Stop the Computer, I Want to Get Off

Keynote Address

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Mr. Chairman, Honorable Guests, Ladies and Gentlemen:

I am delighted and honored to have been invited to address you this morning. I have looked forward very much to this visit since I received an invitation more than a year and a half ago. At that time, I was planning a sabbatical leave during the Spring Quarter of 1979, and I immediately started making out a program centering around this Conference. Somewhat later, I discovered that I had not read the letter of invitation carefully enough, and had missed the point that the Conference was in 1980. This just goes to show you that the absent-minded professor is not necessarily a thing of the past.

A very important aspect of your Conference is that it brings together all of the professionals who are involved in the engineering of structures in geological materials. In other areas of the world, many times we see that there is a tendency to split the people involved in geomechanics into groups, such as the engineering geology, the soil mechanics, and the rock mechanics professionals. As you know, this is also the case for our world-wide, international societies. Consequently, each group will go on its own merry way, and the result is negative in at least two respects. First of all, we lose the opportunity to learn from each other through a meaningful exchange among colleagues from the different subject areas. Secondly, some such conferences tend to become very theoretical. I have left meetings, notably in rock mechanics, so completely overwhelmed by naturally curly deltas and triple integrals that the best comment I could make would be that I was still confused, but on a higher level.

Hence, I commend you for the variety of subjects you have in your program, and the balance that you have in the format and content of your papers, and I look forward very much to the presentations.

As you know, the title of my address is "Stop the Computer, I Want to Get Off." That title came to me last fall when I received a communication from your Program Committee urging me to send a title by cable as soon as possible. It hit me at a time when I was reviewing some proposed research to be done before we develop underground hydro pump storage schemes with a deep, lower reservoir cavern system. It was submitted that it would be necessary to study the stresses that would be induced in cavern walls and roof because the water in hydro-electrical projects changes its temperature during the year. Now, if it were a question of going above the boiling point of water, or below the freezing point, I would be interested too. But to perform such an analysis, and with six decimals at that, for the water temperature conditions that prevail in hydro-electrical power systems is chasing a non-problem. I have not seen a single documentation from the thousands of kilometers of unlined water tunnels that we have indicating any severe effects on the rock due to temperature variations such as those at hand.

A more serious misuse of our admittedly very advanced analytical tools is to be found with many of our designers. One gets the impression that the more complex the program, the more credibility it is given. And, in the end, some people genuinely believe that design is synonymous with analysis. As you may know, some of the programs used in the profession and in industry today originated at the University of California, Berkeley. As an example, I remember well how excited we were back in 1967, when the Joint Element was developed, enabling us to do parametric studies on jointed rock masses. This, and later versions of the program, are very well suited for exactly that.

However, my colleagues and I find ourselves in later years pleading with designers not to pay more attention to analysis than it deserves. Design involves so many other things. First of all, and obviously, a thorough understanding of how geological materials behave in reality, including the behavior as influenced by construction procedures. Time is a factor that we have introduced, of course, for soils such as clay. In the analysis of structures in rock, however, we have not. Still, we know that it is in fact an over-riding consideration in many instances, as I will refer to later.

Let us now leave the computer alone for a while, as I would like to explore with you some examples of geological materials and conditions where knowledge of causes and effects is of particular importance. You will find that most of the examples that I have are from underground openings. This is not only because I am most comfortable with these in terms of my own background, but also because they are structures where construction methods and procedures perhaps have the most profound influence.

It would be remiss if I did not at this point start out with a strong endorsement of geotechnical investigations at the planning stage of structures in soil or rock. Perhaps a news item that appeared in a San Francisco paper about two years ago can make the point clearer. It was from Pescara, Italy, and contained the following:

> "There were plenty of preliminary studies before a super highway company began digging a tunnel under the Gran Sasso Mountain--but maybe

> not the right ones. Manfredi de Luca, President of the Abruzzi Geologists Association said work on the tunnel now approaching completion, is drying up springs on the 9,553 ft. mountain. "This is a subject they should have studied before work started and not now," he said. "The geotechnical report in the preliminary study was only 6 pages long, compared with 46 pages on climatology, 27 on psychology, 17 on religion, and 2 volumes on sociology."

