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Resuspension by impacting bodies

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ABSTRACT

It is well known that a rigid body impacting on a bed of fine particles or dust may resuspend some of this dust into the ambient flow. The impacting body may then recoil to strike the bed again at a different location. The traditional view is that the resuspension is the result of a ballistic mechanism whereby the impacting body transfers some of its kinetic energy directly or indirectly to the particles in the immediate neighbourhood of the point of impact through purely mechanical processes. However, in some parameter regimes a second less localised mechanism will dominate over the ballistic one. This second mechanism is hydrodynamic and is provided by the behaviour of the wake generated behind the body as it approaches the wall. When the body strikes the wall and either stops or recoils, the wake overtakes the body an impacts on the bed. The interaction of the wake with the particles on the bed may lead to resuspension over a region much larger than can occur due to the ballistic mechanism alone. This paper describes a laboratory study of this hydrodynamic mechanism and determines the parameters under which it is important.

1. INTRODUCTION

Resuspension of dust and sediments is important in a wide variety of contexts. In some cases the hydrodynamic stresses and lift forces associated with an ambient (frequently turbulent) flow are themselves sufficient to lift particles from a bed. Frequently these stresses and forces are capable of resuspending only a relatively small range of particle sizes. Larger particles are simply too heavy, while smaller ones are held back by cohesive forces. The particles which are resuspended directly may, however, result in the resuspension of particles of other sizes. In this paper we shall term the particles which are of a size to be resuspended directly as "sand", and the particles which are too small to resuspend directly "dust".

A sand particle, once suspended, will accelerate in the ambient flow, gaining horizontal momentum from the drag of a mean wind (or current) profile before falling back towards the bed. As it strikes the bed some of its kinetic energy is transferred to the particles it collides with, perhaps knocking further sand and dust particles away from the bed. This process is repeated by each of the sand particles until an equilibrium is reached between the rate of removal and deposition of the saltating particles. The efficiency of this process depends, in part, on the size and physical distributions of particles in the bed. Bagnold (1941) demonstrated that a bed of sand upwind of a bed of dust could cause the dust to be resuspended, whereas by itself it would remain immobile.

This ballistic mechanism is traditionally thought responsible for the presence of a wide range of particle sizes to be resuspended and little attention has been given to other contributions. The hydrodynamic mechanism described in this paper was first proposed by Own (1980) who noted that dust particles are widely dispersed across the surface of the natural sediment, and consequently the range of influence of an effective mechanism of dust resuspension must extend well beyond that accountable for by the ballistic mechanism alone. In his original work, Owen (1980) examined the dynamics of dust particles in the flow around a body moving perpendicular to a wall, but later (Owen 1986) performed experiments to illustrate the role played by a sphere colliding with a wall. He observed the intense wake vortex of the sphere threading over the surface of the sphere, subsequently striking the wall, removing and resuspending the dust, and concluded that the impact of the sphere's wake on the wall was the dominant contribution to resuspension.

This suggestion by Owen appears to have been largely overlooked in the context of resuspension. While low Reynolds number flow of bodies moving near walls has a substantial literature associated with it (*eg.* Brenner 1961), high Reynolds number flow has been restricted to a discussion of space probes landing on Titan (Lorenz 1994). The related problem of a vortex ring impinging on a wall has received somewhat more attention (*eg.* Orlandi & Verzicco 1993).

The work presented here and in Eames & Dalziel (1998) returns to Owen's (1980) suggestion to consider the importance of the wake behind an impacting body. This new study considers in detail the high Reynolds number flow due to a sphere impinging upon a wall and determines the critical conditions under which dust is resuspended by this hydrodynamic flow.

2. FLOW AROUND A SPHERE

We have investigated experimentally the flow around a sphere impinging on a wall by attaching the sphere of radius a = 20mm to a slender rod (radius 2mm) and driving this rod by a simple traverse mechanism. In this manner a constant sphere velocity U could be achieved almost instantaneously after starting the traverse. The nature of the traverse was such that it was not necessary to decelerate the sphere prior to it touching the floor of the tank.

The depth of the tank (~500mm) imposed an upper limit on the distance the sphere could traverse before hitting the tank floor and for the experiments presented here the sphere was started impulsively from a height of $20a$ above the tank floor. At the high Reynolds numbers being considered ($300 \lesssim Re \lesssim 3500$; $Re = 2aU/\nu$) this distance was comparable to that associated with vortex shedding from a sphere in an infinite flow, and our traversing distance was adjusted so that the sphere impacted with wall with a fully developed wake structure.

