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Subsurface Engineering — Opportunities and Challenges

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ABSTRACT

After decades of neglect of the physical infrastructure, the U.S. appears ready to start addressing this major national concern. The importance of this task is reinforced by the urgent issues of climate change. Observing the immediate consequences of extreme weather, it is seen that many of them are "surficial," i.e., associated with the Earth's immediate surface. This characteristic is also true of some of the effects of earthquakes. This paper provides examples of how engineered structures in the shallow (approximately 100 m or less) rocky subsurface can significantly reduce the adverse effects compared to those experienced at the surface.

A challenge of engineering in rock in situ is that it has been subject to tectonic and gravitational forces for many millions and even billions of years. It contains large-scale fractures and related discontinuities such that, unlike tests on fabricated materials or soils, the constitutive behavior of a rock mass cannot be determined in a classical laboratory. The paper discusses in detail the possibilities offered by the numerical Discrete Element Method (DEM) to develop a realistic mechanistic model of a rock mass, which will allow numerical experiments to assess practical design options.

Infrastructure, Rock Engineering Discontinuities, Numerical Modeling

INTRODUCTION

> *We set out to explore the Moon and instead discovered the Earth. The sense of isolation — and closeness — of our humanity. I wish more people would think on it.* — Astronaut Frank Borman

> *We felt we were going there to show you the Moon. No! We went to the Moon; we learned a lot about the Moon; but most of all we learned about a new way to look at the Earth.* — John Aaron, Mission Control, Apollo 8

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Having that unifying experience, I think, is a very profound and moving moment for people on Earth. We are all on the one spaceship together; we'd better start taking care of it. — Frances (Poppy) Northcutt, Mathematician, Apollo 8

These comments are from key members of Apollo, when asked recently to reflect on their participation in the Program (NOVA, 2018).

In presenting this paper on Subsurface Engineering, the authors hope that readers will be persuaded that "planet Earth" is more than the visible spherical surface. Without the essential and varied contributions from the subsurface — from the roots nourished by groundwater, underground transportation networks, isolation from the biosphere of toxic and other waste product, extraction of essential minerals, geothermal energy., and much more — Earth's surface would be a far less hospitable environment.

In some respects, rock engineering has similarities to medical practice. Both are dealing with animate systems. Modern humans have evolved over the order of two million years, i.e., some 2000 times *less* than the evolution of Earth. Medicine is concerned with the health of the individual; Rock Engineering —or "Earth Resources Engineering" — is about the health of society (the latter term being adopted by the U.S. National Academy Engineering in 2006 to encompass Petroleum, Mining, Geological Engineering and others associated with the subsurface). In the U.S., the National Institute for Health (NIH) was founded in 1887; today, it is the *"largest biomedical agency in the world"* with a budget of $40 billion for 2018.

The U.S. Bureau of Mines, founded in 1910, was closed by Congress in 1995 (with a budget of approximately $150 million). Civil engineering R&D, through the Army Corps of Engineers and the U.S. Bureau of Reclamation, has also been reduced. This can be attributed, in part, to an increasing tendency in the U.S. to consider the engineering activities in these fields to be destructive of the environment. As stated by The Boring Company, owned by renowned engineer-entrepreneur Elon Musk, "In the United States, there is virtually no investment in tunneling Research and Development (and in many other forms of construction). Thus, the construction industry is one of the only sectors in our economy that has not improved its productivity in the last 50 years." (The Boring Company, 2018).

The general merits of subsurface construction for civil infrastructure in the U.S. were studied by the Underground Construction Research Council (UCRC), a group organized jointly by the American Society of Civil Engineers (ASCE) and American Institute of Mining Engineers (AIME). Table 1 provides an interesting example from a 1972 report of this group. Note that $58.6 billion in 1972 is equivalent to $350 billion in 2018. With costs extrapolated to the present day, this suggests that the savings by increased use of the (shallow) subsurface are potentially huge — approximately 50% of the 2019 budget recently approved for the U.S. Department of Defense ($716 billion). Note that an important aspect of such estimates is the assumption that costs are usually based on lifecycle rather than replacement estimates.