Let me contrast this with what happened in the city of Duisburg in the Federal Republic of Germany. Duisburg is the main port serving the great industrial district of the Ruhr. It is situated at the confluence of the rivers Ruhr and Rhine. Its harbor has about 45 kilometers of wharves, and is used every year by some 50,000 vessels with tonnages up to 4,000. The city itself has large industrial complexes, including steel mills and petro-chemical industries. Since the turn of the century, dredging in the Rhine downstream from Duisburg had, by the 1950's, led to a lowering of the water of more than two meters, and further dredging would lead to a lowering by the end of this century that would be intolerable. The large number of vessels precluded the building of locks to raise the water in the harbor itself, and another solution was found.

It was known to the Director of the harbor that an old law in Germany precluded the mining of coal under cities because of the problems that would arise due to surface subsidence. This led him to approach mining engineers, inquiring if it would be possible for them to settle the harbor and part of the city of Duisburg two meters by mining coal under the city. They said that they could provide a settlement trough with an accuracy of ±5%. And they did. At the completion of the mining in 1968, only a few signs could be found in terms of distress to surface structures. I submit to you that this is an excellent example of what we can attain if we have adequate knowledge of the geological conditions, and adequate knowledge in terms of experience from similar work elsewhere.

And now to the materials:

<u>Shales</u> are claystones, siltstones, or mudstones that exhibit fissility, although the name shale is often used even if the fissility is not present. A characteristic problem with these rock types is their tendency to slake due to environmental changes, most commonly drying and rewetting. While relatively strong, cemented shales may not slake for decades, leading, for example, to deterioration and settlement of embankments. Compaction shales may slake vigorously within seconds or minutes when rewetted after being dried out with even a modest decrease in water content.

Today, we are in the process of improving our understanding of the underlying mechanisms of slaking, which are basically air entrapment and differential swelling. While the first one is rather easy to understand, the second is a very complex physicochemical phemomena. There are so many variables involved that it is doubtful that we in engineering practice will see routine tests established to predict slaking behavior on the basis of physicochemical characteristics.

Rather, we will have to live with the old and simple test of studying <u>how</u> a shale slakes by dropping samples in a beaker of water. It is then possible to note whether the shale, with time, will "body" slake to chips and pieces, "surface" slake to small particles, or "dispersion" slake, or show a combination of these.

Clearly, this approach is not very sophisticated. But it does provide us with meaningful information, and aids in our deciding if measures such as the application of a sealant is needed.

For swelling shales, a sealant is obviously not a sufficient measure to prevent deterioration. In addition to the slake durability, we therefore need to assess the swelling capacity. I often find that this is done by x-ray diffraction and/or by Atterberg's Limits. Both are inadequate. Some shales may not show a significant content of smectites in an x-ray analysis, but exhibit a high swelling potential. Here, the reason is that we may have a high content of clay minerals that are so poorly crystallized that the specific surface, and therefore the swelling potential, is exceptionally high.

The Atterberg's Limits may also be somewhat misleading because the results obtained will be a function of how the shale was disaggregated. Hence, it is necessary to perform a direct swelling test. There are quite a few of these around, and again, the results will vary, depending upon the particular procedures used. I believe that it is best to use one procedure for which results are available for other shales whose actual field behavior in terms of swelling is known. Thus, the approach is to establish a relative swelling potential, rather than attempt to establish absolute values for this potential.

As an argillaceous material, many shales will have a tendency to squeeze when tunneled through. We have both field and laboratory data that has taught us that we can expect heavy squeeze if a reasonably wide zone of shale is tunneled through where the ratio between the overburden stress and the unconfined compressive strength of the shale exceeds 1. When this ratio exceeds 2-3, we can expect an accelerating intrusion of the tunnel face. This does not mean that tunnels cannot be built when this ratio is high. The highest ratio I am aware of as being successfully handled is, in fact, 10. However, it is very slow and difficult tunneling. We know that we will have to alleviate the situation by having a cross section of the tunnel that is as close to circular as possible and also by allowing the ground to move to reduce the squeezing loads. Allowing for a reduction in tunnel diameter as excavated of around ten percent is not uncommon. Trying to fight the squeeze by installing heavy steel sets, for example has again and again turned out to be costly, often because remining is required. Using a more flexible system has proven quite successful. This may include rather long, fully grouted rock bolts all around the periphery of the tunnel in combination with light steel sets and shotcrete. Regardless of the method of stabilization that is used, the basic principle is that the ground must be allowed to move.

