A QUANTITATIVE ASSESSMENT OF AN IMPACT GENERATED RING VORTEX Olivier S. Barnouin and Peter H. Schultz, Dept. Geol. Sci., Brown University, Providence, R.I. 02912

Introduction: Studies show the importance of an atmosphere in the ejecta emplacement process [1,2,3,4,5] where an advancing ejecta curtain displaces atmosphere to form two ring vortices at its upper edge [3,6,7]. The stronger vortex forms near the target surface and can dominate the ejecta emplacement process by entraining and depositing sufficiently the fine ejecta thereby producing contiguous ramparts and/or flow lobes over a wide range of scales [3,4]. Theoretical studies [6,7] analytically estimated the circulation in the lower vortex generated by the advancing impermeable ejecta curtain and the decay of the flow velocity in the vortex. These attempts to quantify the formation and evolution of the lower vortex only qualitatively replicate observations made at both small and large scales. A refined theoretical assessment in conjunction with new experiments performed at the Ames Vertical Gun Range (AVGR) provide a new framework for predictions at large scales depending on target and atmospheric conditions during impact.

Theory: For a small enough vortex, the impermeable ejecta curtain advancing through an atmosphere can be considered a semi-infinite plate [9]. A similarity solution exists for an incompressible fluid under these conditions, and dimensional analysis gives a circulation:

$$\Gamma = 3.7\ V_e\ H\ t^{1/3} \qquad (1)$$

where Ve and H are the curtain velocity and height at time t after impact [9]. The exact time, impermeable length, and velocity of the curtain when the curtain becomes porous must be known in order to estimate the circulation accurately. High speed video images allows approximating these parameters at the time when the vortex essentially no longer gains momentum from the curtain. Since the height H measured does not account for partial permeability of the ejecta curtain [10], the circulation estimated using the latter variables should be greater than its actual value.

The motion of the lower vortex can be predicted by Helmholtz's law which states that a vortex moving in an irrotational flow will continue unaffected unless acted upon by another flow. Since the upper ring vortex is disrupted extremely rapidly [1,2,3], the lower vortex should continue to move radially outward at the velocity imparted to it when the curtain becomes porous. However, this prediction does not hold true if viscous forces at the target surface significantly reduce the advance of the vortex. These forces may be important for small circulation Reynolds numbers ($Re = \Gamma/\nu$ where ν is the kinematic viscosity) but are not important for high Re where the viscous drag at the surface of the target are confined to a thin boundary layer.

Two models estimating the decay time for the flow velocity in the ring vortex are considered. The first is the Oseen or Lamb vortex model for two dimensional flow [7]:

$$V_\Theta = \Gamma(1-\exp(-r^2/4\nu t))/2\pi r \qquad (2)$$

where V_θ is the azimuthal velocity at r , the radial distance from core axis of the vortex, and t, time. This model has two forms: 1) ν is equal to the kinematic viscosity and the flow in the vortex is laminar; 2) ν is replaced by $K^2(\Gamma/\nu)^{-1/2}$ where K is a constant and the flow in the vortex is turbulent [11]. As in [12], the radius R for an impact generated ring vortex is very much greater than the radius of its core r and eq.(2) should successfully describe the decay of these. However in [12], the ring vortex was allowed to move parallel to its axis and did not expand laterally as for impacts. Thus, the simple Oseen or Lamb vortex may not describe the behavior of ring vortices generated by impacts.

To overcome this problem, a second modified Oseen vortex model includes the effect of the laterally expanding ring by ensuring that the kinematic energy initially imparted to the vortex is conserved, excepting for internal energy losses due to viscous decay already included in eq.(2). Because this energy must be conserved over the volume of a toroid, the circulation in the vortex must reduce by the square root of the radial distance R(t) to give:

$$V_\Theta = \Gamma(R_o/R(t))^{1/2}(1-\exp(-r^2/4\nu t))/2\pi r \qquad (3)$$

where R_o is the vortex radius when the curtain becomes impermeable. As for eq.(2), ν in eq.(3) can be modified for turbulent flow with Γ multiplied by the energy conservation factor indicated in eq.(3).

The long-term behavior of a ring vortex does not only depend on viscous decay as described by the Oseen vortex model. For some cases when Re of the vortex exceeds a certain critical value [8], a ring vortex will break into a number of waves [8,13,14]. This occurs because at higher Re, certain instability modes grow rapidly in the vortex core [14]. An interesting feature is that once the critical Re is achieved, the growth rate of the waves seem to be unaffected by the magnitude of Re [8].