Although considered by some engineers at the time to exaggerate the benefits of subsurface construction, it is worth re-examining the potential benefits of underground construction in the light of current challenges, such as the effects of climate change, "green energy" options, infrastructure needs, urbanization — in the US and globally — and the extraordinary technological advances that have occurred over the almost five decades since the 1972 report.

***Table 1**. Annual Economic Benefits Accruing from Transferring Civil Works Functions (in USA) to Sub-Surface Space, in Billions of Dollars (after Baker et al., 1972)*

Cost Category	Shelter	Production Systems and Industrial Structures	Resources	Waste Water Control	Solid Waste	Transport-ation	Commu-nications	Energy Distrib-ution	Total
Direct Costs	2.8	3.5	1.0	1.0	2.0	2.3	0.5	1.2	14.3
Time	0	4.0	0	0	0	8.0	0	0	12.0
Land	1	0.3	0	0	0	1	0.1	0.1	2.5
Energy	3.8	3.8	0	0	0.1	0	0	0	7.7
Pollution	0	0	0	1.3	0.1	4	0	0	5.4
Safety	3	0	0	0	0	3.1	0	0.1	6.2
Reliability	0	0	0.1	0	0	0.2	0.1	0.1	1.4
Material Resources	3	2.5	0.8	0	0.8	1.0	0.5	0.5	9.1
Total	13.6	14.1	1.9	2.3	3.0	19.6	1.2	2.9	58.6

METHODOLOGY

The overall goal of this paper is to indicate the major contributions — current and potential — of the rock subsurface of Planet Earth in addressing urgent problems of rapidly rising world population, climate change, and infrastructure renovation. In some cases, current technologies can be more widely applied, and in others, sustained interdisciplinary R&D will be required. Development of an effective "laboratory" to stimulate innovation in rock engineering is described as an example of the latter.

The authors of this paper cover a range of backgrounds, with a common goal of trying to design engineered structures in rock (tunnels, dams, slopes, mines, etc.) and to improve on current design methods, which often rely heavily on empirical rules. The validity of such rules need to be evaluated, especially as applications of subsurface engineering extend beyond experience.
All designs are based on some level of Newtonian mechanics, but the constitutive behavior, i.e., the response of a rock mass to applied loads, is generally not well defined. This leads to considerable uncertainty in design. Figure 1, adapted from Starfield and Cundall (1988), illustrates the situation. Design problems are divided into four categories based on the level of understanding of the problem and the data available.

In Region 1, there is ample data but little understanding of it. Statistics, or more recently, "Big Data" methods, may be applied to advantage. Region 3 defines many branches of engineering, in which there is ample, well-defined data and a good understanding, with little size effect, i.e., laboratory values of stress/strain behavior can be applied reliably to the full-scale structure.

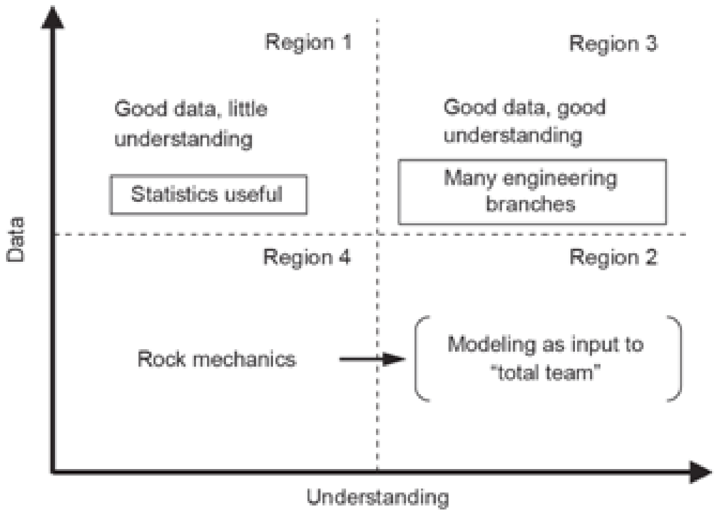

Figure 1. *Categories of engineering design (*modified from Starfield and Cundall, 1988)

