

## PAPER

## ENGINEERING SCIENCES

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## Forensic Fluid Dynamics and the Indian Spring (1991) Cave Collapse Problem\*

**ABSTRACT:** Nof and Paldor (*Safety Sci* 2010;48:607–14) suggested that resonance in the air pockets in the Indian Spring cavern might have contributed to the 1991 collapse. Here, we extend the resonance theory to one pocket in the cavern and a very broad basin that serves as the other branch of the U-tube. Our methodology is to apply familiar fluid dynamics principles to the situation that occurred in the cave. We did so on the basis of our interviews with four of the five surviving cave divers. We dissected their testimonies to arrive at a physically plausible scenario determined on the basis of a fluid dynamics application to the natural flow in the cave, the flow induced by the compressed air released by the divers and the mudslide. We found that there was a temporary flow *blocking* during the collapse, but no total flow *reversal* within the cave.

**KEYWORDS:** forensic science, cave collapse, cave fluid dynamics, resonance, mud slide

The Indian Spring cave is situated in the panhandle in north Florida (Figs 1 and 2). Like many other submerged caves in the region, it was explored primarily in 1980s and 1990s. A bizarre accident occurred in 1991 when the cave collapsed while two divers were still in it, causing the drowning of a very experienced cave diver, Parker Turner. To date, this is the *only* cave-diving accident in cave-diving history (of several hundred), which is said to occur because of natural causes rather than diver error.

Here, we follow up on the earlier article of Nof and Paldor (1), where it has been suggested for the first time that resonance resulting from air/gas exhaled by open circuit divers (at regular intervals) caused the tragic cave collapse that trapped Parker Turner inside the cave, causing him to drown. The article left a number of important questions unanswered, and the purpose of the present work is to place the resonance proposition on a more solid ground by answering these, still open, questions.

### Issues at Hand

The first issue has to do with the air tubes (pockets). In the original article, the pockets were not specifically identified. Here, not only do we identify the specific main pocket (Figs 3 and 4), but we also show that the basin can act as one of the U-tube arms, implying that only one pocket was actually needed to be identified within the cavern for the resonance to be active (Figs 5 and 6). In

this scenario, the oscillations are now between the open basin and the pocket identified within the cavern rather than between two adjacent pockets within a cavern.

The second, and perhaps more important, issue that is addressed here is how the proposed physics fits what has been actually observed by the cave divers present in the cavern during the accident. Previously, we were not in a position to speak to those who witnessed the event directly because, understandably, without seeing an article that already appeared in the scientific literature, they were very reluctant to talk to us. In sharp contrast, after the appearance of that article, the divers provided a wealth of useful information, which helped shed more light on the processes in question. Much of the present article is based on the information that they provided and on questions raised by that information.

For instance, did the collapse cause an actual *reversal* of the flow within the cave as originally claimed in some of the blogs? We shall argue that what was actually observed was most likely only a partial reversal (i.e., a reversal of the flow near the bottom), not a complete reversal in the entire water column. Similarly, surface support personnel claim that the water level in the basin dropped 0.30 m in 10 min. Was that because water flowed back into the cave? We shall suggest that this drop was simply because the spring flow was temporarily blocked, so the water exiting the basin downstream (Fig. 3) had no compensating inflow coming in upstream so it drained the basin fairly quickly.

Why was sediment typical for the cavern zone found 150–200 m into the cave if there was no flow reversal? We shall argue that this is because a mudslide flow is very similar to the familiar lock-exchange problem—while the heavy muddy water flows one way (downhill), there is a compensating flow above (of the clear water) flowing in the opposite way, so there is no net exchange across a complete cross-section.

For clarity, we define four different stages of the collapse process (Fig. 4). During the first (or initial) stage, a resonance is established in the pocket, the pressure rises uncontrollably, and the

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FIG. 1—A map of the southeastern United States showing the location of the water-filled Indian Spring cave. The cave spring water, which flows at a speed  $\sim 0$  (0.1 m/sec) within the cave, ultimately ends up in the spring pool which eventually empties into the Wakulla river. Figure adapted Nof and Paldor (1).

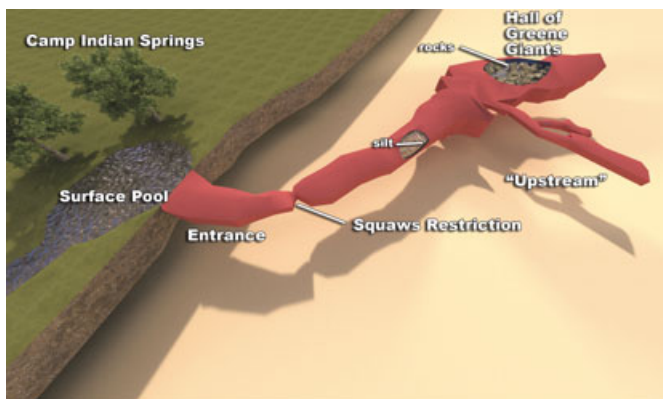


FIG. 2—A schematic three-dimensional view of the Indian Spring cave. The cave walls, ceiling, and floor are all shown with the red envelope. Limestone is outside that envelope whereas water occupies the inside of the envelop (the cave). Our proposed collapse mechanism involves resonance in the region downstream to the Squaws Restriction. That resonance increased the pressure in divers-induced air pockets (in the cavern region) beyond the level that which the cavern’s ceiling could sustain. As a result, part of the ceiling fell on the steeply sloped sediment, which, in turn, slid and blocked the Squaws Restriction (see Figs 3–5). Adapted from Nof and Paldor (1).

