Cave Gate Airflow Disturbance—
A Qualitative Study

Brian Roebuck
Aerospace Engineering
Sverdrup Technologies Inc
Tullahoma, Tennessee

Ahmad Vakili
Professor of Mechanical and Aerospace Engineering
University of Tennessee Space Institute
Tullahoma, Tennessee

Lynn Roebuck
National Speleological Society

Abstract

Cave gates have been used for many years to protect cave resources from damage and destruction by intruders. Such gates, if not designed properly, impose certain restrictions on the natural airflow in and out of the caves. Recently improvements have been made that help minimize their effect on the cave environment. Modern cave gates employ improved strength, ease of installation, and reduced airflow disturbance designs. New gates, when designed and installed properly, attempt to protect the caves without altering the delicate cave environment.

The materials and construction techniques for cave gates typically consist of steel pipe, angle iron, and steel bar sections. The components can be assembled in various ways to both protect the cave and minimize airflow disturbance into and out of the cave. To date no quantitative or qualitative study has been conducted on airflow disturbances caused by a typical cave gate. Little is known about how much effect various gate designs have on cave airflow at typical airflow velocities at a cave gate.

This paper describes a qualitative study of cave gate generated airflow disturbances. This study was performed in a water tunnel at the University of Tennessee Space Institute using half-scale cave gate sections. Flow velocities tested are representative of typical large cave gates in large cave passages with Reynolds numbers on the order of 100,000. Different flow visualization techniques have been used to observe the flow patterns and disturbances generated by different gates. Interpretation of the observed flow fields identifies differences between various gate designs.

Many years of cave gating experience in the United States has shown increasingly better ways of how, where, and when to install gates in sensitive cave locations. Although the exact reasons to gate caves varies, the methods involved must be sensitive to the cave environment and the caves' inhabitants. Early gate installations were focused on keeping out unwanted visitors without much thought going into what changes the gate itself could make to the cave. Besides discouraging the passage into and out of the cave for bats and other cave dwelling creatures early gates also changed air flow patterns enough to impact some cave environments severely. Cave gate builders[10] [12] [15] soon learned to build gates that were less restrictive to both bat flight and airflow. Many major improvements have been made in the last decade yet cave gate technology is still in its' infancy. Gate designers have met the challenges of design by creating tamper resistant, free flowing gates that bats tolerate well. These gates are constructed of inexpensive materials [1] [10] [12] and can easily be built by volunteer labor. Studies and observations have shown them where gates should be placed to minimize airflow disturbance and maximize the protection of the cave environment. To date however there have been no published studies of what effects a gate has on the air flowing through it in typical cave environments.[1-5] [12] [15] Much can be learned from the study of airflow through various gate designs to improve future gates. This paper investigates the flow quality of airflow through typical cave gate structures and will attempt to determine the impact that gates have on the amount of flow through them. Some of the important aerodynamic concepts needed to understand flow through gate structures is explained to allow readers to better appreciate the effects cave gates have on airflow.

Because gates must be positioned so that they do not adversely affect airflow through the cave system[12] [15] one of the most important aspects of cave gating is the location of the gate. Air flowing through a typical cave passage must flow over and around objects such as rocks, formations, and man-made structures like gates. Flowing air must turn corners, go through restrictions, and interact with rough solid surfaces. When fluid flow is constricted by any means (such as smaller area sections or objects that reduce the available flow area) several changes occur in the fluid flow. A scientist named Bernoulli[8] did fluid experiments through tubes fitted with reduced area sections. He noted that the fluid velocity increased while its pressure decreased through the reduced area sections. For frictionless incompressible fluids the Bernoulli Equation is $P + \frac{1}{2}\rho V^2$ = a constant where P is pressure, ρ is density, and V is velocity. This equation will not apply for very fast fluid flows where the velocity is over approximately one third of the speed of sound of the fluid. Slow moving airflow such as that in caves is considered to be incompressible and the Bernoulli equation applies well for this type of flow. Another important concept is that for frictionless incompressible flow the mass flow of fluid through a system is constant.[8] The equation for mass flow is ρAV where ρ is density, A is area, and V is velocity. A change in flow area A and/or density ρ requires that the velocity increase to keep mass flow constant. Using these equations it is apparent a cave gate will not reduce the amount of air travelling through the cave since the velocity of the air through the openings in and around the gate will simply increase to allow the same mass of air to pass through the cave passage as would without the reduced flow area induced by the gate. In real life fluid flows friction does exist between the fluid and solid objects. Some loss of flow can and does occur for all real fluid flows due to friction and other phenomena. Some of these shall be discussed in later sections of this paper.