Design of structures in rock must consider large-scale discontinuities and the anisotropy introduced by them. These features, not present in soils, were the motivation behind the formation in 1962 of what is today The International Society for Rock Mechanics and Rock Engineering (ISRM), distinguishing it from the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE, which was founded in 1939 as the International Society for Soil Mechanics and Foundation Engineering, or ISSMFE). The constitutive behavior of soils as determined in small-scale laboratory tests can be applied with some confidence to large-scale design situations. This is not the case for rock.

Rock *in situ* has been subject to changing tectonic and gravitational forces plus geothermal evolution, etc. throughout the complex 4.5 billion years of Earth's existence. The term "rock" embraces a wide variety of solid materials. Rock formations of widely different constitutive behavior are often found adjacent to each other. Rock permeability, also variable, stores groundwater and subjects the rock to hydrostatic pressure. Earthquakes and some engineering activities, e.g., blasting, can impose force changes on the rock mass over small fractions of a second. Given this complexity, it is not surprising that empiricism has been a strong component of engineering design in rock and remains so to the present. Despite such complexity, there are some situations where the advantage of even a shallow sub-surface location is obvious. Some examples are discussed in the next section.

OPPORTUNITIES – EXAMPLES OF SUBSURFACE APPLICATIONS.

Surficial Effects

Anyone observing the enormous damage resulting from extreme weather events occurring both in the U.S. and internationally in recent years will recognize that many of these are essentially surficial, i.e., restricted to the surface. Downing of domestic power lines and loss of power to communities, for example, can be avoided by burying these services at a shallow depth underground. Indeed, this is the practice, both on practical and aesthetic grounds, in a number of communities and countries. Advances in "trenchless technology," an application of directional drilling developed by the petroleum industry, has transformed sub-surface technology in "built-up" regions. More comprehensive use of the subsurface is envisaged in "three-dimensional cities" being contemplated to help address the increasing trend towards urbanization in both developed and developing countries.

Surface temperature variations are rapidly attenuated with depth. Domestic water lines to and from homes are usually buried at depths of a few meters, i.e., below the frost line, to ensure that the systems do not freeze in the winter. Communication, gas, and electrical power lines are often placed underground in communities to avoid damage and interruption of services due to severe storms, as well as for aesthetics. Addition of a basement to homes provides significant protection in regions subject to tornadoes, hurricanes, and earthquakes. The use of underground shelters to protect communities from potential hostile attack is well known. The Cold War era (1945-1991) stimulated some interesting protective measures in Scandinavia — neutral countries on the potential flight path of ICBMs — should hostilities erupt between the two major powers of the time. Blessed with an abundance of high-quality granites and crystalline rock, these countries took the lead in developing underground facilities and integrating them as part of the daily life of communities; e.g., museums, concert halls, sports facilities, etc. (see Winquist and Mellgren, 1988). Bergman (1978) Bergman (1980)

Earthquake Protection

Shallow (0-50 m) underground locations in rock are generally superior to surface locations with respect to earthquake resistance. The energy content of a stress wave traveling in the interior of an elastic material is divided equally between strain energy and kinetic energy. A "free surface" cannot support strain; hence, the strain energy is converted to kinetic energy, i.e., the kinetic energy of the wave at the surface is doubled. Typically, this near-surface effect occurs within the upper 50 m or so (Varun et al., 2014). Thus, a free-standing structure on the surface will be subject to a higher level of shaking than the same structure underground due to a seismic event. Also, the underground structure can be connected to the rock mass to further reduce differential movement of the underground structure (to be discussed further in regard to Figure 3.)