During this work we considered both spheres impacting the tank floor at a variety of oblique angles, although we present here only the 90° results. We shall consider first the flow around the sphere for a sphere moving vertically.

2.1 STRUCTURE OF THE WAKE

By attaching a ring of solder to the rod adjacent to the sphere and passing an electric current through it a fine white precipate could be produced and entrained into the wake of the sphere as it propagated towards the tank floor. This visualisation technique, used in conjunction with a thin sheet of light, provides an excellent method for marking the wake vortex and observing its behaviour subsequent to impact. Figure 1 shows a sequence of images recorded at a spacing of approximately $2a/U$ starting $2a/U$ prior to impact. In this case $Re = 350$ and we can see a well developed attached wake prior to impact in figure 1a. At the instant of impact the wake structure is identical (figure 1b), but the wake continues to propagate downward due to its inertia and self-induced motion. A short time later at a/U following the impact, shown in figure 1c, the wake has started to thread itself over the now stationary sphere as a vortex ring. As it does so the vortical elements are stretched, increasing the local vorticity but conserving the circulation. At the same time vorticity of the opposite sign is generated on the surface of the sphere due to the no-slip boundary condition on the surface.

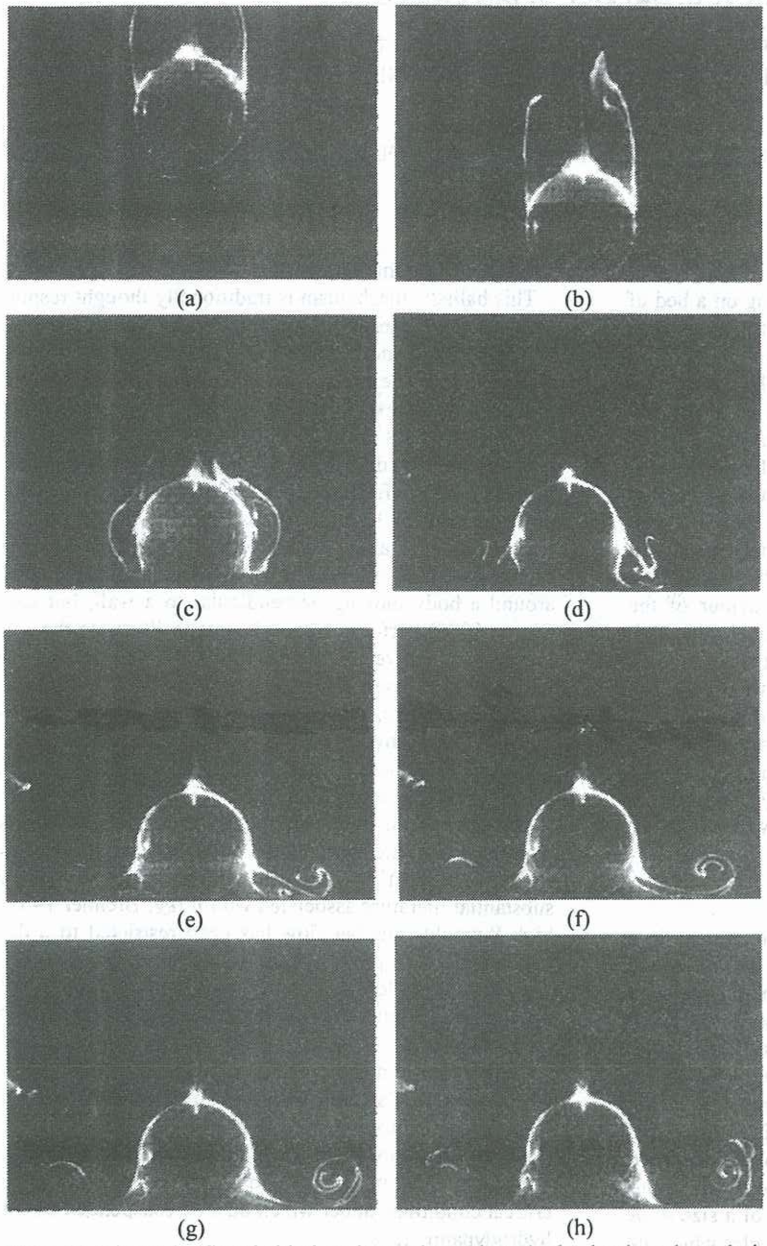

Figure 1. The wake flow behind an impacting sphere is dyed using electrolytic precipitation. The times relative to impact: (a) $-2a/U$, (b) 0, (c) $2a/U$, (d) $4a/U$, (e) $6a/U$, (f) $8a/U$, (g) $10a/U$ and (h) $12a/U$. The Reynolds number is $Re = 850$.

