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In this issue

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Editor's Note

Rock mechanics, although not formally recognized as a scientific/engineering profession, has been practiced since mankind lived in caves, the stability of which had to be assessed before 'moving in'. The ancient Egyptians, Persians, Greeks and Romans learned how to take advantage of weakness planes in outcrops. That helped them carve large blocks of rock using primitive tools, and use the blocks to build colossal palaces. However, it was not until the 1950s that the field of rock mechanics was recognized in the United States as a discipline, and taught at some universities, where it was incorporated as part of the curricula of mining, civil, and petroleum engineering.

Several years ago the ARMA Publications Committee launched a new initiative, to ask some of the pioneers in the field of Rock Mechanics in this country to tell their career stories. By general consensus, the first to be asked was Dr. Charles Fairhurst. His life before and after he developed the rock mechanics program at the University of Minnesota was published in the Newsletter in 2013-14.

The present issue of the newsletter is dedicated to the life story of another rock mechanics pioneer, Dr. Richard Goodman, emeritus professor at University of California-Berkeley. I hope you find his informal essay interesting, exciting, and encouraging — especially to our young rock mechanics practitioners.

—Bezalel Haimson, Chair
ARMA Publications Committee

Tales and Remembrances: Reflections of an ARMA Fellow

Submitted by Richard E. Goodman, Professor Emeritus, Department of Civil and Environmental Engineering, University of California-Berkeley

As the first boy born on Christmas morning of 1935 at the Mary Immaculate Hospital in Jamaica, N.Y., the nurses sent me home with a bundle of gifts. Looking back now, at age 81, I realize I have enjoyed a very lucky life and career, even if time quickly showed I was no Jesus. If I have been successful along the way, it is mainly for having a flow of ideas (some of which have worked out), unbridled energy, rich education, and a great number of brilliant students.

Having shown significant promise at the piano (and perhaps excessive energy in public school), at the age of 10 my parents enrolled me in a private pianist training academy in Manhattan. The stern program — directed by tough European musicians — allowed only two hours per day for normal elementary school academics, which were taught by a gifted teacher to a class of four or five students ranging in age from six to thirteen years. (Interestingly, I found that I was keeping up with (or even exceeding) the learning rate of kids in my neighborhood who attended New York Public Schools.) Then, at the age of 13, I entered the public high school. But, after the sophomore year, at the age of 15, I won a scholarship competition and became a "Ford Foundation Scholar" at the University of Wisconsin, in Madison.

I had five roommates — all "Fordies"— sharing an attic of an old mansion in Madison. These five chose to take the science elective courses in chemistry and physics. To be different, I elected "Introductory Geology", taught by Prof. Sheldon Judson. This course so fascinated and captivated me that I determined to pursue a geology major. On hearing this, my mother jumped on a plane and showed up on campus to ask the professor what kind of career employment I might expect. Professor Judson was cordial, but honest, and frank; he informed her that Jews were unlikely to find employment in geology because most of the jobs were in the oil business, and oil companies operating in Arab lands were prevented from employing Jewish geologists.

After two years at Madison, the serious illness of my father led me to transfer my college education closer to home, at Cornell University. The Cornell geology program included a summertime field geologic mapping course in the mountains of Pennsylvania. Geologic field mapping requires maintaining simultaneously one's precise point on the topographic map (a challenging art before the development of GPS), and one's precise position in the stratigraphic succession of geologic formations. The latter could often be discovered by either 1) identifying the relative ages of fossil specimens in the rocks, or 2) (in sedimentary mountain ranges) by the relative stratigraphic positions of conspicuous red or green "marker beds." Though finding great enjoyment in the game of mapping the strata, I had to confess that geologic mapping was not going to be my forté as I am seriously red-green color blind.