limestone in the immediate vicinity of the pocket breaks. During the second stage, broken debris fell on the slope below, which causes the mud to slide, creating an initial cavity in the sloping bottom. In the third (or intermediate) stage, the sediment initially contained in the cavity establishes a lens-like turbidity current that rushes quickly downstream, blocking most of the restriction shortly afterward. In the fourth (terminal) stage, the smaller lens-like turbidity current (whose top was effectively “sliced off” by the restriction) propagates more slowly downhill beyond the restriction.

**The Event as Perceived by the Cave Divers**

The particular dive in question was one of the many exploratory cave dives conducted by various groups (during the last 50 years)

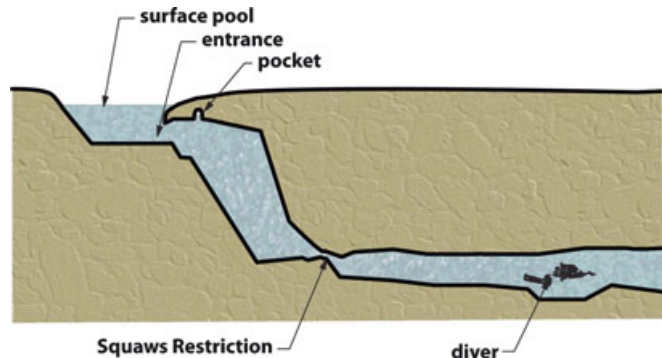


FIG. 3—A schematic long vertical cross-section of the cave extending all the way from the entrance to the Hall of Greene Giants situated a few hundred meters within the cave.

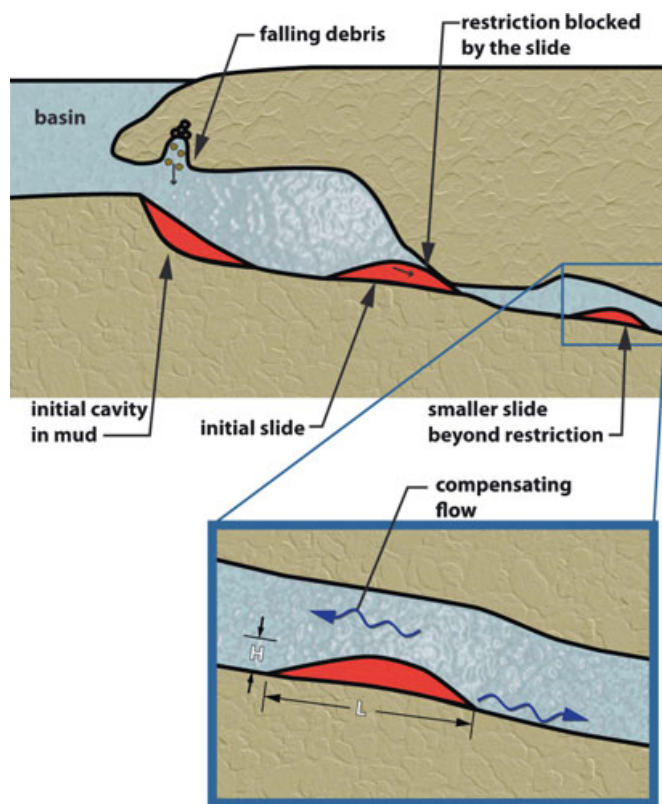


FIG. 4—A schematic short vertical cross-section of the cave extending from the entrance to a short distance beyond the restriction (politically incorrect named the Squaws Restriction).

in the Wakulla County area (Fig. 1). It was executed by what, at the time (1980s and 1990s), was probably the most organized, sophisticated, and accomplished cave-diving group in the world, the Woodville Karst Plain Project (WKPP). They set several world cave-diving records in terms of penetration distances and times spent underwater, mapping submerged caves that are roughly 15 km long, staying at depths of 60–100 m for nearly 4 h (on one dive), and decompressing for as much as 10 h or more.

There were three teams in the cave and cavern system on the day in question. One team (Gavin and Parker) did the deep and long exploration dive in the cave, while the second team (George Irvine and Lamar English, divers A and B) did a scooter dive. The third team consisted of Bill Main and Alexander Kaye (divers C and D). Both the second and the third teams were already doing