Observations: A series of quarter space experiments were undertaken at AVGR in order to test the theory above. Ring vortices were generated by using a coarse sand target, but unnecessary complications due to extensive ejecta entrainment in the vortex flow were avoided. A Venturi pressure gauge was used to measure the flow past the quarter space plate to obtain two maximum vortex flow velocities in the lower ring vortex passing by the gauge.

As Fig. 1 shows, the experiments indicate that the outward motion of the lower ring vortex is unaffected by

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viscous drag affects, confirming theoretical expectations.

Table 1 compares the initially generated circulation obtained by eq.(1) to that obtained by eq.(2) and eq.(3), for both laminar and turbulent flow for three sample experiments. The magnitude of Γ from eq.(2) and eq.(3) for laminar flow are much less than values from eq.(1). Hence, flow in the these ring vortices are not laminar. Model (2) for turbulent flow generates Γ values which are still significantly less than Γ obtained from eq.(1). Model (3) for turbulent flow does the best job in duplicating the values from eq.(1). Furthermore, the values of Γ obtained by the latter model for both vortex velocities measured, very nearly equal each other as expected theoretically. The discrepancy between Γ calculated by eq.(1) and eq.(3) for the turbulent case for shot 931010 and 931015 may be explained by the overestimation of H in eq.(1) described above. Thus, the modified energy-conserving Oseen vortex model appears to describe adequately the decay of the vortex prior to its possible breakdown.

Although the observed vortices are turbulent, their Re are not sufficient to cause the breakdown of the lower ring vortex into dominant wave modes. At higher atmospheric pressures with fine grained target, the large Re results in an initially stable circular lower ring vortex that scours the inner rim and generates flow lobes attributed to the break up of the ring vortex into waves [3].

Discussion: Laboratory results illustrate certain aspects of the behavior of impact -generated ring vortices that should apply at large scale. First, they indicate that these vortices are turbulent. Second, they show that the outward motion of the ring vortex is unaffected by the surface. The breakdown of the vortex cannot be then attributed to surface shear effects; rather its occurance reflects instabilities in the vortex flow as described in [9,13,14] . Third, prior to the vortex break up by these instabilities, the magnitude of the flow in the vortex can be described by eq. (3) although it should be modified for incompressible flows. Fourth, multiple lobes can be explained by a variety of means: 1.) Concentric contiguous distal ramparts result from a simply decaying circular ring vortex enhanced by a bimodal target distribution [3,7]; 2) A contiguous rampart surrounded by multi-lobate flow-like structures could indicate vortex breakdown: sudden growth of a vortex core instability growth forms the rampart while the unstable ring vortex forms the flow lobes ; 3) Several lobate structures could be a combination of the above processes plus flow separation at the distal ejecta edges and autosuspension [3].

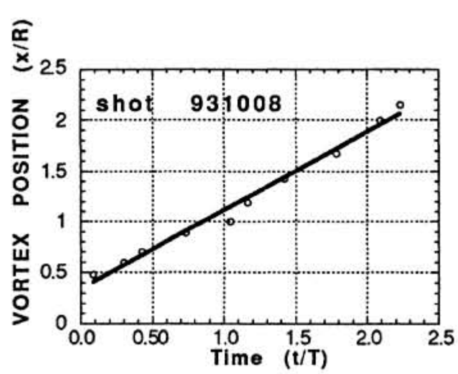

Fig. 1: Vortex position as function of time indicating a constant advancing velocity .

Table 1: Comparison of circulations obtained from ring vortex flow velocities measured

shot	Γ from eq(1)	Γ from laminar	eq(2) for flow	Γ from turbulent	eq(2) for flow	Γ from laminar	eq(3) for flow	Γ from turbulent	eq(3) for flow
931009	0.0460	0.0070	0.005	0.0232	0.0159	0.0165	0.0160	0.0545	0.0485
931010	0.0851	0.0049	0.003	0.0143	0.0084	0.0091	0.0078	0.0266	0.0200
931015	0.0951	0.0070	0.005	0.0251	0.0147	0.0108	0.0094	0.0384	0.0294

Values for Γ are in m^2/s

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