In large cities, underground mass transit systems are recognized increasingly as a necessity for effective transportation. Underground systems can have a significant additional advantage in cities in earthquake-prone regions.

In 1961, Duke and Leeds (1961), suggested that

> *Severe tunnel damage appears to be inevitable when a tunnel is crossed by a fault or fault fissures which slip during the earthquake. Tunnels outside the epicentral region and well-constructed tunnels in this region can be expected to suffer little or no damage in strong earthquakes. Within the usual range of destructive earthquake periods, intensity of shaking below ground is less severe than on the surface.*

More recently, as indicated by Kieffer et al. (2000), tunnel design has advanced to allow such fault slip regions to be negotiated successfully. A lined tunnel for water transfer was designed to accommodate up to 2.3m of slip on a fault[2] crossing the Claremont (California) water tunnel, without disruption of the water supply, As yet, no such earthquake has occurred.

Negotiating such faults for subway systems presents a greater challenge. However, subways are being recognized as an important component of the emergency response system for earthquakes. The Los Angeles Metro subway system first opened in 1993. In the earthquakes since then, including the 1994 Northridge quake, "the subway tunnels have not suffered any damage and train service was quick to return.

Generally speaking, subways in many other areas have survived earthquakes with minimal or no damage — and often far less damage than is suffered by buildings and roads" (Hymon, 2012). Reportedly, subway

[2] Associated with the Hayward Fault, near San Francisco

service was interrupted because the station supplying power to the subway was on the surface and lost power during the earthquake. The merits of subsurface power stations will be discussed later in this article.

The January 17 2014 issue of 'The Atlantic' has graphic illustrations of freeway collapse during the Northridge Earth quake https://www.theatlantic.com/photo/2014/01/the-northridge-earthquake-20-years-ago-today/100664/ (See esp. Figures 5,6,7.)

Some thought has been given also as to how to include the subway network in the defense against rising sea levels for urban communities in low-lying areas. Subways could be used to evacuate populations rapidly to higher ground, provided the standard station access is designed with bulkheads that can be closed in an emergency along with a supplementary higher-level access level. The supplementary level could be incorporated, for example, into an upper floor of a shopping area, and used regularly so that the general public would be well aware of their existence in case of emergency, as discussed in the previous section, Surficial Effects.

Underground Power Plants

As noted earlier, subway systems are less vulnerable to earthquakes than surface transportation systems and can be used as an important component of emergency systems, provided the power required to run the system remains available during and after the earthquake. This suggests that the power generator system also should be located underground.

The following discussion was stimulated by the Fukushima nuclear accident of March 2011, and interest in alternative design of nuclear power plants, but the comments regarding underground nuclear power plants are applicable generally to other facilities. Varun et al. (2014; 2017), Damjanac et al. (2006), and Lin et al. (2007) provide technical details of analyses available to demonstrate the relative safety of surface and underground location of facilities. With respect to Figure 2, it is seen that the underground location allows the modular reactors to be attached to the bedrock, whereas they are essentially freestanding in the above-ground situation. The response of reactors in the two situations during an earthquake is essentially similar to that of a passenger standing in the aisle of a bus compared to that of a seated passenger wearing a fastened seat belt when the driver suddenly applies the brakes. Muller (2016) has recently presented details of a relatively inexpensive technique for disposing of used nuclear fuel rods using petroleum directional drilling technology. The system, which is under development, could be applicable to the disposal of used fuel rods from such small nuclear plants.