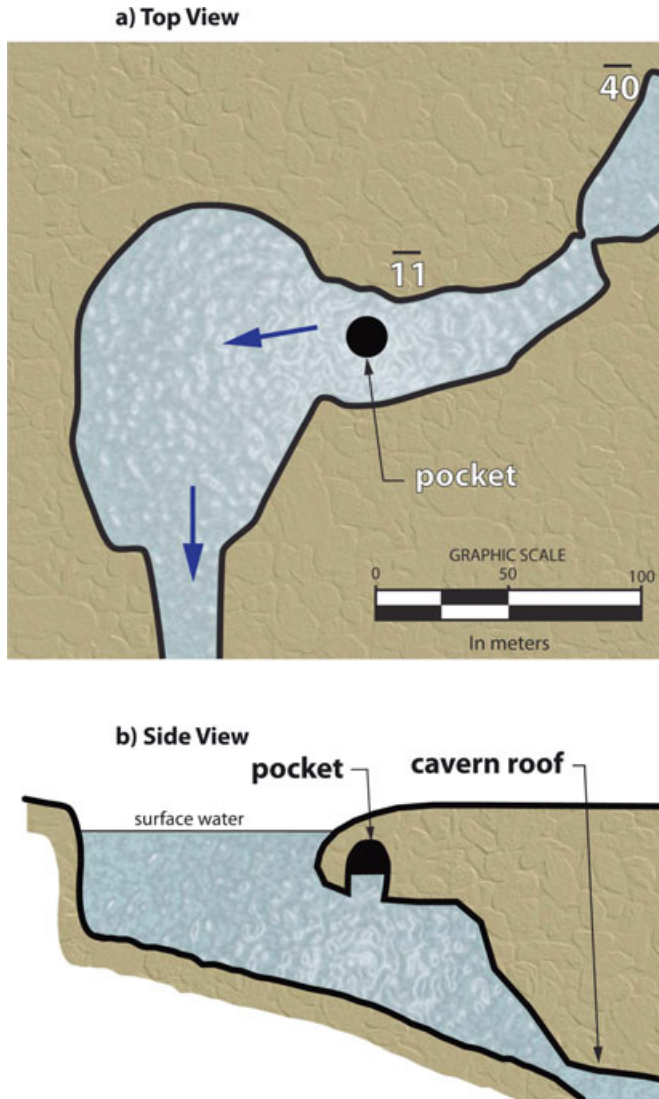


FIG. 5—(a) The position of the pocket (black solid circle) relative to the basin and the restriction. Numbers with a bar above them indicate the depth of the cave ceiling. (b) Side view is schematic, it is not drawn to scale.

their decompression stop in the cavern when the first team, which was the last to exit, encountered the avalanche within the cave. We spoke to all the divers mentioned above with the exception of Gavin who indirectly indicated that he is not willing to speak to us.

Evidently, as part of his decompression, diver A stuck his head in one of the air/gas pockets in the cavern at a depth of 5–7 m. This is a common practice among cave divers who do it routinely either to get warm or to blow their noses and clear their sinuses. His scooter was not with him at the time as they already completed the scooter portion of the dive and had already tied their scooters to the guideline below. After a few minutes, while his head was still in the pocket, the avalanche started from the very same pocket that he was in. As the second step in the process, broken rock and debris fell from the ceiling on the steep slope below, which, in turn, developed into a mudslide that resulted in the blockage of the first downstream restriction (politically incorrect named the “Squaws Restriction”).

In contrast to common anecdotes implying the involvement of a scooter (peculiarly persisting among cave divers for two decades), no scooter was involved in the collapse as both scooters were tied

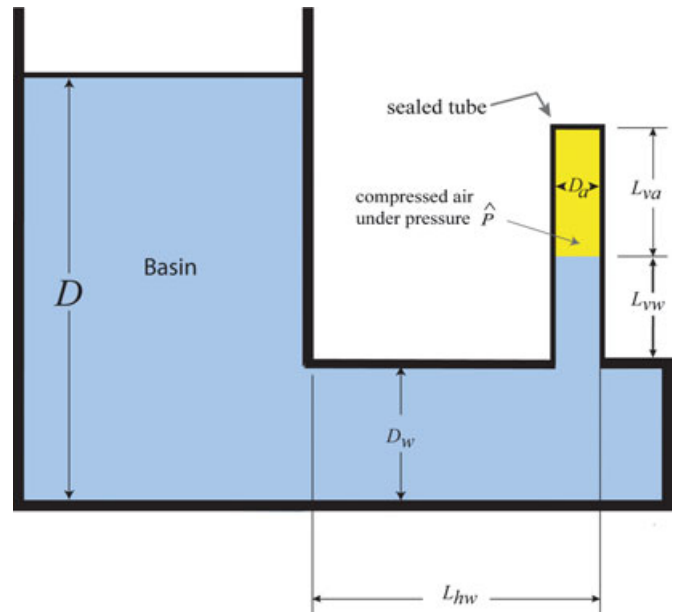


FIG. 6—Schematic diagram of the U-tube model with one narrow (right) and one thick (left) arm. The thick (uncapped) arm corresponds to the basin whereas the thin (capped) arm corresponds to the pocket.

to the line below the divers. Note, however, that, at some point, diver A thought that his scooter, which he left tied to the line below his decompression position, was turned on accidentally and runaway, but it turned out that this was not the case. Anecdotal claims that a seismic event might have contributed to the collapse are also unsubstantiated. According to the seismic records ([http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic\\_global.php](http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_global.php)), a total of 137 quakes were recorded worldwide from November 16 to November 18, 1991, but none was even close to Florida.

