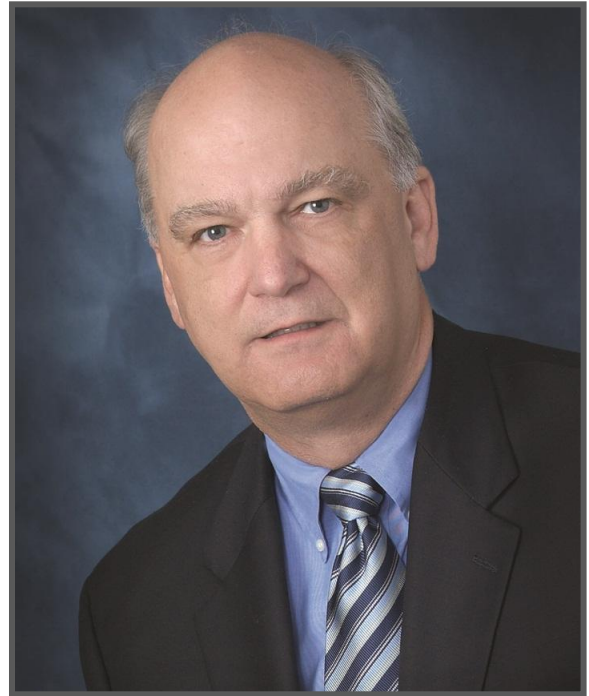


The Twentieth Spencer Buchanan Lecture
Friday, November 30th, 2012
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**Active Risk
Management in
Geotechnical
Engineering**

*The 2012 Spencer J. Buchanan
Lecture*
By Dr. Allen Marr



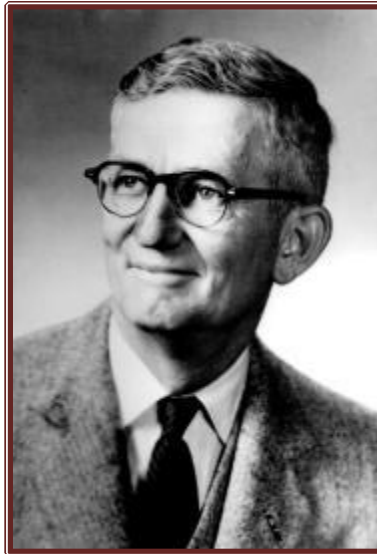
**Seismic Measurements
and Geotechnical
Engineering**

The 2011 Karl Terzaghi Lecture
By Dr. Kenneth Stokoe

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SPENCER J. BUCHANAN



Spencer J. Buchanan, Sr. was born in 1904 in Yoakum, Texas. He graduated from Texas A&M University with a degree in Civil Engineering in 1926, and earned graduate and professional degrees from the Massachusetts Institute of Technology and Texas A&M University.

He held the rank of Brigadier General in the U.S. Army Reserve, (Ret.), and organized the 420th Engineer Brigade in Bryan-College Station, which was the only such unit in the Southwest when it was created. During World War II, he served the U.S. Army Corps of Engineers as an airfield engineer in both the U.S. and throughout the islands of the Pacific Combat Theater. Later, he served as a pavement consultant to the U.S. Air Force and during the Korean War he served in this capacity at numerous forward airfields in the combat zone. He held numerous military decorations including the Silver Star. He was founder and Chief of the Soil Mechanics Division of the U.S. Army Waterways Experiment Station in 1932, and also served as Chief of the Soil Mechanics Branch of the Mississippi River Commission, both being Vicksburg, Mississippi.

Professor Buchanan also founded the Soil Mechanics Division of the Department of Civil Engineering at Texas A&M University in 1946. He held the title of Distinguished Professor of Soil Mechanics and Foundation Engineering in that department. He retired from that position in 1969 and was named professor Emeritus. In 1982, he received the College of Engineering Alumni Honor Award from Texas A&M University.