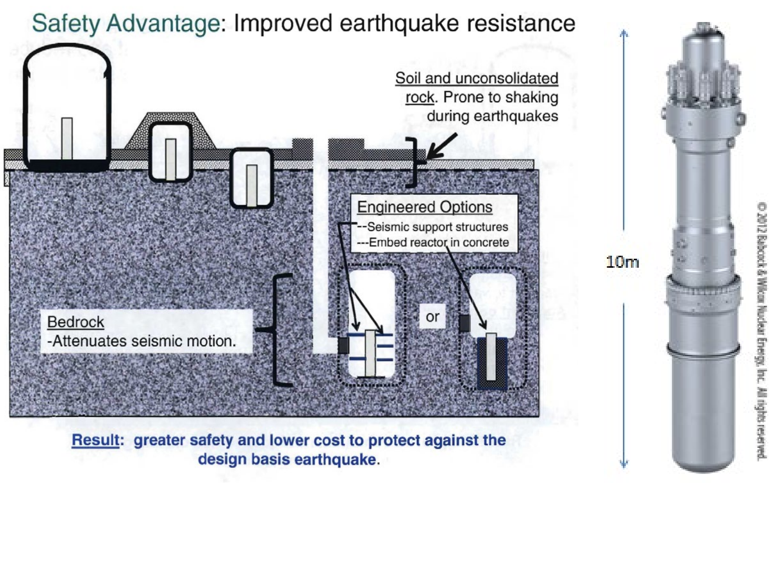

Figure 2. Relative advantages of underground vs. surface location of modular nuclear reactor power plants (Myers and Mahar, 2011). 25 m rock cover provides protection equivalent to an above-ground containment structure.

CHALLENGES TO DEVELOPMENT OF SUBSURFACE ENGINEERING

As mentioned earlier, the primary stimulus for formation of the ISRM in 1962 by Dr. Leopold Müller was the need to direct international attention to the role of large-scale fractures in rock. Unlike classical continuum mechanics and soil mechanics, it is not possible to establish the constitutive behavior of a rock mass *in situ* by classical bench-scale laboratory tests. Müller felt that design in rock was going beyond the understanding of how mechanics applied to rock *in situ* at that time. How then could a proposed design in rock be tested? Full-scale tests were not realistic.

Müller's actions stimulated considerable effort to examine how to assess the role of large-scale discontinuities, such as laboratory physical models incorporating fractures/joints, incorporation of individual discontinuities into numerical continuum models (finite element, boundary element), etc.

Although computer power was very limited compared to today, Cundall (1971) developed the numerical Discrete Element Method (DEM), in which he represented the rock mass as a series of interacting blocks defined by the system of fractures in the rock. Cundall and his colleagues at Itasca have continued the development to the present. Figure 4 illustrates the calculation procedure used in the DEM. The development of deformation of the jointed block system is followed over very small time intervals, as the forces propagate dynamically through the blocky system. A major advantage of the system is that deformation of the rock mass can be followed from initial loading until equilibrium is reached or collapse occurs. Lemos (2013) provides a more detailed explanation of the DEM. It is recognized widely as the most direct representation of discontinuities in rock –and the rock mass deformations likely to occur when the forces on the mass are changed during engineering.

A significant disadvantage of the method is that it is computationally intensive. Large problems can require days of computation in order to arrive at a solution and several analyses may be required to examine the influence of uncertainties (e.g., the stress/strain relationship for the system). Computer technology and computational speeds have developed remarkably over the nearly five decades since Cundall's 1971 paper.