Upon graduation from Cornell in 1955, I began a summer job as an assistant to the Corps of Engineers' geologist, Raymond Whitla, regarding design and construction of the St. Lawrence Seaway Project. The chief problem the Corps faced was the safe excavation and support of marine clays with absurdly low friction angles. But I was more directly involved with the geological-engineering issues posed by the engineers concerning the safety of heavy concrete walls bearing on karstic dolomitic-limestone foundations. I wanted to learn more about engineering. Consequently, I elected to return to Cornell University as a graduate student, where I studied soil mechanics under Professor B.K. Hough, and air photo interpretation from Professor Donald Belcher. Dr. Belcher had earned considerable recognition from a series of consulting projects embracing air photo interpretation methods in which he estimated the foundation conditions of soil and rock terrains. His projects included the siting of a new capital city for Brazil (to be called *Brasilia)* in a remote, previously undeveloped wild landscape.

Dr. Belcher's consulting company was now planning an adventurous, virgin mineral-prospecting expedition in the Canadian Arctic's "Baffin Island." I was pleased to be added as the third and final member of this glorious, wild, adventure — the others being geologist King Davis, and a veteran prospector. We travelled to the far north in an old DC-3 equipped to take off from a hard runway and land on deep snow. On arrival at Cape Dorset, we travelled by dog sled to a base camp near a target area that had been pre-selected by air-photo interpretation. After the thaw, we were hiking and climbing on boulders and rock slopes to reach pre-selected target outcrops. We were learning to perform rock blasting of mineral showings, surveying and marking of claims, and mapping of mineral prospects. This experience opened my eyes and increased my curiosity about the mechanical properties of jointed and highly structured rock formations.

It also taught me that it is the wiser path to be pre-educated than to just learn on the job. Our lead prospector angrily abandoned the expedition (after a sad disagreement over the baking of a goose) just as we were initiating exploratory drilling and blasting in a mineral-rich series of outcropping rocks. Neither of us had blasting experience but we followed the directions in the Blaster's Manual — about stemming the hole, placing the caps in the dynamite sticks, etc. When the first shot was detonated, to our horror, we observed rock blocks flying over our heads, descending well behind our observation point. The shot also damaged our drilling machine. This experience was a "good lesson" in what not to do in rock drilling and blasting (but not as good as a passing grade in a blasting course).

On completion of my Masters degree from Cornell, and newly married to Lillian (Sue) Gates, I began employment with the engineering and geology staff of Hunting Technical Services in Toronto. I was subsequently assigned to apply air-photo interpretation methods to assist in a number of projects, including route selection and design of rock-cuts on new freeway routes in Pennsylvania, Indiana and Mississippi; site selection for a railway bridge across the Wabash River; and planning steeper rock cuts to allow straightening of the Southern railway's freight route through the thrust-faulted metamorphic rocks of the southern Appalachians.

It was disappointing to me that the engineers on these projects seemed satisfied to represent rock mass strength merely by reporting the state of weathering and the unconfined compressive strength of drill-cores. I felt that rock mass behavior must be too complex to be considered so naively. Anxious to learn more, in 1959 I entered the new graduate program in geological engineering at the University of California, Berkeley, in the Department of Mineral Technology. A new program in geological engineering at Berkeley had been initiated by Parker Trask — a petroleum and engineering geologist who had been engaged to investigate the properties of sedimentary strata beneath the San Francisco Bay, in anticipation of new bridge crossings. On Professor Trask's untimely death in my second year at Berkeley, the Department selected me to continue lecturing his course for the remainder of that term.

In the following term, the department recruited three leaders from industry to temporarily enrich the geological engineering faculty. They were: Roger Rhoades, the former chief geologist of the U.S. Bureau of Reclamation; Tommy Thompson, former chief geologist of the Corps of Engineers and the Panama Canal Authority; and Tom Lang, the former chief of the Australian Snowy Mountain Authority and then Vice President of Bechtel International. Rhoades and Thompson conducted a rich weekly seminar on engineering geology and rock mechanics, and Tom Lang presented his developing draft book on applied rock mechanics and rock bolting that he had initiated in Australia. I was their teaching assistant. Subsequently Daniel Moye, chief geologist of the Snowy Mountain Hydroelectric Authority, joined our faculty for one year to take charge of the geological engineering program. It was my lasting good fortune to serve under and learn from these outstanding geologists and engineers.