In order to understand airflow through cave gates it is necessary to have a basic understanding of how to characterize fluid flows. An important parameter used to characterize fluid flow is called the Reynolds number. Reynolds number is defined as the flow velocity multiplied by a characteristic length (measured in the direction of the fluid flow) divided by the kinematic viscosity of the fluid flow.

$$R_e = \frac{VL}{v}$$

Reynolds number[7] [8] can be used to compare one fluid flow to another. It can also be used to determine the best model scale and fluid velocity combination to correctly simulate a fluid flow in a wind tunnel. For example a half size model would need to be tested at twice the fluid velocity to correctly simulate full size flow in the same fluid. Similarly using a test fluid with ten times the kinematic viscosity would require flow velocity only one tenth that of the real fluid to match the Reynolds number condition with a full size model. It can be shown that the typical Reynolds number for cave gate airflow is on the order of 100,000. This is based on a characteristic length for a cave gate section (in the direction of flow) of three inches and a velocity of 10 ft/sec. Large cave gates likely have average airflow velocities lower than 10 ft/sec. Velocity was experimentally determined in Hubbards Cave by the authors using smoke to observe the airflow through the north and south gates. It was found that the average typical summer day velocity through the cave gates at Hubbards was three to 4 ft/sec. This suggests that for many properly gated caves the flow of air is very slow through all but small constrictions in the passages. For this paper a Reynolds number of 100,000 was used to determine the flow velocity and model scale for testing in a water flow tunnel. A water tunnel was chosen due to the superior flow visualization capabilities it provides over that of wind tunnels using air or other gases. Dye is injected into the water flow to help observe the structure of the flow through the half scale cave gate models.

In real fluid flows friction[7] [8] is created by the interaction of the fluid with other objects. Objects in the path of a moving fluid create disturbances to smooth steady flow. In caves these objects can be walls, formations, holes, rocks, and even gates. Disturbances to smooth flow are under the general category of turbulence. The change from smooth flow to turbulent flow can be induced by many sources.

Surface roughness, protrusions, blunt objects, and even streamlined objects can cause fluid flow to become turbulent under various conditions. The friction and fluid turbulence created by objects in a flow create drag. Drag is measured as the force applied on an object by a fluid passing over and around it due to friction. Drag in any fluid flow can result in a loss of flow rate since some of the momentum of the flow is used to change the direction and circulation of the flow field. Under most conditions drag causes an area of lower pressure due to the momentum loss the fluid experiences. This phenomenon is usually called pressure drag. The pressure drag of individual objects can be determined in wind tunnels while measuring the pressure drop across the object as well as the drag forces it creates. A drag coefficient for any object can be experimentally determined for a range of Reynolds numbers and can be used to compare the efficiency of various objects with matching flow Reynolds numbers. Many times the fluid flow interaction between objects in flows creates drag that is higher than the combined drag of the individual objects. It is therefore important to model each object carefully and to study the combination of all objects in a flow when possible. The ideal case is to have a near full scale model of the object in question in a wind tunnel. Most of the time this is not practical and smaller sections or scale models must be tested in the space permitted by the wind tunnel. Since drag can and does lower the amount of flow through fluid conduits such as caves it is important to try to find what effect a cave gate type of structure will have on air flow in caves.

Cave gates are routinely constructed with vertical and horizontal members[12] that resemble the protective screens and grids used for foreign object protection in wind tunnels and engine inlets. These structures have been studied to obtain data for pressure drag and the associated pressure loss, turbulence, and structural loads. These data can then be used to increase the efficiency of the screens and grids to obtain maximum performance of the tunnels and inlets. Some relations are available to get a good idea of the magnitude of the drag effects in screen like structures subjected to fluid flow. Hoerner has generic equations for calculating the loss coefficient for such objects. He starts with the concept of solidity ratio which is simply a ratio of area covered by the object (cave gate for example) to the area of the original opening. A solidity ratio of 0.5 for example would mean that a cave gate would reduce the area available for airflow by half. This does not mean that the airflow is reduced to half that of the original airflow. The velocity will simply increase across the gate to allow most of the airflow to pass through as stated earlier per Bernoulli and mass flow equations. Some small quantity of airflow is lost due to the effects of pressure drag. Thus we can easily see that the more efficient a screen or cave gate structure is aerodynamically the less flow loss the flow path will experience. Hoerner quotes two useful equations[7] that describe the loss coefficient for both screens made from round rods and those made from sharp edged strips. These equations are for fluid flows with Reynolds numbers greater than 1,000 and thus are similar in scale factor to cave gate airflow. Since screens and cave gates have many differences in construction, interference between vertical and horizontal members, and cross sectional shape of members they can only be used to approximate the relative difference in loss coefficient between cave gate designs. Even with these limitations the following analysis proves useful to illustrate the pressure drop characteristics of these types of structures. The equations follow:

$$\zeta_{round} = (\delta / (1 - \delta))^2$$

The above equation is used for round rod screen or grid where δ is the solidity ratio for the screen or grid.

