thing. I mentioned this to you. Look him up. He's an interesting guy. And I will mention in the notes-- you all got copies of the notes, right? Just in case you want to look at them.

And I'm referring these things to a particular page. There's something called the Hjulstrom diagram. I think he was Swedish. I'm pretty sure. And Sundborg, I know he was Swedish.

Variants or extrapolations of the Shields diagram. So this is standard initiation of motion stuff. So I think I'm going to quit because-- well, I'll return to this. I got to stop. It's 4 o'clock, so I'll stop.

But we'll pick that up to what we do to deal with initiation motion better. And I'll go from there. When we have established motion, you have a lot of things to talk about. So I have to quit. And I'll see you next week. Same time, same place, right?