On their departure, and the completion of my doctoral thesis — a study of earthquake-induced slope failure in cohesionless soils (under Prof. Harry Bolton Seed) — I continued at Berkeley as an Assistant Professor in the Department of Mineral Technology. Later, the geological engineering program was transferred into the Geotechnical Group in the Department of Civil Engineering. Our Geotech faculty (over the years including Paul Witherspoon, Tor Brekke, Nick Sitar and Steve Glaser) was blessed with outstanding graduate students. With field studies in the geologic richness of the adjacent Berkeley Hills, and occasional excursions to western national parks, dams and mines, the geological engineering sub-program was popular. I was fortunate to direct the research of some forty gifted and diligent doctoral students who contributed significantly to the profession of rock mechanics, as well as to my own education and ambitions.

I started out directing student research with great interest in their choice of the dissertation subject. One of my first doctoral students, John Cadman, was interested to learn the origin of "pop-ups" of granitic rock slabs in the Sierra Nevada and other granitic mountain ranges. Cadman examined how uplift and erosion could cause the granite in the ground to become stressed to the breaking point. His studies assumed that the liquid rock at depth was initially stressed equally in all directions. Vertical erosion at the surface would reduce all the vertical overburden stress, but only a fraction of the horizontal stress; specifically, the vertical erosion of *h* feet of granite, with unit weight γ and Poisson's ratio μ would remove vertical stress in the amount of γh, while the horizontal stress would be reduced by the lesser amount $\gamma h\left(\frac{\mu}{1-\mu}\right)$. Thus an initial condition of stresses in all directions at birth would become one, *upon erosion,* that is characterized by larger compressive stress in all horizontal directions. This could explain why granitic bodies conspicuously exhibit sheet joints parallel to the ground surface.

John and I hiked together across the Sierra Nevada granites of Yosemite Park, examining sheet joints, as well as the little elliptical basins left by supposed "pop-ups" in the granitic surface. There are, of course, significant unanswered questions with this simplistic theory — notably including the influence of temperature changes as weathering brings the surface downward. But John Cadman's ideas returned to me with vigor a few years ago on inspecting the failure of Twain Harte Dam in the Sierra Nevada granite. The granite surface under the dam had *suddenly popped up* in various locations all through the cool night that followed a hot day. The "pop-ups" were associated with audible cracking that formed new sheet joints *parallel to the bedrock surface*, and many new elliptical basins in the rock surface.

The soil engineering Master's Degree program of the Geotech group consistently brought a number of clever French graduate students. I was lucky enough to entice two of the very best (Alain de Rouvray and Jacques Dubois) to stay on for the doctorate. At this time, Finite Element Analysis was *the new tool* (and toy) of many engineers. With the help of Professor Robert Taylor, I had developed and applied a rock-joint element sub-routine for finite element analysis (which the Chinese love to call "The Goodman Element"). We could now attempt to represent bedding, faults and shear zones in numerical models of rock foundations and abutments. These were times of revolution in geotechnical engineering, particularly in soil mechanics. But it quickly became evident that civil engineering rock problems were essentially discontinuous, and therefore not readily solvable with simple finite-elements. (I referred to this in my 2005 ARMA Legacy Lecture — noting that statics and dynamics with force systems, DDA or Particle Flow methods might be preferable for stability analyses of discontinuous rock masses).

