Questions & Answers at Indian Springs

Why did the Indian Spring cave collapse while Parker Turner and Bill Gavin were in the cave?

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This article is a "layman's" version of a scientific paper that just appeared in the peer-reviewed journal Safety Science (Nof and Paldor, 2010). In that article, we propose a natural physical process that might explain the 1991 Parker Turner accident, and propose some general steps that can be taken to avoid similar accidents in the future. Specifically, it is suggested there that resonance in the air pockets in the cavern (or cave), created by open circuit (OC) divers, may have contributed to the collapse. Namely, we propose that divers present in the cavern during the dive may have (unknowingly) caused the collapse through the pressurized gas that they released with each breath. When the breathing period of the diver(s) matches the natural oscillations period of the new "cave oscillator" which we propose, the ensuing resonance causes the air pressure in the pockets to increase uncontrollably.

We model the system as a non-uniform U-tube filled with water on the bottom and compressed gas on top. The top of the tube is sealed on both sides so that the compressed gas is trapped in the chambers above the water. The bottom part of the tube represents the water filled cavern (or cave) whereas the vertical tubes represent the gas cavities. We show that such a system is subject to natural oscillations with a period of roughly the same as the breathing rate of the typical diver. One would, of course, like to have such study confirmed by other's more elaborate investigations before adopting any draconian measures, such as limiting diving in some particularly fragile caves to closed circuit rebreathers (CCR) only. Nevertheless, it is suggested here that, at the very least, OC divers in fragile caves should attempt to move around and avoid hanging in one place even during decompression.

Introduction: Indian Spring (latitude 30° 15.082, and longitude 84° 19.317) is a fresh water spring located in Wakulla County, Florida. It is approximately 90 feet deep and its length is unknown; a combined distance of about 2 miles has been surveyed upstream and downstream of the cave. Like most Florida springs, Indian Spring contains both a cavern and a cave. The typical cave usually "snakes" around leaving concave portions that often contain pockets of compressed gas released by cave divers. An interesting related question that comes immediately to mind is whether the composition of the exhaled breathing gas affects the limestone stability in the gas pockets to the extent that regular, frequent diving weakens the limestone in these concave areas and increase the risk of collapse. We do not know how to estimate this possibility with the tools that we presently have. Very strong flows occasionally flush the pockets out but new ones are formed when the flow subsides. Also, in most caves, the gas in the pockets gradually percolates upward through the porous limestone. Despite both processes, however, gas pockets are found on most cave dives indicating that they are present most of the time. Although we shall focus on Indian Springs where the particular accident in question occurred, the conditions in that cave as well as its structure are not that unique. The resonance that we propose may well also apply to other caves in limestone (e.g., aquifers in Florida, the Yucatan and the Karst regions in central Europe), ice caves, and perhaps even wrecks.

What is reported here is a blend of a forensic study and an investigation of the fluids stability within the cave. This is not a forensic study per se, however, because: (i) the emphasis here is on the stability of the fluid system, and (ii) much of the accident reporting is anecdotal. We attempted to be much more quantitative with regard to item (ii) above. However, the event has been very traumatic to many of those involved and has generated much friction among them. As a result, some have quit cave diving all together and those who did not quit do not wish to speak about it. So much so, that all of our continuous and persistent requests to speak about the accident to those that were present in the cave and cavern fell on deaf ears. This unfortunate (but understandable) situation results from the fact that the agencies associated with cave diving (e.g., NSS-CDS, NACD, GUE) are self-regulated, so that there is no means to force individuals to speak about this, or any other case.

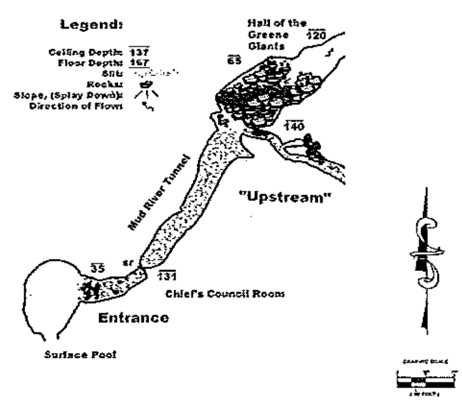

Fig. 1
A close-up map of the entrance to the Indian Springs cave system and the first few hundred meters. Depth is given in feet. The passage that was blocked during the event in question is marked as "sr" (Squaws Restriction). It is situated about 200 feet to the right of the entrance from the Surface Pool (to the cavern) and is roughly 120 feet deep. (Map adapted from a larger, NSS-CDS map.)

The Event: The accident in question occurred in 1991 prior to the establishment of the IUCRR (International Underwater Cave Rescue and Recovery, www.iucrr.org) so there is no official analysis available to the public other than the original report written by Gavin (1991), some of which is reproduced verbatim below and some is summarized in the next two paragraphs.