$$\zeta_{sharp} = (0.5 + \delta)^2 / (1 - \delta)^2$$

The second equation is used for sharp edged strip construction screens and grids where again δ is the solidity ratio for the screen or grid. Arbitrarily choosing a solidity ratio of 0.4 gives a loss coefficient for round screen equal to 0.444 whereas the sharp edge screen loss coefficient will equal 2.25 using the same solidity ratio. The definition of loss coefficient is given by the equation:

$$\zeta = \Delta P / 0.5 \rho V^2$$

Where ρ is the density and V is the velocity of the fluid. Using this equation the Pressure drop ΔP can be calculated for each loss coefficient using density for air at sea level of 0.00237 lb-sec/cu-ft and choosing a velocity of 10 ft/sec to simulate slightly faster cave gate airflow through the gate passages between members of the gate. For a loss coefficient of .444 the pressure drop is 0.053 lbs/sq-ft and similarly for a loss coefficient of 2.25 the pressure drop calculates to 0.226 lbs/sq-ft. Using a standard air pressure of 14.5 lbs./sq-in the percentage of pressure loss calculates to 0.009% and 0.010% respectively. Either of these pressure drops is so small at low velocity as to be insignificant. Of course using the above equation it can be determined that the pressure drop would rise with the square of the velocity. Figure 1 shows the Pressure Loss versus Velocity for several Loss Coefficients. From this figure it is obvious that larger Loss Coefficients produce larger pressure losses. Also the figure shows that pressure loss is very small for velocities less than 50 ft/sec. Mass flow of fluid through a screen or gate is affected in the same proportion as is pressure loss. To illustrate this consider the fluid flow downstream of a screen or cave gate where a small pressure loss has occurred and the temperature and density have stabilized with smooth steady flow conditions. Since mass flow is defined as density times flow area times velocity,