I greatly value the dissertations achieved by my doctoral students, and recall the good times we spent together in the office, the lab, and the field as their research and writing developed. The opportunities to advance the state of geological engineering through graduate research took a leap forward for me on arrival of an applied mathematician from China, Gen-hua Shi. As a post-doctoral researcher of topology in China, Shi had been forcibly redirected by the "Cultural Revolution" to work as a construction laborer in the excavation of the surge-chamber for a large power-dam in Manchuria. From the work site, he managed to send messages to friends to request books on geology and dam construction. To his (and my own) good luck, Shi eventually received a copy of my book "Methods of Geological Engineering", which quickly showed that his immediate danger was the potential fall of rock-blocks from the high rock walls and roof of the developing excavation. Accordingly, he developed a method to identify incipiently dangerous rock blocks and where *one must not dare to stand* in his work underground. Together, at Berkeley, we expanded his theory and wrote the book "Block Theory and its Application to Rock Engineering" (1985).

Doctoral Students of Richard Goodman

Toshi Adachi
Bernard Amadei
Glenn Boyce
William Boyle
Anders Bro
Tom Brunsing
John Cadman
Tarcisio Celestino
Lap Yan Chan
Rodolpho de la Cruz
John Curran
Alain de Rouvray
Jacques Dubois,
Derek Elsworth
Hans Ewoldsen
Dom Galic
Yossi Hatzor
John Hollfelder
Francois Heuze
Mark Hittinger
Antonio Karzulovic
T. Chi Ke
Scott Kieffer
Joel Kuszmaul
Eric Lindquist
Ashraf Mahtab
Matthew Mauldon
Edwin Medley
Richard Nolting
Yuzo Ohnishi
Pierre-Jean Perie
Joe Ratigan
J. David Rogers
Rodolfo Sancio
Gen-hua Shi
Bhaskar Thapa
Richard Thorpe
John Tinucci
Tran K. Van
Manchu Ronald Yeung
Duncan Wyllie
Jesse Yow

Subsequently, Shi entered the graduate program and produced a doctoral dissertation that generated "Discontinuous Deformation Analysis" (DDA) — a new computational method for analysis of the safety of slopes, tunnels, and foundations that are partly or completely in rock masses. The application of DDA has been elaborated in the newly released book "*Discontinuous Deformation Analysis in Rock Mechanics Practice*" by Yossef H. Hatzor, Guowei Ma, and Genhua Shi (2017).

The failure of Malpasset Arch-Dam in France (1959) shocked the entire dam industry (Figure 1). Its self-destruction was found to have been initiated by the movement of a large wedge-shaped rock-block underlying the lower left abutment of the arch. The foundation was largely underlain by schist, which was cut by a very dense network of joints and shears that carved the foundation into isolated rock-blocks. *One of these blocks underlay the foundation of a critical section at the base of the left abutment of the dam.* Extensive investigations by Pierre Londe, of the firm, Coyne and Bellier, that had designed and constructed the dam showed convincingly that it was the gross movement of this critical rock block that had triggered the *sudden, total structural collapse of the entire left portion of the dam.* The immediate sudden emptying of the reservoir cost large loss of life in downstream Frejus, and destroyed the region's harvestable vineyards and crops.

Figure 1. The remains of Malpasset Dam (France).

If the movement of one large rock block could conceivably destroy or seriously damage an entire dam project, I reckoned that the dam community needed to develop a program of exploration for potentially dangerous rock blocks in the foundations of existing dams, as well as for potential future dam sites. Our block theory seemed perfectly appropriate for such a study and, fortunately, the Corps of Engineers, the Bureau of Reclamation, Pacific Gas and Electric Company (PG&E) and other dam owners began to request my help. With my Berkeley colleague Professor Tor Brekke, we responded by forming *The Geological Engineering Foundation* to conduct annual short courses for industry. Among other topics, within each course I introduced the methodology of rock block analysis. (These courses have continued on an irregular schedule, with Professor Nick Sitar as co-instructor.)