Evidently, surface personnel witnessed a sudden drop of the water level in the basin (0.5 m within 10 min or so) and swirling water above the cave entrance and interpreted these to mean that the flow in the cave had totally reversed its direction. Technically, this is in general feasible, and indeed, Lake Jackson, situated in northwest Tallahassee (Fig. 1) about 30 km to the north of the cave (and within the same karst aquifer), has occasionally disappeared (almost overnight) during the last 50 years. Presumably, an underground passage opened up draining the lake. (In most occasions, the lake came back after several years, but its last disappearance in the late 1980s has not seen a reversal.)

While such a sudden opening of a previously closed underground passage is technically possible, it is extremely unlikely that it would happen just when the cave divers happened to be within the cave. We employ here the same logic that we used earlier—it is unlikely that a cave collapse just accidentally happened to occur while divers were in the cave. A much more likely scenario is that the sudden drop of water level in the basin is simply because the cave exit/entrance (exit to the water, entrance to the divers) was temporarily blocked (so there was no flow out of it), whereas the downstream exit of the basin remained opened, quickly draining the basin. Taking the average volume flux out of the cave to be roughly  $5 \text{ m}^3/\text{sec}$  and the surface area of the basin to be  $100 \times 100 \text{ m}^2$ , we found that the water level would drop 0.5 m in just 17 min if the feeding tunnel were to be abruptly shut down. As we shall see later, we attribute the observed swirl to a horizontal vortex that initially formed above the cave entrance when the mudslide just occurred.

This study is organized as follows. In the next section, we present the basin–pocket resonance model, and in the third section, we present the mudslide calculation. The fourth section addresses the resulting turbidity current issue, and the fifth addresses the vortex in the open ocean. The results are summarized in the Discussion. There is some, but very limited, overlap (particularly in the figures) between the present article and the Nof and Paldor’s (1) article, because an attempt has been made to make the present study self-contained.

### Methods—The Basin–Pocket Resonance Model

Consider again Fig. 4 and the U-tube shown in Fig. 6, which represents the situation shown in Fig. 5 in a simplified manner. In contrast to the Nof and Paldor’s study (1) U-tube problem (see their Fig. 6), our new resonant U-tube configuration contains only one narrow vertical tube capped at its top (shown on the right of our Fig. 6). The left tube in Nof and Paldor’s study (1) is represented here by the broad basin, which is, of course, open on its top (Fig. 6). The narrow tube on the right represents the pocket in the upper regions of the cavern where the compressed air/gas accumulates (see Fig. 5). Its diameter is  $D_a$ , the corresponding cross-sectional area is  $A_a$ , total length is  $L_v$ , and the lengths of its components that are filled with air and water are  $L_{va}$  and  $L_{vw}$ , respectively (see the Appendix for explanation of the symbols). The thick horizontal tube (below it) represents the cave (or cavern) and has a diameter  $D_w$ , much larger than the vertical tube diameter  $D_a$ , and a length  $L_{hw}$ . The tubes diameter ratio ( $D_a/D_w = 1$ ) represents the actual situation in nature, but, as it turns out, it has no bearing on the calculations presented here. The corresponding cross-sectional area of the horizontal tube is  $A_w$ , and its wet length is  $L_{hw}$ . The excess pressure (i.e., the pressure above the atmospheric pressure) in the air-filled component depends on the cave’s depth and is denoted by  $\hat{P}$ .

This new U-tube model is adopted as a means of representing resonating flows that are superimposed on the usual one-dimensional (horizontal) flow in the cave. The modeled resonating flow, which is induced by the air/gas pocket, is limited to the region between the pocket and the basin, so the lower part of the modeled tube is taken to be blocked on two sides, forming a U-tube with one sealed vertical component (pocket) and one open (basin).

When the water level in the right vertical tube (shown in Fig. 6) is elevated an arbitrary infinitesimal distance  $\eta$  above its neutral position, there are two restoring forces. The first is the familiar weight of the displaced water  $\rho_w g A_a \eta$ , where  $\rho_w$  is the water density. The second is the new not-so-familiar force because of the incremental increased pressure in the air-filled section,  $\hat{P} \eta / L_{va}$  (derived from the linear gas law,  $\hat{P} \hat{V} = \text{const.}$ , where  $\hat{V}$  is the volume of the air pocket). Fortunately, this new force (i.e., the incremental increased pressure times the cross-sectional area  $A_a$ ) turns out to be linear. In the absence of friction (i.e., the inviscid limit), the sum of these two forces causes the fluid to accelerate (in both the horizontal and vertical tubes as well as the infinitely large basin) in response to the initial perturbation (e.g., increase) of the water level in the right vertical tube.

In the narrow vertical tube containing the gas, the (time-dependent) acceleration is  $d^2 \eta / dt^2$ . Conservation of mass implies that in both the horizontal tube and the vertical broad-basin tube, the acceleration is much smaller,  $(d^2 \eta / dt^2) A_a / A_{wc}$  and  $(d^2 \eta / dt^2) A_a / A_{wb}$ , where  $A_{wc}$  is the vertical cross-sectional area of the cave and  $A_{wb}$  is the horizontal cross-sectional area of the basin. This is because the velocity in these sections of the tube is also much

smaller [ $(d\eta/dt) A_a / A_{wc}$ ;  $(d\eta/dt) A_a / A_{wb}$ ]. Assuming that the fluid velocities are uniform within each cross-section and neglecting the corners of the U-tube, the inviscid governing equation ( $F = ma$ ) can be written as