The dive was the first in a series of planned exploration dives. The dive plan consisted of a 40 minute transit at a depth of no more than 140 feet while breathing an EAN 27 travel mix, a descent and exploration to no more than 270 feet using trimix 14/44 (14% O2, 44% He, balance N2), followed by a return 40 minute transit to exit the cave. The 270 feet deep working phase of the dive was expected to last 20 to 25 minutes. The 140 feet deep penetration and exit was done using two stage bottles, whereas the 270 feet deep portion was accomplished using back mounted doubles. The dive went almost exactly according to plan during the penetration. Bill Gavin and Parker Turner began their exit at 63 minutes into the dive. They reached their staged nitrox bottles in two to three minutes, began breathing them, and did not use their back mounted doubles again until they later encountered the obstruction that caused the accident at what is known as the "Squaws Restriction" ("sr" in Fig. 1). There was a distinctive arrow marker at the upstream/downstream junction, which is about 500 feet from the entrance. As this arrow came into view, they estimated that their bottom time was going to be somewhere between 105 to 110 minutes. They made the left turn at this arrow and immediately noticed that the visibility in the cave had decreased. The floor was completely obscured by billowing clouds of silt, but the line was still in clear water near the ceiling. As they got closer and closer to the entrance, the visibility became progressively worse. Finally, they had to stop using their DPVs and swam while maintaining physical line contact.

When they arrived to the point where the restriction should have been, the line disappeared into the sand on the bottom of the cave. They attempted to pull the line out of the sand, but reached a point where it was buried too deep. Visibility in this area at that time was one foot or less. Closer to the exit there were two lines running parallel in the cave. They tried following both of them, but each time reached a point where the line could not be pulled out of the sand that had covered it. Ultimately, Gavin somehow managed to exit the blocked cave by removing debris and pulling himself out but Parker run out of gas and drowned (by the time that he was out of the cave, Gavin had almost no gas left in his tanks). This is the description of the accident according to Gavin.

There are numerous blogs that discuss the case primarily because it is so unique. Bill Gavin also wrote one of these interesting blogs. In that blog he stated his suspicion that divers present in the cavern (not cave) might have inadvertently caused the collapse and associated mudslide that blocked the exit. His reasoning was that, otherwise, the chance that such a collapse would occur exactly at the same time that the divers were in the cave is miniscule. In Nof and Paldor (2010) and in the present simplified version of it, we place his suspicion on a firmer ground by suggesting an actual physical process ("cave resonance") that could lead to such an outcome.

As is typical with issues of such nature, there is variability in the anecdotal descriptions of what actually happened even among those that were present in the cavern when the incident occurred. Among those descriptions, there is one alluding to exhaust bubbles released by divers decompressing in the cavern. According to this description, the resulting bubbles dislodged a large amount of sediment up in one of the solution tubes next to the ceiling, which cascaded down onto the sediment slope, causing it to slump and plug the Squaws Restriction situated downhill. One person described it as if it "looked like someone emptying a trash dumpster from the ceiling", which continued until the visibility was obscured in the basin. As we shall see, this fits very well with the resonance mechanism that we propose here (Figs. 2, 3). It is worth mentioning here in passing that a large-scale avalanche of sediment resulting from a weight dropped on the sediment slope (leading to the cave) during the US Cave Expedition of the Wakulla Springs in the late 1980's was reported by Stone (Greg Stanton, personal communication). A similar event resulting from divers digging for artifacts is described in Burgess (1999). Next, we shall briefly review the ideas behind some well-known cases of resonance, which will serve as an introduction to the new resonant case presented here.

Resonance: Many processes in nature are subject to resonance. The simplest case is that of a swing, which goes higher and higher when pushed at the right frequency. Another example is that of a tidal resonance, which occurs when the tide excites one of the resonant modes of the ocean. The effect is most striking when a continental shelf is about a quarter wavelength wide. Then an incident tidal wave can be reinforced by reflections between the coast and the shelf edge, producing a much higher tidal range at the coast. Famous examples of this effect are the Bay of Fundy, where the world's highest tides are found, and the Bristol Channel. Large tides due to resonances are also found on the Patagonian Shelf and on the N.W. Australian continental shelf.