The identification of potentially sliding blocks and the methods for analysis of their stability were described in the paper "Behavior of Rock in Slopes" (R.E. Goodman and D.S. Kieffer), in the *Journal of Geotechnical and Geo-environmental Engineering*, (Vol. 126, no 8, August, 2000) and in my book *Introduction to Rock Mechanics, Second Edition*. We recognized principles that favor different modes of rock failure as follows:

1. Finite rock blocks are formed by the intersections of existing discontinuities and the excavation surfaces.
2. Adversely oriented blocks move first, leaving behind a new space into which adjacent blocks might be able to move; the first blocks to move are termed "*key blocks.*"
3. Sliding along an adversely oriented face or block edge occurs if the direction of incipient motion "daylights" into the excavation.
4. When sliding opportunities are blocked because the sliding layers do not daylight, *toppling (Figure 2), buckling, block slumping,* or *torsional failures may yet occur.*
5. Incomplete blocks that would tend to slide, but which are not completely delimited by the joint system, might fail when new rock fracturing creates isolated sub-blocks.

The kinematics of block failure can be conveniently described using stereographic projections. In the

Figure 2. *A toppling failure in a rock slope, seen on an ARMA excursion in Utah (led by R. Goodman)*

Figure 3. Emergency Spillway Control Structure, Folsom Reservoir (California)

field, potentially "removable" blocks are recognized by mapping the traces of joints, beds, and faults across the terrain of interest. The relevant block failure-modes for various directions of outcropping rock walls are exhibited in the shapes of angular voids mappable in the steep rock cliffs. Photogrammetric methodology was applied to gather relevant information describing the rock walls that were remote or unclimbable.

The most probable failure modes include not only sliding on one face, but also sliding on two faces in the direction of a block edge (the line of intersection of two contiguous faces). A block can also fail by rotating on a face. If a dam or another structure overlies a removable block, the calculation of the factor of safety for all modes of failure must take into account the additional forces, and water pressures that may be acting on the block *in situ*.

The friction angles for block surfaces were measured by conducting simple tests of sliding under gravity load to identify the angle of the normal to the sliding surface at the point of incipient motion. This is not atomic physics, but arranging and conducting tests in the field sometimes demanded creative operational set-ups in order to evaluate identifiable hazards. For remote or inconveniently positioned blocks, terrestrial photogrammetry can be applied to establish *in-situ* factors of safety.

A large number of potentially sliding or overturning blocks on joint and bedding plane outcrops were measured so as to provide a range of applicable friction angles. In this way, the study of rock outcrops representative of the dam abutments and foundations enabled evaluation and correction of geologically-related dam deficiencies. As a result, such analyses affected the safety and performance of a large number of existing dams and dam projects of the U.S. Bureau of Reclamation, the PG&E, the Corps of Engineers, and other dam owners.

Over the years I consulted on questions related to specific issues or general geological-engineering evaluations for many existing dams and potential dam projects. The list includes Boulder, Caribou 1 and 2, Cheesman, Coolidge, Folsom, Fontenelle, Horse Mesa, Hungry Horse, Libby, Mammoth Pool, Mormon Flat, Morrow Point, Pardee, Pathfinder, Pit 3, Ricobayo, Scott, Seminoe, Spaulding, Teton, Upper Stillwater, Vajont (Italy), and Laxiwa (China). There follows a short description of several of these investigations.

One example is the installation of rock bolts and straps in the left abutment for the *Folsom Reservoir (California)*. The blocks are formed by the intersections of five joint sets in the granite rock. (see Figure 3.)