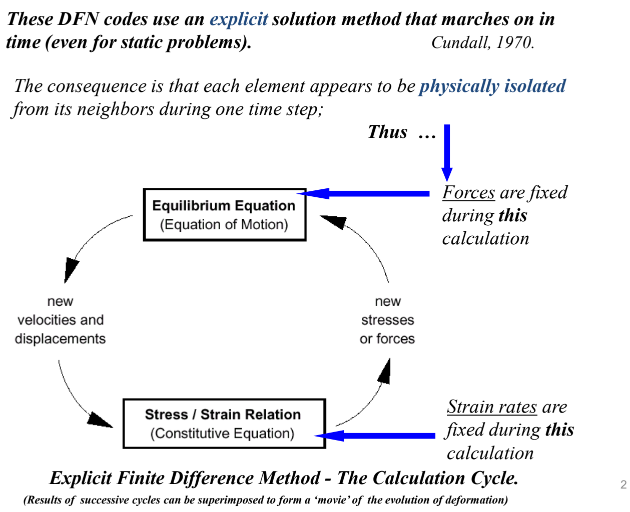

Figure 3. Calculation cycle for the discrete element method

For much of this time, computational speed has followed what became known as Moore's Law, i.e., essentially doubling the speed approximately every 18 months. For the past several years, the speed has remained fairly constant, indicating that chip technology may have reached its limits. In order to continue to take advantage of the power of the DEM, it is desirable to parallelize the codes, with emphasis on *3DEC* (several other Itasca codes are already parallelized), and to anticipate the development of other techniques (e.g., quantum computing). Fortunately, increased computation speeds are important in many technologies, so this issue is receiving urgent attention by various groups.

Figure 4 illustrates how a fractured rock mass is developed for analysis by the DEM. The strength of the yellow "intact" core is established via the strength and deformability of the intergranular contacts to match the deformability and strength measured in the laboratory. A cubic block of "intact rock" equal in dimensions to the middle cube in Figure 5 is created with the properties of the core. A discrete fracture network (DFN) based on field observations or, in the (frequent) absence of such observations, an assumed DFN, is superimposed onto the large intact block to create the fracture rock mass. Stresses are then applied to the boundaries of the fracture block to create the *in situ* rock mass. Excavations can now be developed and the response of the rock mass *in situ* observed.

In many practical situations, the DFN for a specific site is not available. Considerable effort is directed at trying to establish what fracture networks can be assumed to provide a realistic estimate of the rock mass response (e.g., around tunnels) in such situations. Garza-Cruz et al. (2014) address this topic.

The following conclusion to their paper should be noted:

….these models show that the unloading cycle does more damage than the loading cycle…As a consequence, the support will be more severely strained during unloading (relaxation) than during loading. ***This aspect of relaxation driven straining is not evident from conventional, continuum models and seen as a critical support design element. Furthermore, relaxation- related rockmass degradation and straining is not captured by any rock classification system.*** [Emphasis added.] *Hence, support systems designed on the basis of rock classification may be suitable for tunnel construction, but are likely inappropriate for situations where mining induced straining due to fracturing and related geometric bulking is to be expected.*

Thus, reliance on empirical rules may lead to dangerously erroneous design procedures.

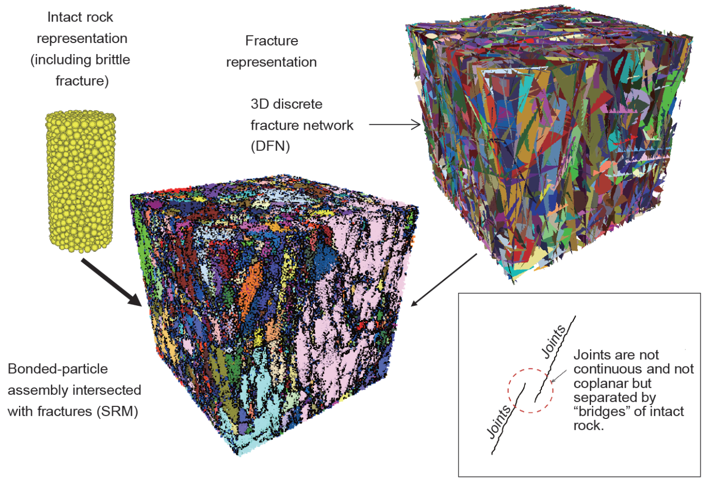

Figure 4. Synthetic Rock Mass (SRM) **(**Mas Ivars et al., 2011)