In assessing the squeezing potential, it is necessary to have some knowledge of the strength of the shale. In rather massive shales that have not been tectonically disturbed, laboratory results on the unconfined compressive strength can be used with reasonable confidence provided that the samples have not been allowed to dry out. In shales that have been tectonically disturbed by folding and/or faulting, establishing the unconfined compressive strength that is representative for the rock mass can be very difficult. Whether the samples are cores or rock samples taken in the tunnel, the results will often be biased simply because the very best pieces are the only one tested as the rest of the material may be so bad that an unconfined compressive strength test cannot be performed. In particular, the clay matrix of a sheared shale may dominate the behavior in terms of squeezing, regardless of how strong intact pieces of good shale floating in the matrix are.

We all know that some siliceous sandstones can be as strong and competent as any granite. However, we also know that there are argillaceous sandstones that will slake just as shales can do. This is often overlooked during the exploration phase, with sad results during construction.

Further, there are many, notably younger, sandstones that are poorly indurated. Such sandstone may be so friable that even a modest water pressure may turn the sandstone back into sand. In tunneling under the groundwater table, this is a very dangerous and hazardous situation, as flowing ground will ensue. In somewhat less friable sandstone, the sandstone may in part have been turned back to sand due to tectonic movements. Again, tunnels have been completely filled with sand when such zones have been encountered below the groundwater table.

We have several methods available to us to handle these ground conditions provided that we know where we are to expect them. Freezing and grouting are two techniques that have been used. Neither is foolproof. The freezing technique will only work if the groundwater flow in the area is quite modest. Grouting can leave windows of flowing material due to variations in permeability.

Under all circumstances, it is imperative when tunneling through ground where flowing ground conditions might exist, to have adequate feeler holes way ahead of the advancing tunnel face. A case history from the Chivor II Project in Colombia can attest to this. There, a penstock tunnel had been driven through a fault zone and into steeply dipping, interbedded sandstones and shales that were crushed. Indications of instability of the tunnel face led to the evacuation of the 1.2 kilometer tunnel. Just thereafter, about 50,000 cubic meters of slide material came roaring out the portal of the tunnel. The tunnel was later completed by driving a by-pass tunnel, this time using numerous feeler holes to bring down the water pressure around the advancing tunnel face. While the inflow was several hundred liters per second, the by-pass tunnel was safely excavated.

While karstic limestone long had special attention when sites for dams and reservoirs are explored, it is not always the case for tunnels. For example, the planning of a subway in Miami had proceeded for quite awhile before it was realized that karstic caverns connected to the Atlantic Ocean could make the construction of such a subway a very hazardous undertaking. Also, the solution of porous and flakey limestone, or porous or flakey calcite in joint and fault fillings, may in the long run threaten the stability of a tunnel.

Another geological setting that has caused problems in some tunnels, notably in the Alps, is when the tunnel is in anhydrite. If water has access to the anhydrite, it may, with time, try to go to gypsum which involves a volume increase. The swelling pressures that can develop if this process is confined by a tunnel lining, can be significant.

Swelling can also be expected when tunneling through bentonitic tuff. Such tuff will also have a tendency to slake, and will have a very low stiffness. The low stiffness problem is significant when the tunnel is a pressure tunnel. If the tunnel is concrete lined without reinforcement, the concrete lining may crack to an extent that it can totally collapse if the tunnel is dewatered.

One group of geological materials that has had too little attention in geotechnical research is the residual materials or weathering profiles. This seems to be particularly true for metamorphic rocks. I would like to quote to you a classification that we have been using for the subway in Baltimore, Maryland. Our particular effort there was to try to delineate the material between underlying rock and overlying residual soil into two zones, one which could basically be excavated using soil tunneling techniques, the other which would basically require rock tunneling techniques. The definition of the zones are as follows:

"Residual material designated as Residual Zone #1 (RZ-1) is considered transitional between Residual Soil and the less decomposed Residual Zone #2. It consists of material derived from the *in-situ* decomposition of the parent rock with soil-like components and partially weathered and/or fresh rock components. RZ-1 material usually retains some cohesion of the parent rock and exhibits visible remnant rock structure such as schistosity and relict joints. Materials in this zone can normally be sampled with soil sampling techniques. In most, but not all cases, the Standard Penetration Test results are greater than 100 blows per foot.

"In a few cases, RZ-1 material was cored to provide a continuous sample. The material in the RZ-1 zone and its constituents, when the material is disaggregated by hand or using mortar and pestle, are described as soils.