The Bureau of Reclamation's *Morrow Point Arch Dam*, in western Colorado, was constructed in a highly sheared, schistose geological terrain that is remarkably similar to that of the ill-fated Malpasset Dam. During construction, a major rock slide damaged the excavation for the partially completed underground

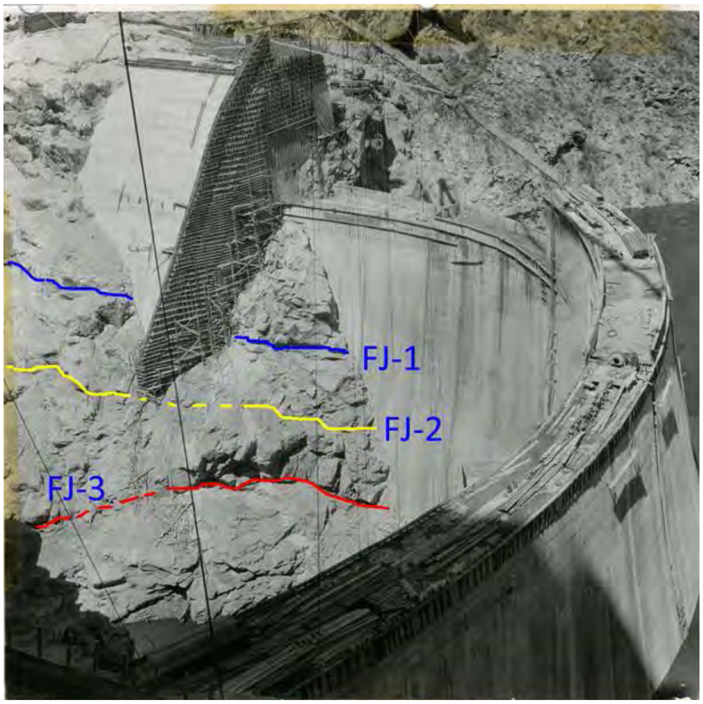

Figure 4. Horse Mesa Dam during construction, showing three previous joints (labelled FJ-1, FJ-2, and FJ-3).

power house. Reclamation was able to show, however, that the slick clayey-shear-zone that had liberated the powerhouse-slide definitely did not intersect the dam's foot-print. We identified a large number of removable rock wedge blocks in the outcrops around the site. Reclamation performed a sophisticated analysis of one potentially dangerous removable block beneath the right dam abutment and demonstrated its safety.

Horse Mesa Dam, a thin arch dam in the Salt River Canyon, north of Phoenix, suffers a three-dimensional set of leakage paths through the right abutment of this structurally complex site. Three stacked lava flows, with inter-flow sediments, had given an irregular, horizontally layered appearance to the steep right abutment rock wall (Figure 4). A significant rate of reservoir leakage passes beneath the dam within these flow boundaries, and cross-cutting faults provide some hydraulic connections between the flows. Leakage through the right abutment, increasing through time, had significantly reduced the power output of the project. To mitigate this loss, a horizontal drainage adit was excavated beneath the foot-print of the dam, and a forest of long drain holes were drilled from the adit walls and roof, and outward beneath the reservoir. Stability analyses — complicated by the complex shape of any assumed failure surface — have yielded a minimally acceptable condition and the dam remains under the engineering spotlight.

The high *Laxiwa Dam*, on the Yellow River of China, was visited because its construction had somehow liberated an enormous *toppling failure* of the phyllites comprising the steep, contiguous, upstream rock slope (Figure 5). The Chinese engineers quickly initiated a comprehensive and imaginative investigation, including extensive tunneling *beneath the slide*, in order to investigate the underlying geology, and to evaluate various ideas for preventing a catastrophic acceleration. Professor Nick Sitar, Dr. Gen-hua Shi, and I climbed up multiple ladders and stairways on the surface to inspect a network of newly excavated investigation tunnels and shafts. These exposures surprisingly exhibited much *surficial mud* at the base of the slide. The mud must have worked its way downward from the surficial soils along cracks within the toppling mass. Professor Sitar and I advised that the principal hazard was the potential acceleration of the slide-mass by the effects of a major earthquake.

Figure 5. The surface of the enormous toppling failure immediately downstream to the high Laxiwa Dam (China).