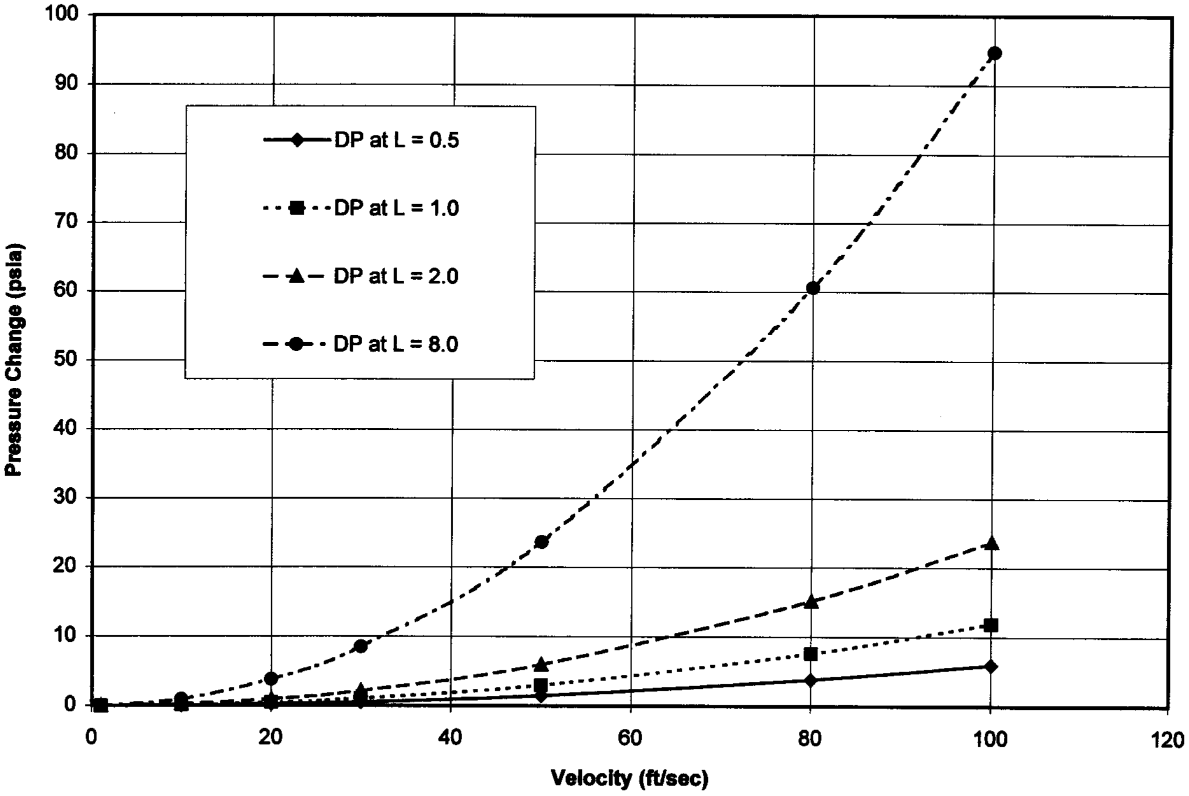
$$\dot{M} = \rho A V$$

and density is defined (for ideal gases) as pressure P divided by a constant R times temperature T,

$$\rho = \frac{P}{RT}$$

if we assume temperature is constant then density ρ varies directly with changes in pressure. So with area A and velocity V held constant (for a given flow path) the mass flow of that flow path will change proportionally to any change in the pressure. This means that for example a 1% loss in pressure will equate to a 1% loss in mass flow rate. Though the above loss coefficient equations are for screen or grid meshes having square flow paths and not for cave gates they do show that the pressure drop across structures such as these at Reynolds numbers representative of cave gate airflow is very small at the low flow velocities occurring near cave gates. Since cave gates have fewer vertical members than the square flow path of screen structures the interference effects to fluid flow between vertical and horizontal members should be less for gates than for screen struc-

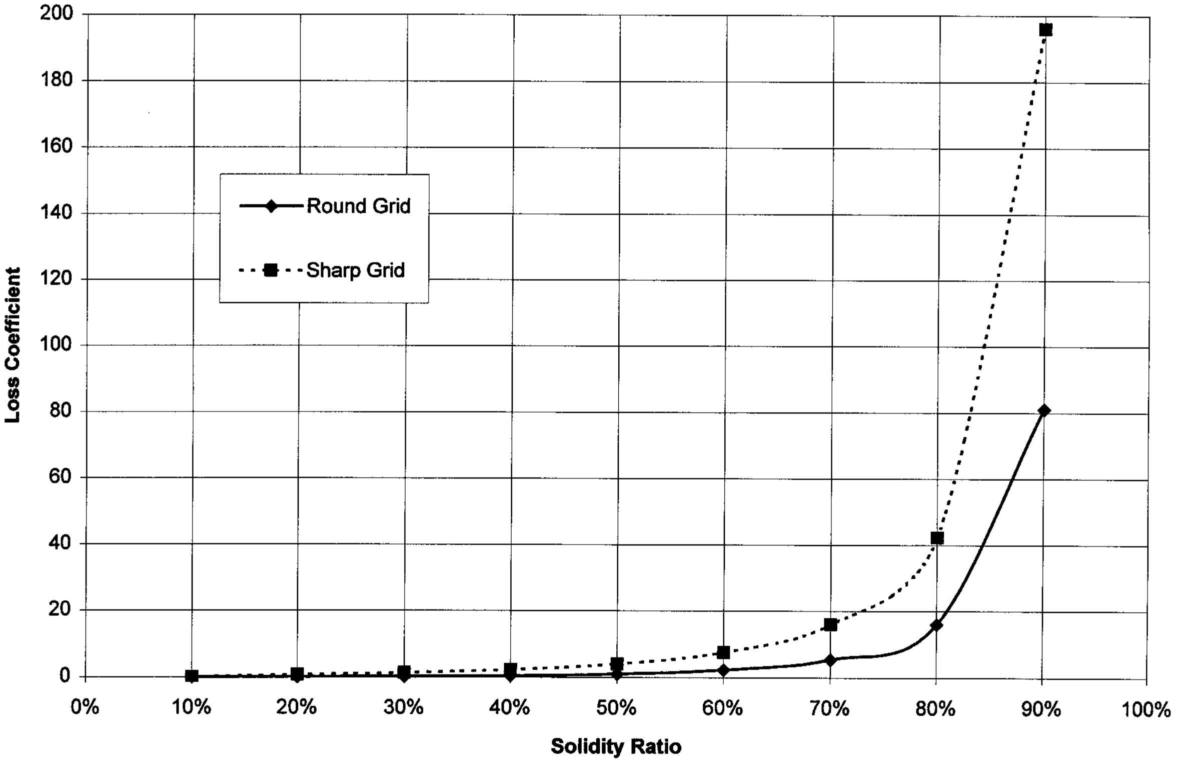
Figure 1
Pressure Change (DP) vs Velocity at Various Loss Coefficients (L)