$$\rho_w A_a (L_{vw} + D + L_{hw}) \frac{d^2 \eta}{dt^2} + (\rho_w g A_a + \hat{P} A_a / L_{va}) \eta = C_1 \cos \omega t + C_2 \sin \omega t \quad (1)$$

where  $D$  is the basin depth (Fig. 6). Here, the first term on the left-hand side corresponds to the familiar acceleration of the water times the mass in both the narrow and thick segments of the U-tube. Interestingly, it turns out to be independent of the cross-sectional areas of the thick horizontal tube representing the cave and the thick and short vertical tube representing the basin. This is because, although the cross-sectional areas are large in both of these sections ( $A_{vw}$ ;  $A_{hw}$ ), the velocities there,  $\frac{A_a}{A_{wc}} (d\eta/dt)$  and  $\frac{A_a}{A_{wb}} (d\eta/dt)$ , are proportionally smaller so they compensate for the increase in mass associated with the increase in area (this implies the counterintuitive result that the ratio of the tubes diameters does not enter the problem). The second term is the restoring force, which now consists of both the familiar gravitational pull and the new, not-previously-discussed force, associated with the *compressed* air/gas in the pockets. Luckily, this new term is linear. The terms on the right-hand side represent the (known) periodic forcing associated with divers releasing air that further accumulates in the closed sections of the tube. (Given the concave nature of the cave’s ceiling, this additional air/gas does not have to be released directly into the air/gas chambers. For most caves, air released nearby will slide along the slanted ceiling and will ultimately reach the highest point representing the top of the tubes.) When the terms on the right-hand side are zero, the solution of Eq. 1 is a harmonic oscillations solution. We shall refer to this state as the “free state” as it is not subject to any outside forcing. Interestingly, the inclusion of the new enclosed (air-pressurized) sections of the tube on top does not change the mathematical nature of this solution. All they do is to make the restoring force larger.

Assuming an inviscid solution of the form  $\eta = A_{m1} \cos \omega t + A_{m2} \sin \omega t$ , we obtain from Eq. 1

$$A_{m1} = C_1 / (\beta - \omega^2 \alpha); \quad A_{m2} = C_2 / (\beta - \omega^2 \alpha)$$

where  $\alpha = \rho_w A_a (D + L_{vw} + L_{hw})$  and  $\beta = \rho_w g A_a + \hat{P} A_a / L_{va}$ .

We see that regardless of the choices for the constants  $C_1$  and  $C_2$  (representing the strength of the forcing), the amplitudes  $A_{m1}$  and  $A_{m2}$  go to infinity (i.e., resonance) when  $\omega^2 = \beta / \alpha$ . As in other resonance cases, this frequency is also the frequency of the natural oscillations, that is, the frequency of the free state ( $C_1 = C_2 = 0$ ). Just like a swing is forced higher and higher when pushed at the same frequency as its natural oscillation frequency, so are the oscillations in the U-tube.

Accordingly, the period of the forcing leading to a resonance is found to be

$$T = \frac{2\pi}{\{g / (D + L_{vw} + L_{hw}) + \hat{P} / \rho_w L_{va} (D + L_{vw} + L_{hw})\}^{1/2}} \quad (2)$$

This formula gives values that are approximately  $\sqrt{2}$  larger than that of the period obtained by Nof and Paldor (1), because there are only one narrow tube and one chamber of compressed air/gas so there is less of a restoring force and, consequently, the water

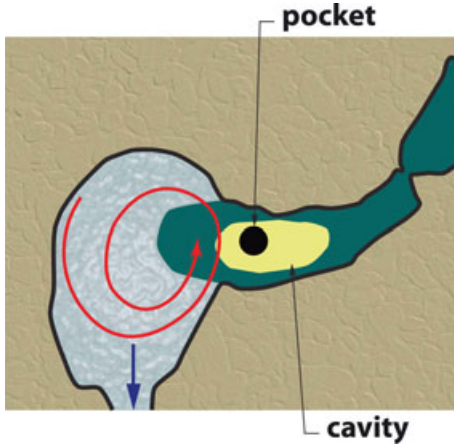


FIG. 7—A top view of the basin and cave entrance showing the pocket, initial cavity on the bottom and the surface vortex in the basin.

moves more slowly. When the forcing is at the above period, the pressure at the gas-filled chambers,  $\hat{P}\eta/L_{va}$  (where  $\hat{P}$  is the undisturbed pressure), goes to infinity (i.e.,  $A_{m1}$  and  $A_{m2}$  become infinitely large). It is this infinite increase in pressure that, we argue, might have caused the collapse. Note that, practically,  $\eta$  ranges from almost zero in the beginning of the resonance process to the full extent of the gas pockets when resonant takes hold. For most Florida caves, this maximum length might be as high as  $\sim O$  (10 cm) or several meters.