DEM Modeling of Small-scale Discontinuities in Rock and Soil

Although DEM was stimulated by interest in modeling systems of large fractures, networks of discontinuities also occur in rock (and soils) at smaller scales, e.g., fragmentation of rock on a granular scale, as in crushing and grinding for mineral extraction and in rock drilling. An interesting example of the value of DEM on the small scale s found in Cundall and Strack (1979). As noted by Lemos (2013), "The leading motivation at the time was the micro-mechanical study of soils based on a conceptual representation of granular media as assemblies of rigid circular particles." The Cundall and Strack (1979) paper has proven to be very popular. It is by far the most highly cited in the 70-year history of the journal Géotechnique. Potyondy (2015) provides additional details of recent DEM developments for small-scale applications.

CONCLUSIONS

Where is the Laboratory for Rock Engineering?

The urgent need to address the severely adverse consequences of global warming, along with the decades of inattention to maintenance of physical infrastructure in the U.S., provides an exceptional opportunity to take advantage of the resource of the rock subsurface at shallow depths as part of the solution to these major challenges. The complexity of rock *in situ* as an engineering material has led to a strong dependence on empirical rules. Rock engineering requires a sounder, mechanics-based foundation on which to move forward. The DEM numerical modeling procedure appears to provide such an opportunity. As the computational issue is overcome, as it will be within the next several years, the DEM will provide a means of testing the validity of empirical rules against sound Newtonian principles. This will transform the practice of rock engineering.

One of the consequences of the complex structure of rock *in situ* has been an unwillingness to conduct full-scale tests of proposed designs because of the cost, especially dealing with the consequences of a failed test. The possibility of conducting numerous computer simulations of design options with a "realistic" *3DEC* numerical model of the *in situ* rock may provide the missing "laboratory" component of rock engineering.

ACKNOWLEDGMENTS

Although this paper was written by the first author, it is the result of many valuable discussions and insights from the co-authors. The primary author accepts responsibility for any errors or misrepresentations of the views of his colleagues.

Movies Generated from DEM Analyses

The DEM modeling procedure allows "movies" to be developed to aid in communicating results of analyses to colleagues who are not modeling specialists. The following five cases are provided as examples.

1. PFC Rockslide, COR (Coefficient of Restitution Rock/Ground). These analyses were made to assess the effect of the coefficient of restitution (COR) between the ground and boulders on the trajectories of the boulders and energy to be absorbed by rockfall barriers in mountainous terrain.

   a. COR 0.3: https://youtu.be/NTCV9EEUF6M
   b. COR 0.6: https://youtu.be/qmIyQqiQow4

• 1

. *3DEC* Temple Earthquake See Psycharis et al; 2003, https://youtu.be/ObtnN4NABFc

3. *PFC* rock cutting (wet): https://youtu.be/5WW9T_4bNUo

4. *PFC* rock cutting (dry): https://youtu.be/cVhlUj8AhxI

1.

   a. https://youtu.be/qmIyQqiQow4

2. *3DEC* Temple Earthquake

3. *PFC* rock cutting (wet): https://youtu.be/5WW9T_4bNUo

4. *PFC* rock cutting (dry): https://youtu.be/cVhlUj8AhxI

5. *PFC* Rockslide, These analyses were made to assess the effect of the coefficient of restitution (COR) between the ground and boulders on the boulder trajectories and energy to be absorbed by rockfall barriers in mountainous terrain.

6. a. COR 0.3: https://youtu.be/NTCV9EEUF6M

7. b. COR 0.6: https://youtu.be/qmIyQqiQow4

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9. . *3DEC* Temple Earthquake See Psycharis et al; 2003, https://youtu.be/ObtnN4NABFc

10. 3. *PFC* rock cutting (wet): https://youtu.be/5WW9T_4bNUo

11. 4. *PFC* rock cutting (dry): https://youtu.be/cVhlUj8AhxI

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