tures. In other words it is likely that cave gates create less pressure drag than screens for similar cross section shapes at the same flow conditions. The solidity ratio is also an important parameter in determining the pressure drag of any gate or grid structure in a fluid flow. Figure 2 illustrates the effects of solidity ratio on the loss coefficient. For ratio of less than 0.6 the loss coefficient remains small but rapidly gets larger as it increases above this value. At a solidity ratio of 1.0 the loss coefficient goes to infinity (corresponding to zero flow through the gate). One other obvious conclusion is that in general round cross section structures are more efficient than sharp edged structures at Reynolds numbers of 100,000. Accordingly it is of interest to investigate the flow qualities of some of the typical cave gate design cross sections.

Some data exists for steel structural shape drag coefficients. Hoerner[7] has examples of round bar, square bar, and angle steel at various Reynolds numbers that can give us an idea of what representative values for drag coefficient are for these shapes. Rounded edges in general have less resistance to fluid flow than sharp edges. Thus round bar has a lower drag coefficient than do square and angle sections. Data on these shapes for air at a Reynolds number of 100,000 varies from a value of 1.2 for round bar to 2.0 for square bar shapes with angle somewhere in the middle. This shows that round bar creates less drag at Reynolds numbers of 100,000 than do the other shapes with sharp edges and corners. From an analysis of drag coefficient alone the logical conclusion is that round bar is a better material for efficient fluid flow in a cave gate. However, an interesting flow pattern can develop using round bar for Reynolds numbers between 10,000 and 100,000 that can affect drag as well as create vibrational modes that could possibly be undesirable. At these Reynolds numbers round bar shapes develop a pattern of vortices on the downstream side of the bar. These vortices (forming what is called a "vortex street") are periodically developed on opposite sides of the shape creating vibrations in the air that generate tones. This is sometimes evident in the plains states where wind makes phone wires "sing" between telephone poles. While there is no data to support any harm will come to cave species from sound vibrations emanating from gate vortices it is undesirable from the stand-

Figure 2
Solidity Ratio vs Loss Coefficient for Round and Sharp Edge Grids



point of causing change to the cave environment. This condition (known as the critical Reynolds number) will change when the Reynolds number rises between 300,000 and 400,000 at which point drag coefficient drops to approximately 0.3. The reduction of drag at these Reynolds numbers is due to a transition from turbulent boundary layer flow from laminar boundary layer flow.[9] The boundary layer of a flow is that which lies close to the surface of an object in a flow. This layer is responsible for all surface friction drag due to the shear forces in the fluid as it reacts with the object in the flow. In the case of round bars transition from laminar flow to turbulent flow allows the size of the flow wake trailing the bars to become smaller and thus the total drag to become smaller.[8] This loss of drag coefficient could be desirable for caves with higher flow velocities where Reynolds number is usually above the critical Reynolds number. Note that these data are based on wind tunnel tests of single round bar shapes and do not incorporate interference effects that vertical members, attachment hardware, and other components of a cave gate or grid type structure have upon fluid flows. Actual flow patterns can only be modeled in wind or water tunnels where these phenomena can be observed and measured. It should be noted however that it is very possible that round-bar cave gates with Reynolds numbers between 10,000 and 100,000 produce vortex streets with resultant tone generation.[7] Depending on the flow conditions the frequency of these tones may or may not be audible to humans. The tone frequency can be calculated using the equation for the Strouhal Number for round bar. At a Reynolds number of 100,000 the Strouhal Number for round bar is 0.2 and with the other flow parameters known the frequency of tone generation from vortex streets can be obtained.[7] The equation for Strouhal number is given as:

$$S = f h / V$$

where S is the Strouhal number, f is the frequency in Hertz, h is the diameter of the round bar in feet, and V is the velocity in ft/sec. For a velocity of 10 ft/sec the frequency for vortex streets is about 16 Hz. The strength of the tone is proportional to the energy of the fluid flow and thus low velocity flows will generate weaker tones.

In summary:

- Every cave gate will experience different air flows,
- The best location of a cave gate is where the airflow is very slow,
- Solidity ratio of cave gates must be kept to a minimum to reduce pressure loss,
- There is less than 1% pressure loss for low velocity airflow for typical cave gate materials at solidity ratios of 60% or less,
- To more completely understand the flow modeling of gates either analytically or experimentally is encouraged.

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