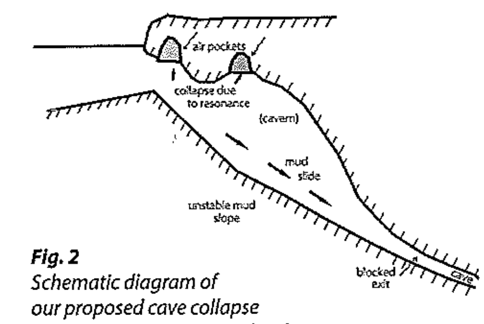

Fig. 2
Schematic diagram of our proposed cave collapse process in Indian Spring, Florida. While two divers were still in the cave beyond Squaws Restriction, divers in the cavern (upper left) generate resonance in the air pockets above them. This causes the fall-out of broken rock from the ceiling onto the steeply sloping sediment on the bottom (slope > 1:2). In turn, this impact generates a mud and sediment slide that rushes to the right and blocks the passage.

In mechanics and construction, a resonance disaster describes the destruction of a building or a technical mechanism by induced vibrations at a system's resonance frequency, which causes it to oscillate. Periodic excitation optimally transfers to the system the energy of the vibration and stores it there. Because of this repeated storage and additional energy input the system swings ever more strongly, until its load limit is exceeded. The dramatic, rhythmic twisting that resulted in the 1940 collapse of "Galloping Gertie," the original Tacoma Narrows Bridge, is sometimes characterized as a classic example of resonance; however, this description maybe misleading. The catastrophic vibrations that destroyed the bridge were probably not only due to simple mechanical resonance, but due to a more complicated oscillation caused by interactions between the bridge and the winds passing through it. There is also an interesting aircraft resonance case involving runway smoothness (and its associated wavelength) resonating with the length of the aircraft.

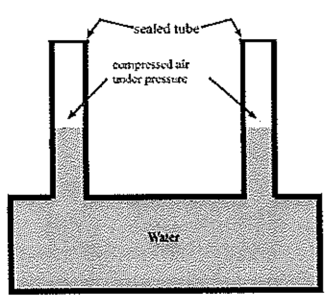

Fig.3
The simplified U-tube model. In this idealized simplification, the distance between the adjacent pockets is much smaller than the distance from the pockets to the free surface in the spring run so that the cave can be taken to be blocked on the two sides.

Model: Consider the U-tube shown in Fig. 3. In contrast to the classical U-tube problem, our new resonant problem contains two narrow vertical tubes capped at their tops, which represents the upper regions of the cave where the compressed gas accumulates. 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. This modeled resonating flow, which is induced by the gas pockets, is limited to the region between the pockets, so the lower part of the modeled tube is taken to be blocked on the two sides, forming a U-tube. The vertical propagation speed of the non-frictional resonating oscillations within the adjacent pockets is a foot per second or more but it is perhaps 100 times smaller within the horizontal part of the cave (because of the large cross-sectional areas ratio) so divers will not necessarily feel the resonance as it takes hold. When the water level in the right vertical tube is elevated an arbitrary infinitesimal distance above its neutral position there are two restoring forces. The first is the familiar weight of the displaced water. The second is the new not-so-familiar force due to the incremental increased pressure in the air-filled section. Fortunately, this new force (i.e., the incremental increased pressure times the cross sectional area) turns out to be linear. In the absence of friction (i.e., the so-called inviscid or frictionless limit), the sum of these two forces causes the fluid to accelerate (in both the horizontal and vertical tubes) in response to the initial perturbation (e.g., increase) of the water level in the right vertical tube. Interestingly, the inclusion of the new enclosed (gas-pressurized) sections of the tube on top does not change the mathematical nature of this solution. All they do is make the restoring force larger. A highly idealized circumstance is obtained in the free state case when the tubes are not sealed. Here, the new problem simply reduces to the familiar oscillations of a U-tube.

The Frictionless Solution: In this no-viscosity limit (i.e., the water is viewed as an idealized fluid which is not subject to friction), the restoring force is the only force available for accelerating the fluid. By contrast, in the high viscosity limit (i.e., a lot of friction), frictional forces along the boundaries oppose it and can be so large that they balance it altogether so that the fluid does not accelerate. As in other resonance cases, the resonance frequency is the frequency of the natural oscillations, i.e., the frequency of the free state. 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.

We shall now consider two examples (Fig. 4) associated with cave dimensions typical for caves in Florida. Again, it is assumed here that friction is not important. The first example deals with the case where the ceiling of the cavern/cave is just below the water elevation in the spring run and the combined horizontal length of the cavern/cave and the vertical tubes is 30 feet. For these values, the oscillations period is calculated to be about 4 seconds, which is of the same order as the typical time elapsing between two consecutive breaths of a typical diver. In reality, the distance between the pockets corresponding to the same frequency will be shorter because the speed of the disturbance propagation will be slowed down by friction. As a second example, suppose that the cavern/cave ceiling is 30 feet deep, the height of the gas-filled chambers, (which, as mentioned, are not necessarily fully, or even partially, visible) is 15 feet, and the combined length is 120 feet. Under such conditions, the oscillation period is about 6 seconds, which is also comparable to the time elapsing between two consecutive breaths. We see, therefore, that the forcing period corresponding to resonance (i.e., the pressure in a typical cave pocket becomes infinitely large) is comparable to the natural breathing period of divers in the cave. It is hard to tell today where, relative to these two examples, the Indian Spring was in 1991 because the pre-collapse ceilings then was not the same as the ceiling today. However, it makes sense to assume that it was somewhere between those two examples.