"Residual Zone #2 material is rock-like, being derived by partial decomposition of the parent rock with partially weathered and/or fresh rock components. This material, *in-situ*, usually retains the rock structure and considerable strength of the parent rock. The RZ-2 material is commonly heterogeneous with respect to weathering ranging from decomposition throughout the entire body to partial decomposition throughout the material. This material cannot usually be disaggregated by hand and is described with rock descriptions, notation of soil-like matrix or filler when appropriate, and a notation of the RZ-2 designation. Material in this zone usually requires rock sampling techniques to obtain specimens from boreholes.

"It should be noted that although the residual materials have been categorized by the aforementioned criteria, the transitions between RS, RZ-1, RZ-2, and Rock are frequently not sharp boundaries as may be inferred from the boring logs. Also, one or more zones may not be present above the basement rock at all locations. The interface between RZ-2 and Rock does not imply that decomposition has not occurred below this level. The effects of decomposition are highly variable and the assignment of materials to a specific residual zone is judgmental."

As you can imagine, all contractors would not always be in complete agreement with the owner's representative as to whether what they actually encountered was RZ-1 or RZ-2. However, overall it has proved very helpful to have this classification identified in the contract documents.

Finally, I would like to discuss briefly with you some aspects to be remembered when gas is encountered underground. As a profession, we have long been aware of the fact that explosive gas concentrations can occur in what we could call a coal environment, where the major emphasis is on the possible inflow into the tunnel of methane. What has been less appreciated is that tunnels are also driven through a petroleum environment, whether that is in sedimentary rocks or through geological structures with which oil could be associated.

Methane is lighter than air. As a consequence, the literature dealing with the detection of methane emphasize the importance of paying particular attention at the crown or the back of the tunnel or mine. In the petroleum environment, however, we also have higher hydro-carbons that, with the exception of ethane, are heavier than air. Consequently, both the detection procedures, and the ventilation requirements must be different. For example, in a major gas explosion in a tunnel in the San Fernando Valley in California some eight years ago, it was found that these higher hydrocarbons had bled from the muck in the muck cars, and that the gas concentration in those cars had gone above the lower explosive limit.

The lower explosive limit is the percentage of gas mixed with air (by volume) at which an explosion can be ignited. It is 5% for methane, and somewhat lower for the higher hydro-carbons due to their higher density. The gas concentration in a tunnel should never be allowed to approach the lower explosive limit. In fact, every effort should and must be made to keep it below 20% of the lower explosive limit. The gas flowing into a tunnel seldom comes at a uniform rate as the tunnel is being advanced. A "factor of safety" of five is therefore not as comfortable as it looks. It is possible, however, to work up to 40 percent of lower explosive limit, provided all necessary precautions have been made to avoid an arc, a spark, a flame, or a high temperature that could ignite an explosion. To work in a tunnel where the gas concentration exceeds 40 percent of lower explosive limit is foolish. There have been too many tragic accidents to attest to that.

When designing the ventilation system for a tunnel, it is not only necessary to provide sufficient volume of air to keep the gas concentration down. The movement of air must also have a certain velocity in order to mix the gas with the air. This so-called pick-up velocity is about 35 meters per minute. Again, it is prudent to be conservative as the velocity cannot be assumed to be the same behind steel ribs or in recesses, as it is in the middle of the tunnel. Designing the ventilation system for a pick-up velocity of 70 meters per minute is therefore often recommended.

It does happen that the gas inflow into a tunnel far exceeds the amount that was perceived at the planning stage. If the tunnel is rather small, it may not be feasible to bring in another ventilation duct. In that case, it may be necessary to open up a new adit or sink a shaft close to the face of the tunnel in order to get enhanced ventilation. An alternative to this would be to use degasification measures that have been tried in coal mines. This consists of collecting the gas either ahead of an advancing face from the surface or from the mine opening itself. Grouting around an opening, as well as water injection, has also been tried. These measures can help in reducing gas inflow, but they are seldom more than 50% effective. Also, in civil work, we often find that degasification is impractical for geological, topographical, or scheduling reasons, and that the sinking of a ventilation shaft or driving of a ventilation adit in the end is the least costly and most efficient.

In conclusion, I note that the materials and conditions that have been briefly described are difficult ones. However, they can be safety and effectively handled provided that we make maximum use of the knowledge and procedures that have been developed through practical experience, worldwide.