He was the founder and president of Spencer J. Buchanan & Associates, Inc., Consulting Engineers, and Soil Mechanics Incorporated in Bryan, Texas. These firms were involved in numerous major international projects, including twenty-five RAF-USAF airfields in England. They also conducted Air Force funded evaluation of all U.S. Air Training Command airfields in this country. His firm also did foundation investigations for downtown expressway systems in Milwaukee, Wisconsin, St. Paul, Minnesota; Lake Charles, Louisiana; Dayton, Ohio, and on Interstate Highways across Louisiana. Mr. Buchanan did consulting work for the Exxon Corporation, Dow Chemical Company, Conoco, Monsanto, and others.

Professor Buchanan was active in the Bryan Rotary Club, Sigma Alpha Epsilon Fraternity, Tau Beta Pi, Phi Kappa Phi, Chi Epsilon, served as faculty advisor to the Student Chapter of the American Society of Civil Engineers, and was a Fellow of the Society of American Military Engineers. In 1979 he received the award for Outstanding Service from the American Society of Civil Engineers.

Professor Buchanan was a participant in every International Conference on Soil Mechanics and Foundation Engineering since 1956. He served as a general chairman of the International Research and Engineering Conferences on Expansive Clay Soils at Texas A&M University, which were held in 1965 and 1969.

Spencer J. Buchanan, Sr., was considered a world leader in geotechnical engineering, a Distinguished Texas A&M Professor, and one of the founders of the Bryan Boy's Club. He died on February 4, 1982, at the age of 78, in a Houston hospital after an illness, which lasted several months.

The Spencer J. Buchanan '26 Chair in Civil Engineering

The College of Engineering and the Department of Civil Engineering gratefully recognize the generosity of the following individuals, corporations, foundations, and organizations for their part in helping to establish the Spencer J. Buchanan '26 Professorship in Civil Engineering. Created in 1992 to honor a world leader in soil mechanics and foundation engineering, as well as a distinguished Texas A&M University professor, the Buchanan Professorship supports a wide range of enriched educational activities in civil and geotechnical engineering. In 2002, this professorship became the Spencer J. Buchanan '26 Chair in Civil Engineering.

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1995	James K. Mitchell	“The Role of Soil Mechanics in Environmental Geotechnics”
1996	Delwyn G. Fredlund	“The Emergence of Unsaturated Soil Mechanics”
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1998	John B. Burland	“The Enigma of the Leaning Tower of Pisa”
1999	J. Michael Duncan	“Factors of Safety and Reliability in Geotechnical Engineering”
2000	Harry G. Poulos	“Foundation Settlement Analysis – Practice Versus Research”
2001	Robert D. Holtz	“Geosynthetics for Soil Reinforcement”
2002	Arnold Aronowitz	“World Trade Center: Construction, Destruction, and Reconstruction”
2003	Eduardo Alonso	“Exploring the Limits of Unsaturated Soil Mechanics: the Behavior of Coarse Granular Soils and Rockfill”
2004	Raymond J. Krizek	“Slurries in Geotechnical Engineering”
2005	Tom D. O’Rourke	“Soil-Structure Interaction Under Extreme Loading Conditions”
2006	Cylde N. Baker	“In Situ Testing, Soil-Structure Interaction, and Cost Effective Foundation Design”
2007	Ricardo Dobry	“Pile response to Liquefaction and Lateral Spreading: Field Observations and Current Research”
2008	Kenneth Stokoe	“The Increasing Role of Seismic Measurements in Geotechnical Engineering”
2009	Jose M. Roesset	“Some Applications of Soil Dynamics”
2010	Kenji Ishihara	“Forensic Diagnosis for Site-Specific Ground Conditions in Deep Excavations of Subway Constructions”
2011	Rudolph Bonaparte	“Cold War Legacy – Design, Construction, and Performance of a Land-Based Radioactive Waste Disposal Facility”
2012	W. Allen Marr	“Active Risk Management in Geotechnical Engineering”

The texts of the lectures and a DVD’s of the presentations are available by contacting:

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AGENDA

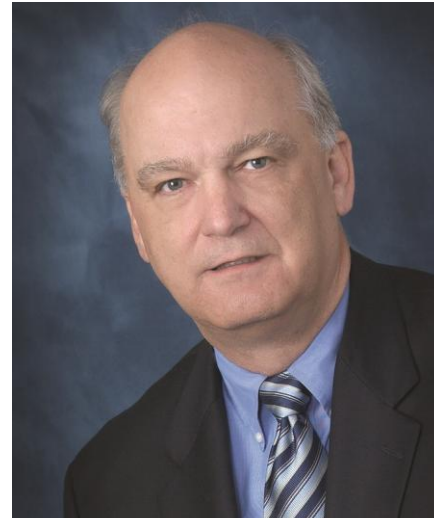
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- 2:00 p.m. Introduction by Jean-Louis Briaud
- 2:15 p.m. John Niedzwecki - The Zachry Department of Civil Engineering
- 2:20 p.m. Phil King - The ASCE Geo Institute
- 2:25 p.m. Introduction of Kenneth Stokoe by Jean-Louis Briaud
- 2:30 p.m. “Seismic Measurements and Geotechnical Engineering”
The 2011 Terzaghi Lecture by Kenneth H. Stokoe, II
- 3:30 p.m. Introduction of W. Allen Marr by Jean-Louis Briaud
- 3:35 p.m. “Active Risk Management in Geotechnical Engineering”
The 2012 Buchanan Lecture by W. Allen Marr
- 4:35 p.m. Discussion
- 4:50 p.m. Closure with Philip Buchanan
- 5:00 p.m. Photos followed by a reception at the home of Jean-Louis and Janet Briaud.

W. Allen Marr, Ph.D., PE, NAE, FASCE

Dr. Allen Marr, President and CEO of Geocomp, has over 40 years of specialized expertise in design and construction of large earthwork facilities, value engineering for earthworks and earth retention systems, risk management for underground construction, and instrumentation and real-time monitoring systems. He has spent his entire professional career focused on incorporating the benefits of applied research in geo-engineering into civil engineering practice.

Dr. Marr holds a Bachelor of Science degree in Civil Engineering from the University of California at Davis as well as a MS and PhD in Civil Engineering from the Massachusetts Institute of Technology. He is an elected member of the National Academy of Engineering (NAE) which recognizes outstanding engineers for their dedication to their discipline as well as for their development of an engineering invention or process that has greatly improved humanity.



Some of his significant contributions in the field of engineering include the development of techniques for monitoring the stability, movement and pressure in earthworks projects by using sensors, wireless communications, automated analysis and visualization of data. In developing sensing, monitoring, measurement and analysis technologies, Dr. Marr has enabled full-scale construction projects to be built more safely and efficiently, at lower cost.

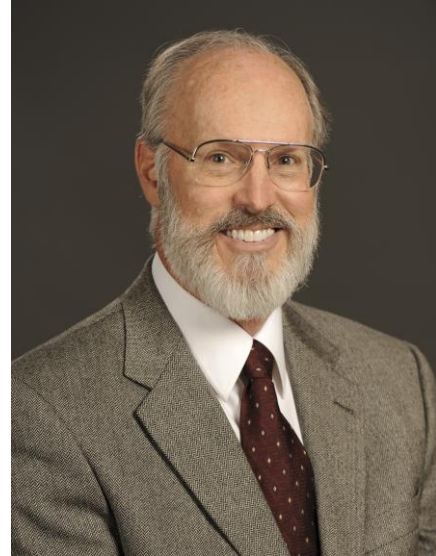
Dr. Marr has developed the concepts of “Active Risk Management”; “Key Risk Indicators” and “Risk Monitoring” to better manage risks associated with heavy civil construction. Active Risk Management assesses risk throughout the design and construction life of a project and indicates where and what mitigation measures should be employed to optimally manage risk. And, as the developer of an integrated *iSite*[™] system which monitors sensors located anywhere in the world via a Web browser, Dr. Marr has created a system that is increasingly used to monitor the safety of facilities during construction and provides early warnings of adverse performance.

His many contributions have been widely published and he serves on a number of professional society committees and boards. Dr. Marr has consulted on such significant projects as Boston’s Central Artery Tunnel; Dulles Airport Expansion; the new World Trade Center construction and the Woodrow Wilson Bridge in Washington, D.C., as well as projects in Canada, the Netherlands, Qatar, Japan, Venezuela and South Korea.