The combination of the secondary vorticity produced at the sphere surface and the curvature of the surface contribute to an adverse pressure gradient being established which decelerates the flow and leads to boundary layer separation. This secondary vorticity is wrapped up to form a secondary vortex ring which is clearly visible in figure 1d $4a/U$ after impact. The coherent structure comprised of the wake vortex and this secondary vortex leave the sphere at an angle of approximately 135° to the rod and continue to propagate dowards the floor of the tank.

While the flow is three-dimensional, the the self-induced motion and stretching of the two vortex rings is much less important than the interaction between the two rings due to the close spacing of the two rings. We may thus consider the subsequent behaviour as approximately two-dimensional and the pair of vortex rings impinging on the floor as a dipole striking the floor at an angle.

The initial inviscid response of the two line vortices in this dipole as they approach the floor is to feel image vortices of the opposite sign in the floor. These image vortices couple with the wake and secondary vortices to pull them apart, the primary vortex propagating away from the sphere and the secondary vortex towards the sphere. However, as the two vortices are of finite extent and not of equal intensity, the primary vortex wraps itself in a cloak of secondary vorticity prior to the splitting of the dipole. The effect of this is to shield to some extent the vorticity in the primary vortex and reduce the vorticity (and hence circulation) of the secondary vortex.

As the weakened secondary vortex propagates towards the sphere it generates tertiary vorticity of the same sign as the wake vortex through boundary layers forming on both the tank floor and surface of the sphere, trapping the vortex close to the sphere.

The wake vortex similarly generates vorticity of the opposite sign (the same sign as the secondary vortex) as it interacts viscously with the floor, wrapping this vorticity around it further reducing the circulation and interactions with its mirror image vortex (which is similarly weakened). The net result of this cloak of secondary vorticity is that the primary vortex propogates only a finite distance from the sphere as seen by a comparison of figures 1e and f. After this point the vortex slowly decays through viscous dissipation.

2.2 DISTURBANCE TO FLUID NEAR THE FLOOR

By introducing a thin layer of fluorescein dye adjacent to the floor of the tank we are able to see the effect of the wake vortex on the fluid elements close to the floor. The sequence of images in figure 2 show this interaction.

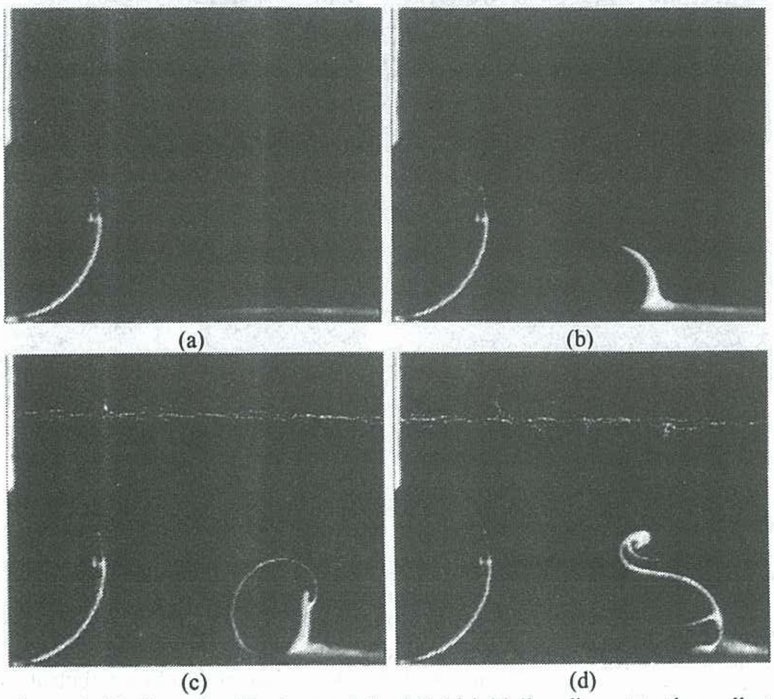

Figure 2: Motion of a thin layer of dyed fluid initially adjacent to the wall at $Re = 1100$. Images at (a) time of impact $t = 0$, (b) $t = 2a/U$, (c) $t = 4a/U$, (d) $t = 6a/U$.