We shall now consider the case (Fig. 7) applicable to the Indian Spring's cave dimensions. Given the simplifications in the model, it is, of course, very hard to pick up values for the various parameters, but some rough guesses can be made. Accordingly, suppose that the ceiling of the cavern/cave where the pocket was identified (Figs 4 and 5) is about 5 m below the water elevation in the spring run (typical decompression depth) that the length of the compressed gas pocket ( $L_{va}$ ) is 0.5 m and that the combined length of the cavern/cave and vertical tubes ( $D + L_{vw} + L_{hw}$ ) is 50 m. For these values, the period is about 4.5 sec, which is of the same order as the time elapsing between two consecutive breaths of a typical diver during decompression. We see therefore that the forcing period corresponding to resonance (i.e., the pressure in a typical cave becomes infinitely large) is comparable to the natural breathing period of divers in the cave.

## Results—The Mudslide

As mentioned previously, we suggest that resonance caused an uncontrollable pressure rise within the pocket, leading to a breakup of the limestone surrounding the pocket. A massive amount of broken rock then fell on the steeply sloping bottom below. Given the high slope of the bottom ( $\sim 30^\circ$ ), it was probably only marginally stable to begin with, so upon impact with the broken rock, a mudslide occurred. A lens-like feature was carved out of the slope turning into a turbidity current downhill (after some dilution). Owing to its origin, that turbidity current had also the shape of a lens that slid downhill. (By "lens" we mean a topological feature having zero thickness along its rim, which is a closed contour. For simplicity and analytical tractability, we shall shortly take the lens to be of infinite extent in the direction perpendicular to the cave, i.e., the top and bottom of the cave will be taken to be parallel slanting planes.) The turbidity current height was probably higher than the height of the Squaws Restriction, so it blocked it once encountering

it. The restriction effectively sliced the top of the turbidity lens off, allowing for a smaller lens to continue propagating downstream beyond the restriction.

There was probably never a complete blockage of the restriction, which explains how Gavin managed to get out of the cave. For all practical purposes associated with cave diving, however, once the visibility went to zero (as it did in the case in question) and the guideline was nowhere to be found (because it was buried in the avalanched sediment), then the restriction was effectively blocked to the divers. Next, we shall estimate the speed of the avalanche.

Consider the downhill propagation rate ( $C$ ) of a two-dimensional turbidity lens, that is, a lens (Fig. 4) with an infinite extend in the long-slope direction situated between two parallel sloping planes representing the cave floor and ceiling (whose distance from each other is  $D_w$ ). The lens length, density, and height are  $L$ ,  $(\rho + \Delta\rho)$ , and  $H$ , and its migration rate can be estimated from the balance between the gravitational force and the form drag on the lens:

$$C_D C^2 H \approx \alpha g (\Delta\rho/\rho) H L \sin \theta \quad (3)$$

Here,  $C_D$  is the *form-drag* coefficient for the lens, which is of order *unity* and needs to be distinguished from the *frictional* drag that is typically three orders of magnitude smaller. Alpha ( $\alpha$ ) is also a coefficient of order unity, which has to do with the shape of the lens. For parabolic lenses, it is  $4/3$  (see, e.g., Watts and Grilli [2, Eq. 5]). Delta  $\rho$  is the density difference between the fluid corresponding to the turbidity lens and the water without sediments, and  $\theta$  is the slope angle (Fig. 4). Friction between the turbidity lens and the material below it (Coloumb friction) is usually small (Watts and Grilli [2]), so we neglect it too. It is important to realize that the term representing the form drag (left-hand side of Eq. [3]) involves the lens height ( $H$ ), not length. Also, note that as  $H \sim O(L \sin \theta)$ , Eq. 3 is equivalent to the statement that the Froude number is of order unity, as should be the case.

In the ocean, where most underwater landslides have been observed and studied (e.g., Jiang and LeBlond [3]), the ratio of depth to length is roughly  $1/100$  (depth of the ocean and the length of the continental rise or continental slope), so the turbidity currents have that ratio too. By contrast, in the cave, that ratio is expected to be more like  $1/1$  or  $1/10$ . An interesting point to note here is that, although the cave is typically much longer (kilometers) than its height or width [ $\sim O(1-10)$  m], most caves consist of relatively short and *dynamically separated* sections, which are bounded by breakdowns or other abrupt changes in their configuration. In the case in question, such a section is between the entrance and the Squaws Restriction, which is roughly 100 m into the cave. The cave is about 10–20 m in diameter, making the thickness/length ratio  $1/5-1/10$ .

The density load associated with a typical turbidity current is  $50 \text{ kg/m}^3$  (see, e.g., Hughes Clarke et al. [4]), so we will take  $\Delta\rho/\rho_w = 0.05$ . Also, in view of the above, we will take  $H \sim 5$  m,  $L \sim 25$  m,  $C_D = 1.5$ ,  $\alpha = 4/3$ ,  $\theta \sim 30^\circ$ . Together with Eq. 3, these choices give a fast propagation speed of 2.5 m/sec into the cave (against the usual outgoing flow in the cave, which is typically no more than 0.5 m/sec). Assuming that the restriction reduced the lens size in half, we obtain that upstream of the restriction (i.e., further into the cave), the lens propagation speed against the usual current in the cave was about 1.8 m/sec.