In 2006, 2010, and 2014, PG&E retained me, together with University of Illinois Professor Skip Hendron, to prepare the draft of its *Potential Failure Mode Analysis Report* to the Federal Energy Regulatory Committee (FERC) for Scott Dam — a concrete gravity structure on the Eel River, completed in 1921 in a remote mountain valley east of Ukiah, California. During the period of its original construction, when the monoliths had been extended about half the distance across the valley, a strong rain-storm had flooded the works and caused a rock-slide on the planned left-abutment ridge. The rock slide released an immense boulder standing alone in the valley, near the last completed monolith. To finish the dam construction, the left abutment site was rotated 45 degrees downstream to a different location, and the boulder, somewhat reduced, was embedded safely in the concrete of the dam.

Figure 6. Leading an excursion for ARMA, San Francisco, 2011.

Figure 7. Richard Goodman in the title role of Verdi's opera Falstaff.

In preparing our inspection report to FERC, PG&E was troubled by apparent low factors of safety calculated for foundation sections of Scott Dam resting on clayey foundation soils containing large and small pieces of rock. Extensive testing of many Scott Dam foundation samples subsequently concluded that the sample strengths varied directly with the proportion of rock pieces in the sample.

Back at the campus, I discussed this proposition with two outstanding graduate students, Eric Lindquist and Ed Medley. We noted that the soil behavior in a foundation could be a non-linear function of the proportion of rocks in the foundation soils, if the rocky seams invited load to function as struts. Lindquist and I went on a field trip to observe appropriate outcrops of rocky mélange formations. Medley pursued this question in laboratory testing of manufactured samples. Lindquist pursued the testing of samples from appropriate melange outcrops. Their dissertations initiated practical approaches that are now in wide use. Both men are now highly appreciated engineering consultants because it ***is*** true that load tends to congregate non-linearly in the stiffest and strongest places (and on the strongest minds and backs).

As a professor, I valued opportunities to develop and apply new knowledge for trying to solve engineering problems associated with rock mass behavior. One of the nicest memories in my career was the discovery of the "base-friction principle," and the subsequent world-wide construction and use of base-friction test tables for teaching and learning. I also appreciated mathematical and physical modelling to identify applicable modes of failure in rock slopes, underground workings, and surface excavations. As a consultant, I was lucky to have been invited to work on major projects of the Corps of Engineers, PG&E, the Bureau of Reclamation, and other American engineering organizations, as well as for projects of engineering companies in Europe and South America.

Two further dimensions to my career are shown in Figure 6, sharing my personal knowledge in leading an ARMA excursion, and perhaps an additional talent seen from Figure 7.

There's no deal better than one that pays you to learn something new. I have been very lucky to have learned together with so many bright and devoted students, colleagues, and friends.

ARMA
american rock mechanics association

ARMA News Briefs

Upcoming Events

Bahrain in April: ARMA and Dhahran Geoscience Society (DGS) are convening a workshop on "The Role of Geomechanics in Stimulations," to be held on 3 – 5 April 2018 in Manama, Bahrain. The workshop will focus on not only the breadth and depth of fracturing technologies but also their values through field applications. For further information and to register, use this link: *http://armarocks.org/2018-arma-dgs-workshop/*

Seattle in June: ARMA invites you to its 52nd US Rock Mechanics/Geomechanics Symposium to be held in Seattle, Washington, USA on 17-20 June 2018. This year, the symposium will be followed by the 2nd International Discrete Fracture Network Engineering (DFNE) Conference on 20-22 June 2018. Both events will be held at the Westin Seattle hotel. The links to the symposium and conference are as follows: **Symposium website:** *www.armasymposium.org* and **DFNE website:** *www.dfne2018.com.*

52nd US Rock Mechanics /Geomechanics Symposium	**Westin Seattle – June 17-20, 2018**
2nd International Discrete Fracture Network Engineering Conference	Westin Seattle – June 20-22, 2018