Kenneth H. Stokoe, II, Ph.D.

*Jennie C. and Milton T. Graves Chair
The University of Texas at Austin*

Dr. Kenneth H. Stokoe, II is the holder of the Jennie C. and Milton T. Graves Chair in Engineering in the Civil, Architectural and Environmental Engineering Department at the University of Texas at Austin. He has been working in the areas of field seismic measurements, dynamic laboratory measurements, and dynamic soil-structure interaction for more than 40 years. He has been instrumental in developing several small-strain field methods for in-situ shear wave velocity measurements. He has also developed two types of resonant column systems that are used to evaluate dynamic soil and rock properties in the laboratory. Over the last Ten



years, Dr. Stokoe has led the development of large-scale mobile field equipment for dynamic loading of geotechnical systems, foundations and structures, an activity that has been funded by the National Science Foundation in the NEES (Network for Earthquake Engineering Simulation) program. The equipment has already led to the development of new testing methods to evaluate soil nonlinearity and liquefaction directly in the field. Dr. Stokoe has received several honors and awards, including election to the National Academy of Engineering, the Harold Mooney Award from the Society of Exploration Geophysicists, the C.A. Hogentogler Award from the American Society for Testing and Materials, and the H. Bolton Seed Medal and the Karl Terzaghi Distinguished Lecturer from the American Society of Civil Engineers.

Active Risk Management in Geotechnical Engineering

The 2012 Spencer J. Buchanan Lecture
By Dr. Allen Marr

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Active Risk Management in Geotechnical Engineering

W. Allen Marr¹, PE, PhD, NAE, F.ASCE

¹President and CEO, Geocomp Corporation, 125 Nagog Park, Acton, MA 01720 wam@geocomp.com

ABSTRACT: *Active risk management, (ARMTM), is a systematic process of identifying, analyzing, planning, monitoring and responding to project risk **over the life of the project**. It involves processes, tools, and techniques that help the project team minimize the probability and consequences of adverse events (threats) and maximize the probability and consequences of positive events (opportunities) throughout the life of the project. It is especially useful in projects with significant geotechnical risks. It provides the project team with more complete information on the risks they face in a format understandable to non-specialists – cost and schedule impacts. It identifies the uncertainties and potential events that create the most risk to the project and develops ways to minimize these uncertainties as they affect final project cost and schedule.*

The concept of Active Risk Management applied to civil engineering projects has been developed by the author on a variety of projects over 35 years. This paper lays out the steps of Active Risk Management and discusses how they are applied in geotechnical engineering. It illustrates the use of the method with a practical example that shows the value of obtaining additional geotechnical information to reduce risk.

INTRODUCTION

Every construction project faces risks that threaten successful completion of the project as measured by cost, schedule and quality. The construction industry is seeking better ways to manage these risks. Since the 1970's, the author and his colleagues have worked with clients in the infrastructure market to identify and quantify risks for specific projects, then develop risk management strategies that provide the most benefit to the project in terms of cost, schedule and quality. This work has led to the concept of Active Risk Management which recognizes that risk management efforts must extend throughout the life of a project and must be based on information that is current and comprehensive. This document represents the synthesis of our experience with risk management into a logical and consistent approach that has saved clients large sums of money by actively managing risk throughout the project.

Project risk is an uncertain event or condition that potentially impacts the project objectives for cost, schedule, and quality. Impacts may be both positive and negative. A risk has a cause and, if it occurs, a consequence. Risk is the combination of the likelihood of the uncertain event times its consequence. A likely event with moderate consequences may expose the project to more risk than an unlikely event with high consequences. **Risk management** is a systematic process of identifying, analyzing, planning, monitoring and responding to risk. It involves processes, tools, and techniques that help the project team minimize the probability and consequences of adverse events and maximize the probability and consequences of positive events.

Many organizations practice some form of risk management on construction projects. Generally these activities focus on risk assessment and risk allocation by individual members of the project team. These activities are organized to manage that member's risk by transferring, avoiding, mitigating or accepting specific risk elements. This is not managing overall project risk. It may in fact increase total project costs because risks do not get allocated to the team member best positioned to manage that risk at an efficient cost.