How far could such a lens penetrate to? Assuming temporarily that the cave would have not had any breakdowns or other changes in configuration, it would have propagated until the sediment settles

out of suspension. We shall now calculate how far that is using Stokes settlement formula for laminar flow

$$V = \frac{gd^2(\Delta\rho_p/\rho_w)}{18\nu} \quad (4)$$

where  $V$  is the particle settling speed,  $d$  the particle size ( $4 \times 10^{-6}$  m for clay and  $0.5 \times 10^{-3}$  m for sand),  $\Delta\rho_p$  the density difference between an *individual* grain particle (sand or clay) and the water ( $\sim 2$  g/cm<sup>3</sup>), and  $\nu$  is the kinematics viscosity ( $10^{-6}$  m<sup>2</sup>/sec). In our cave, the flow is obviously not laminar because the Reynolds number ( $UH/\nu$ ) is roughly  $10^7$  so the viscosity is really an “eddy viscosity” rather than the laminar value given above. But no turbulence measurements have ever been taken in a submerged cave, so we do not know what value to pick. (In the deep ocean, which is relatively calm, the value is an order of magnitude higher,  $0.1$  cm<sup>2</sup>/sec.) Because the turbulence keeps particles in suspension longer than they would be kept in suspension otherwise (i.e., in laminar flow), the Stokes formula would give us an *upper* bound on the particles’ settlement speed and *lower* bound on the penetration distance.

For sand, the above formula together with the adapted choices of parameters gives a settlement speed of  $\sim 0.2$  m/sec, whereas for clay, it gives  $\sim 2 \times 10^{-5}$  m/sec. Silt would be in between the two. This means that for the particles to settle out of the 5-m-thick lens it would take between 25 sec (sand) and 3 days (clay). Silt would sink in several hours. This, in turn, means that, without obstructions and with no turbulence in the water, the lens would have propagated at least 50 m (where the sand would settle) and at the most 500 km (where the clay would settle). Silt would have probably penetrated several kilometers. It is therefore not surprising that Gavin saw sediments 400 m into the cave.

As already alluded to in the introduction, the fact that the sediment was observed on the bottom 300 m into the cave does not at all mean that the entire flow within the cave reversed direction. Just like any other lock-exchange problem (see, e.g., Shin et al. [5], Bombardelli et al. [6]), while the turbidity current itself advances downhill on the floor, the clear water above it flows in the opposite direction (uphill), compensating for its volume flux so that there is no net flow downhill or uphill ahead of the turbidity current head (Fig. 4). Given that the minimum thickness above the turbidity current is  $(D_w - H)$ , where  $D_w$  is the cave thickness, we find that the maximum uphill speed directly above the lens is roughly  $CH/(D_w - H)$ , giving about 0.5 m/sec for  $D_w \approx 20$  m.

### Results—The Vortex in the Basin

We shall now explain the vortex and the sudden drop in water level observed by the surface support personnel. During the second stage of the collapse, when the cavity in the sloping bottom sediment has just been formed, water from somewhere else must rush in to replace its space that is now empty. This water could have come from the spring itself, but evidently, this source could not provide a large enough volume quickly enough. The basin above is another potential source, and apparently, this is where the water came from. Just like water draining in a bathroom sink, such a flow tends to spiral in because even a tiny initial orbital flow ( $V_\theta$ ) present near the periphery of the sink is dramatically magnified when the outlet is reached. This is because of the familiar conservation of angular momentum, which implies

$$\frac{d}{dt}(rV_\theta) = 0 \quad (5)$$

where  $r$  is the radius. Relation (Eq. [5]) states that any fluid particles that approach the center ( $r \rightarrow 0$ ) from a region away from the center have a forever-increasing orbital velocity. This created the vortex that the surface support personnel apparently saw (Fig. 7). It lasted for only a short time (a few minutes at the most) until the cavity space was filled with basin water. At this point, the reversed flow from the basin into the cavern ceased.

Note that the net volume of the cave (i.e., the volume of the space confined by solid media) has not changed because of the mudslide. The mud associated with slide merely changed its position from the cavity on the floor to the mud contained in the lens-like turbidity current (Fig. 4). Consequently, while basin water was drawn into the cave to fill the cavity, other water must have been expelled out of the cave into the basin. Therefore, the basin level did not change as a result of this process, which formed a (temporary) asymmetrical horizontal dipole. Note that, although the expulsion involved the same amount of fluid as the inflow, it must have involved a much weaker flow (and, hence, less noticeable). This is because it was associated with a divergent flow on the surface rather than a convergent flow.

A short time after the slide (minutes), the mudslide lens reached the restriction and blocked most of the flow coming out of the cave. Meanwhile, on the surface, the basin’s outlet downstream continued to flow, and this lowered the water level in the basin. Taking the surface area of the pool to be  $100 \times 100$  m<sup>2</sup> and the flow out of the cave to be  $5$  m<sup>3</sup>/sec, we find that the basin had been lowered by 0.5 m in just 17 min. While this was taking place, the hydrostatic pressure behind the restriction continued to build up within the limestone until there was enough of it to force the sediment out of the partially blocked restriction. At this point, the cave started clearing itself up so to speak.

### Discussion

This is an attempt to bring two different fields, forensic science and fluid dynamics, into one frame of mind. It is not obvious to us how successful we were in achieving a breakthrough, but we did succeed in explaining the events that led to the collapse of the Indian Spring cave and the drowning of Parker Turner. As in Nof and Paldor’s study (1), we argue that the whole process started by resonance in one of the air/gas pockets typically present in most caves visited by cave divers (Figs 3–6). In contrast to Nof and Paldor’s study (1), however, we identified the pocket occupied by one of the divers decompressing in the cavern (Fig. 5). Obviously, that diver could have not possibly known about the resonance that we are alluding to.

