On different approaches to modeling

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Commentary

A number of years ago, during a geophysics meeting in Erice, Sicily, Rick Sibson provided the following perceptive observation on a typical relation between the geological complexity of a given situation and the complexity of the corresponding mathematical modeling,

$$Geol\_cmplx \bullet Math\_cmplx \approx 1. \qquad (1)$$

This statement summarizes two end-member cases of modeling that can be illustrated with examples from mechanics of faulting. On one hand, highly complex multi physics/chemistry processes in heterogeneous crustal-scale structures are often analyzed with back-of-the-envelope approximations and simple terms such as dislocations on a planar surface in a homogeneous solid. On the other hand, far simpler engineered rock samples in laboratory experiments under controlled conditions are often analyzed with elaborate mathematical models of complex constitutive laws having many parameters and variables. As noted by the statistician George Box, "all models are wrong but some are useful". The question, keeping in mind Sibson's observation, is which models are useful in what circumstances. The answer depends on whether one is interested in engineering applications or scientific understanding.

In engineering, the primary goal is to provide a description of a certain behavior (e.g. the response of an airplane to various loads) that is sufficiently accurate for a given purpose (e.g. preventing material failure). This may be done regardless of the numbers of parameters and with no attempt to predict new phenomena. Ptolemy-type models with artificial sets of wheels are fine as long as they describe accurately enough the observed behavior. In science, the primary goal is to understand the basic underlying process leading to the observations under consideration. In scientific modeling "less can be more", as expressed by Occam's razor and Einstein's statement that "everything should be made as simple as possible but not simpler". Understanding implies an ability to ignore as much as possible from a complex

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physical situation and distill a minimalistic model that captures the essence of the process. A good scientific model is not necessarily measured by getting the best fit to data (this can always be improved by adding parameters), but by making connections to other phenomena and extending the available knowledge by predicting new observations that did not motivate the model construction.

As an author and editor I occasionally get a comment that a certain model is not "realistic" enough. This usually refers to models with simplified physics and small number of parameters, but simpler is better if the model delivers useful results. The "realism" of a model should not be assessed by the model complexity, but by what it explains and predicts normalized by model complexity. The scientific quality of a model may be quantified by the following indexes (simplified for the sake of a basic argument)

$$K_K = \text{number of explained features / number of model parameters}, \quad (2)$$

and

$$N_K = \text{number of new predicted features / number of model parameters}. \quad (3)$$

The first may be referred to as Known knowledge index and the second as New knowledge index.

The following two examples provide concrete illustrations from studies associated with the heat flow paradox (lack of observable frictional heat around the San Andreas and other large faults predicted by Byerlee's laboratory measurements of rock friction) and non volcanic tremor (small slip events radiating relatively low frequency waves that occur below the seismogenic sections of many subduction zones and several large strike-slip faults). The most popular models on these topics involve elaborate rate- and state-dependent friction laws augmented with rapid weakening at high slip velocity and/or fluid effects. These models have many (order 5-10) sensitive parameters that require careful tuning to explain a few observations and they make no new predictions. They provide detailed descriptions of frictional behavior, but have $K_k < 1$ and $N_k = 0$ so they do not deliver much scientific knowledge. In contrast (and here I may be biased by my own works), models of bimaterial ruptures for the heat flow paradox and critical depinning transition for non volcanic tremor have each a single sensitive parameter. Both explain additional observations (e.g., pulse type rupture with preferred directivity, power law frequency size statistics with specific exponent) and make new predictions (e.g., rock damage asymmetry across faults, dynamic tensional stress with potential for fault opening and rock pulverization, source time function, shape of failure areas). These models do not incorporate detailed frictional phenomenology, but have $K_k > 1$ and $N_k > 0$ so they score relatively high on scientific knowledge.

In summary, both engineering and scientific models attempt to explain observations with mathematical frameworks. Engineering modeling can provide highly important information such as at what levels of ground motion different structures are expected to collapse, but scientific modeling is essential for developing deeper understanding and expanding the boundaries of knowledge. Engineering and scientific studies are closely connected; many topics are studied by both communities and topics belonging to one domain often move to the other. New scientific understanding typically leads to new engineering research, while a lack of understanding in engineering studies (e.g. background electromagnetic radiation and ambient seismic noise) can open up new scientific frontiers. Eq. (1) encapsulates the common relation between engineering and scientific modeling approaches to mechanics of earthquakes and faults (and perhaps other geological/geophysical phenomena). Eqs. (2) and (3) may be used to evaluate the type and performance of different models. In the final analysis, the ultimate test for the usefulness of any model is its ability to match as many different old and new observations as possible.