The initial impact of the sphere with the fluorescein layer creates very little disturbance other than a horizontal movement of the layer away from the point of impact. This motion is due to the interaction of the potential flow field associated with the moving sphere with the wall. Note however that viscous effects will not be negligible on the scale of the dyed layer. It is not until the wake and secondary vortices strike the floor of the tank approximately $2a/U$ after impact (figure 2b) that we can see a significant disturbance to the fluorescein and fluid being swept around the wake vortex. The expulsion of the dyed fluid by the potential flow of the approaching sphere means that we are unable to see much of the structure associated with the secondary vortex close to the sphere, although sufficient fluorescein remains for us to see that fluid is lifted off the floor.

As stated before the wake vortex generates additional secondary vorticity on the tank floor which it wraps around the wake vortex. This process is accompanied by the dyed layer also being wrapped around the wake vortex in figure 2c. The secondary vortex becomes unstable to azimuthal modes as it is wrapped around the wake vortex in a manner similar to that found for vortex rings impinging on a wall (Orlandi *et al.* 1993). Here we see this instability through the more complex structure observed in figure 2d.

3. RESUSPENSION

As for resuspension resulting from other hydrodynamic mechanisms, we characterise the process in terms of a Shields parameter. Here we define the critical *particle* Shields parameter as

$$\theta_p = \frac{U_c^2}{g'b}, \qquad (1)$$

where U_c is the velocity of the impacting body required to just resuspend the dust particles, b is the diameter of the dust particles and $g' = g(\rho_p - \rho_f)/\rho_f$ is the reduced gravity of the dust particles. The density of the dust particles and fluid are ρ_p and ρ_f, respectively.

Figure 3 plots the experimentally determined critical Shields parameter as a function of the dust particle Reynolds number $Re_p = v_T b/\nu$, where v_T is the terminal fall velocity of the dust particle and ν is the kinematic viscosity of the fluid. Also plotted in figure 3 are $\theta_p = 2/Re_p$ and $\theta_p = 3$ which Eames & Dalziel (1998) showed by a scale analysis to represent the critical values for small and large particle Reynolds numbers, respectively. A comparison of these predictions and the experimental results shows a remarkable level of agreement.

The resuspension process is shown in plan in figure 4 where the floor of the tank was covered with a thin layer of Pliolite particles ($b = 100$ *to* $150\mu m$, $\rho_p = 1030 kg/m^3$). The sphere velocity was approximately 3.3 times U_c and $Re = 3100$. As before the spacing of these images is $2a/U$ with figure 4a corresponding to the point of impact.

As expected from the dye visualisations the particles on the floor of the tank remain essentially undisturbed until

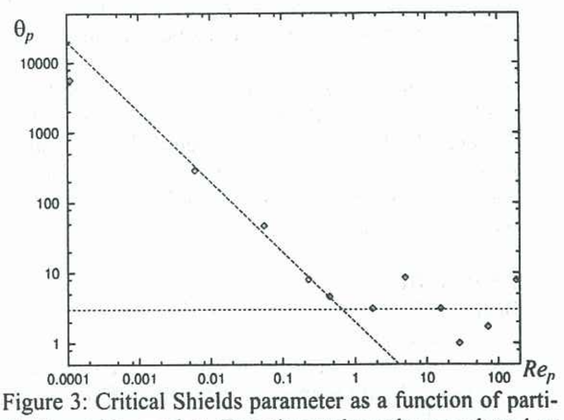

Figure 3: Critical Shields parameter as a function of particle Reynolds number. Experimental results are plotted as symbols and predicted values as dotted lines.

$2a/U$ after impact (figure 4b) when the wake vortex has threaded past the sphere. Particles are pushed aside by the wake and secondary vortices and resuspended from the floor of the tank. Many of the particles swept aside by the secondary vortex remain trapped close to the sphere while those caught by the primary vortex are clearly visible in figures 4 c and d. Also visible here are the azimuthal instabilities noted before.

Figure 5 shows the size of the eroded region as a function of the impact velocity U to the critical velocity U_c. The data presented here includes not only the Pliolite particles used for the visualisations in figure 4, but also a range of other "dust" particles (*eg.* silicon carbide and polystyrene). Some of the data was obtained using bodies in free-fall rather than the traversed sphere described in this paper.