We distinguish between four different stages of the collapse. During the first (or initial) stage, a resonance is established in the pocket, the pressure rises uncontrollably, and the limestone in the immediate vicinity of the pocket breaks (Fig. 4, left side). During the second stage, broken debris fell on the slope below. This caused the mud to slide, creating an initial cavity in the sloping bottom (Fig. 4, left side). In the third (or intermediate) stage, the sediment initially contained in the cavity gets diluted with fresh water and establishes a lens-like turbidity current. This current then rushes quickly downhill, blocking most of the restriction shortly afterward (Fig. 4, central part). In the fourth (terminal) stage, the smaller lens-like turbidity current (whose top was effectively “sliced off” by the restriction) propagates more slowly downhill (Fig. 4, right side).

Eq. 2 was used to calculate the periodicity associated with the resonance. It is about 40% larger than the value calculated by Nof and Paldor (1), which is still very relevant to the problem at hand because of the simplifications involved. The main difference between the two is attributable to the basin serving as one of the U-tube arms. (The periods that we present in the Nof and Paldor's study [1] and here are actually the same because the identified pocket was deeper than the pockets considered in the Nof and Paldor's study [1].) We then used Eq. 3 to calculate the speed that the mudslide migrated downhill and found it to be roughly 2.5 m/sec. The clear water above the mudslide moved in the opposite direction at approximately 0.5 m/sec, so there is no net flow upstream ahead of the turbidity current.

With the aid of Eq. 4, we then estimated how long would such a turbidity current last before the sediments (sand, silt, and clay) settle out of it. Using this information, we then showed that it could penetrate large distances into the cave (kilometers, had there been no obstacles). With this scenario, there was never a complete flow reversal where water rushed into the cave instead of rushing out. There was, however, a brief period (minutes) when basin water rushed into the cave to fill in the space created by the mudslide that detached from the bottom. This flow created the surface vortex observed by surface support personnel (Fig. 7). A weak current exiting the cave and carrying the same volume compensated for it, so the mudslide did not create any *net* flow.

In both the resonance and mudslide calculation, we have ignored the preexisting current within the cave, assuming that as our processes are linear, this flow can simply be superimposed on our calculated flows. A reviewer of Nof and Paldor's study (1) asked about the relationship between the two flows, and we erroneously answered at the time that the resonance flows within the cave are much faster than the preexisting flows. We realized later that this is incorrect—only the resonating flows within the narrow vertical tube are faster, and the corresponding flows within the cave itself are actually smaller. Still, however, the superposition argument holds. We hope that this study will encourage further investigations involving more accurate and detailed calculations.

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#### Appendix—List of Symbols

- $D_a$  – Diameter of the pocket in the upper regions of the cavern (m)  
 $D_w$  – Diameter of the cavern (m)  
 $L_{va}$  – Length of the air mass in the pocket (m)  
 $L_{vw}$  – Length of the water column in the pocket (m)  
 $L_{hw}$  – Length of the cavern (m)  
 $L$  – Turbidity lens length (m)  
 $H$  – Turbidity lens height (m)  
 $D$  – The basin depth (m)  
 $\eta$  – Water level elevation from its neutral position (m)  
 $d$  – The particle size (m)  
 $A_{m1}, A_{m2}$  – Amplitudes (m)  
 $r$  – Radius (m)  
 $A_a$  – Cross-sectional area of the pocket in the upper regions of the cavern ( $m^2$ )  
 $A_w$  – Cross-sectional area of the cavern ( $m^2$ )  
 $A_{wc}$  – Vertical cross-sectional area of the cave ( $m^2$ )  
 $A_{wb}$  – Horizontal cross-sectional area of the basin ( $m^2$ )  
 $\hat{P}$  – Excess pressure ( $N/m^2$ )  
 $F$  – Force (N)  
 $m$  – Mass (kg)  
 $O$  – The order of  
 $\rho_w$  – Water density ( $kg/m^3$ )  
 $\rho$  – Density of fluid causing turbidity (sediment) ( $kg/m^3$ )  
 $\Delta\rho$  – The density difference between the fluid corresponding to the turbidity lens and the water without sediments ( $kg/m^3$ )  
 $\Delta\rho_p$  – The density difference between an individual grain particle ( $kg/m^3$ )  
 $\nu$  – The kinematics viscosity ( $m^2/sec$ )  
 $g$  – Gravitational acceleration ( $m/sec^2$ )  
 $V$  – Particle settling speed ( $m/sec$ )  
 $V_\theta$  – Orbital flow velocity ( $m/sec$ )  
 $a$  – Acceleration ( $m/sec^2$ )  
 $\hat{V}$  – Volume of the air pocket ( $m^3$ )  
 $t$  – Time (sec)  
 $\omega$  – Frequency (per sec)  
 $T$  – Period (sec)  
 $\theta$  – Slope angle ( $^\circ$ )  
 $C_D$  – Drag coefficient  
 $C_1, C_2$  – Constants