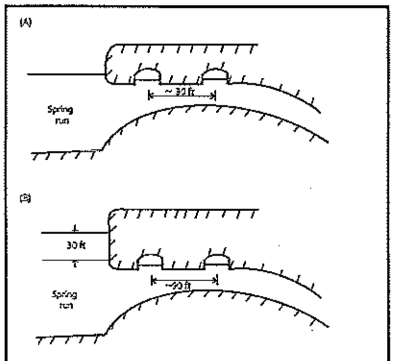

Fig. 4

Summary and discussion: We presented a hypothesis regarding a new physical process in water-filled caves regularly explored by OC cave divers who release compressed gas into the caves. The essence of the new mechanism is resonance induced by the divers' breathing apparatus, which expels compressed gas with each breath. When the frequency of these breaths matches the frequency of natural oscillations in the cave gas pockets, the system is just like a swing pushed higher and higher when the pushing occurs each time that the swing is in its highest position. While the theory is clean and straightforward, its application to real caves is not so simple due to the need to examine the behavior of the gas pockets that might be partially embedded in the porous medium as well as friction that will slow down the oscillations. Nevertheless, the results are informative indicating the possibility of resonance leading to very high pressures in the gas pockets generated along the cave ceiling.

We expect that there will be some lateral bubbles motion but most of this lateral motion will be due to curvature of the ceiling rather than due to the flow in the cave. Regardless, when we speak about the pockets, we speak about the final position of the bubbles and it does not really matter how the bubbles get there. The only aspect that the resonance requires is that the resonance-inducing diver will be positioned in such a way that her/his bubbles accumulate in one of the pockets.

Second, a comment needs to be made on the length of time required to excite the system to a state close to resonance. (This can be calculated by dividing the total energy of the resonant oscillation by the rate of input of energy and is estimated to be several minutes.) This time should be at least of the same order as the time that a diver is present near the chambers. In the case in question, postings in the blogs stated that there were OC divers "hanging out" in the cavern area during the entire dive, particularly one diver hanging out in one spot, perhaps trying to get into a particular sub-tunnel. Given that the periodicity is only several seconds, the time involved was much larger, as required by the resonance. Note that, because divers use a broad spectrum of breathing rates, a single diver located near a tube resonating at his/her breathing rate is more likely to produce resonance than a group of divers. Namely, a group of divers will inevitably have divers with a breathing rate that does not match the natural oscillation. This will throw the system out of resonance just as a swing is thrown out of resonance when it is pushed at times other than those corresponding to its maximum displacement. Note that the two divers in question (Gavin and Parker) were much too far away (from the collapsed region) for contributing themselves to the collapse with their own released gas, and that no divers in the cavern were on rebreathers.

In this context, it is useful to examine the gas chambers size needed for our mechanism to work. Going back to our first example at the end of Section 3 (Fig. 7), suppose that the diver has a SAC rate of one half cubic feet per minute and that he/she is 30 feet deep. Upon rising to the cave ceiling, which, in this particular example, is just below the surface, the bubbles occupy double the volume that she/he originally releases. Suppose now that the diver stays around for 10 minutes during which she/he releases 10 cubic feet. This implies an increase of 20 cubic feet of gas injected into the pockets. Clearly, this is an enormous increase for many pockets, whose initial pre-resonance size are often no more than about a single cubic foot.

A third comment should be made regarding the integrity of the air chambers. Since the cave boundaries are porous, air does not remain within the cave forever but gradually escapes upward through the porous medium. Evidently, this escape is often very slow as one sees these air pockets in almost every cave dive so this should not be an issue for the case in question. Finally, we will probably never know for certain what happened on that tragic day. Our findings do not by any means rule out the possibility of important independent instabilities in the bedrock constituting the ceiling of the cave. Such an instability (unrelated to the resonance) could have certainly been the cause of the collapse. The sole objective of the present analysis is to draw attention to the fact that resonance is a strong possibility. Namely, the results that we present here are informative indicating the possibility of resonance leading to very high pressures in the air pockets generated along the cave ceiling. The long-term practical implications of the present study is that it may be necessary to classify caves according to the risks of resonance, regulate diving there more aggressively and perhaps even allow only rebreather diving in some of them.

Acknowledgements
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