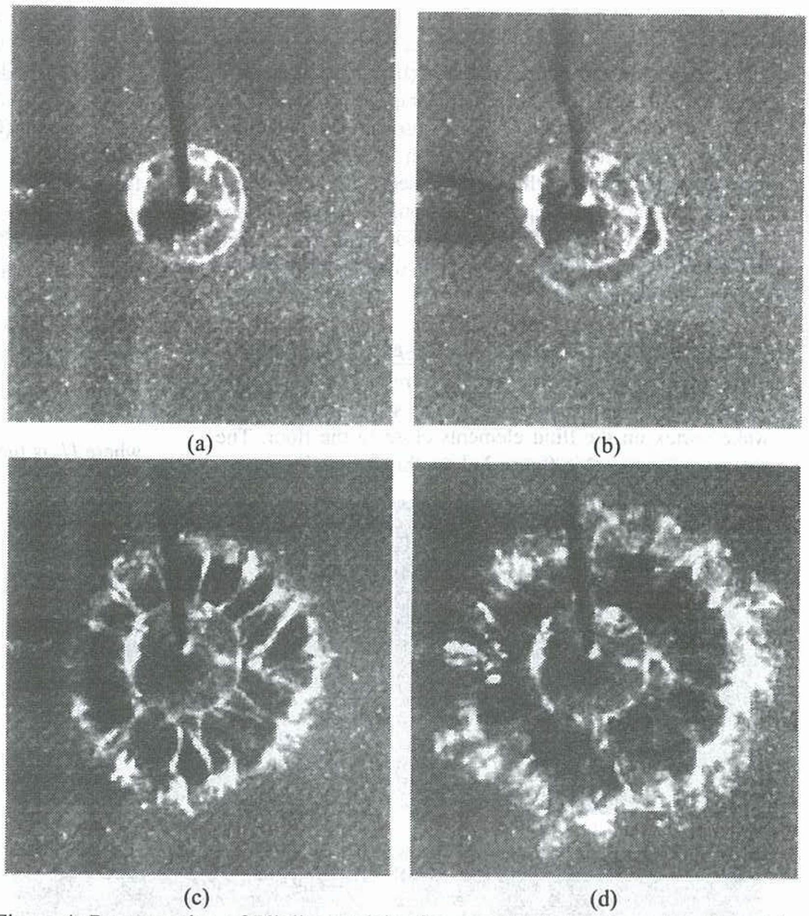

Figure 4: Resuspension of Pliolite particles for $Re = 3100$. Images at (a) time of impact $t = 0$, (b) $t = 2a/U$, (c) $t = 4a/U$, (d) $t = 6a/U$.

4. CONCLUSIONS

This paper has demonstrated that the flow generated by a body impacting an erodible bed is capable of resuspending particles. The criterion for resuspension may be expressed in terms of a particle Shields parameter which depends on the Reynolds number of the "dust" particles when in free-fall. The Reynolds number of the impacting body, provided $Re \gg 1$, is not important: it is the velocity of the body which determines the resuspension. In contrast the area over which particles are resuspended is a function of the size of the impacting body and its Reynolds number (or the impact velocity).

The resuspension process is the result of the wake vortex overtaking the impacting body when the latter comes to rest on the bed. As this wake vortex, which may be viewed as a vortex ring, passes over the body it generates vorticity of the opposite sign. This secondary vorticity, in combination with additional secondary vorticity generated through interactions with the bed cloaks the wake thus limiting the extent to which it propagates along the bed away from the impacting body. The direct result of this is to limit the size of the region of particles resuspended.

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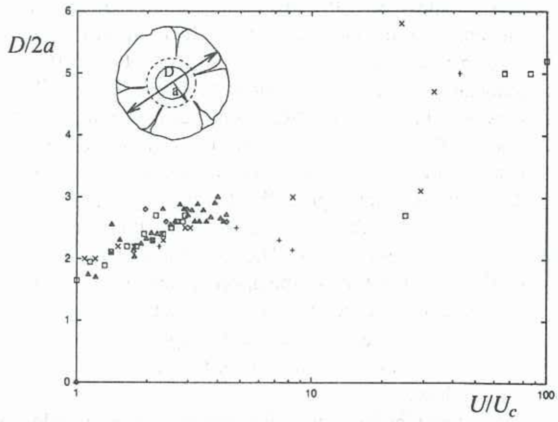

Figure 5: Diameter of region eroded by hydrodynamic mechanism as a function of the impact velocity of the sphere.