ACTIVE RISK MANAGEMENT

The author has developed the concept of **Active Risk Management™** (ARM™) to describe an organized risk management strategy that transcends the entire project. **Active risk management** is a systematic process of identifying, analyzing, planning, monitoring and responding to project risk *over the life of the project*. It involves processes, tools, and techniques that help the project team minimize the probability and consequences of adverse events (threats) and maximize the probability and consequences of positive events (opportunities) throughout the life of the project.

Active Risk Management provides the project team with more complete information on the risks they face in an understandable quantitative format – cost and schedule at risk – and does so in near real-time. This not only helps team members make informed decisions, but also monitor the progress of risk management efforts over the duration of the project.

Active Risk Management provides quantitative information on the impacts of each risk component to cost, schedule and quality so that the most significant risks can be managed with the most effective approach. It applies methods of uncertainty analysis with project management tools to consider all potential risks and find those with the highest potential impact on the project objectives.

The physical processes of construction inherently involve substantial uncertainty that creates risk to the owner, contractor and engineer. These risks are in addition to the conventional risks (those from injury, contract, regulatory, legal, financial, weather and others) associated with the project. No amount of planning and engineering can predict with 100-percent certainty how the various elements of the project will actually perform during construction. Among the unknowns are: the geologic profile; the engineering properties of each component of the geologic profile; the groundwater conditions; the in situ stresses; the effects of environmental conditions, construction activities, and time on the underground conditions; limitations of analysis and design methodologies; unknown obstructions; location,

condition and performance during construction of existing utilities and other structures; and interactions between the ground and structures. There may also be uncertainty in the forces from extreme events that the project will experience. On top of these are the uncertainties that derive from accidents, mistakes, poor judgment, and improper actions of the work force and other construction issues during the performance of the work. These types of risk are referred to as “operational risks”. Operational risks are often ignored in the contractual, financial, and legal discussions of risk management; yet they may jeopardize the entire project.

One approach to managing risks is to develop a conservative design based on what the project team considers a worst-case scenario, and hope for the best. But unexpected factors, such as excessive ground movements or unexpected groundwater flow can damage completed work or adjacent facilities. These, in turn, can cause project delays, add substantial costs, degrade quality, or risk the health and safety of workers and the public. A more cost-effective way to manage risks is to design for the most likely scenario based on an investigation of the underground conditions and potential hazards. The design process includes a risk assessment to determine which sources of uncertainty dominate the operational risks, which risks can be reduced with design modifications, and which risks can be avoided with observation and remedial work during construction, i.e. monitoring how the site actually performs as construction begins, then making adjustments to the design and/or construction methodology as required by the observed performance. The risk assessment is continually reviewed and updated as new information becomes available. This approach is the essence of Active Risk Management™. The ARM™ method has similarities to Dr. Peck’s Observational Method (Peck, 1969) from a geotechnical engineer’s perspective, but looks more broadly at all potential risks to the project; makes quantitative estimates of the relative magnitudes of each risk element and its impact on cost, schedule and quality; and monitors Key Risk Indicators.

Active Risk Management uses historical data, expert judgment with tools from decision theory, and probability theory to make numerical assessments of each component of risk for construction. Measurements of actual conditions as they unfold and opinions from subject matter experts are integrated with formal analyses to produce a balanced quantitative assessment of each source of operational risk in terms of potential impact on cost and schedule. This approach has helped owners and contractors make informed decisions regarding design and construction of major facilities – decisions that have saved hundreds of millions of dollars by avoiding overly conservative approaches and focusing resources on the most beneficial actions.

Effective risk management consists of several steps that can be visualized as a continuous circle of improvement shown in Figure 1. Effective risk management requires the process of risk mitigation to be completed and repeated throughout the project duration as new information becomes available. Past risk management practice on many projects has typically been to prepare a risk assessment during the planning phase of a project, make some decisions on risk allocation, then do little formal work on risk management for the remainder of the project. This practice does not provide the substantial benefits of a complete risk management program. Effective risk management of project construction starts in the planning phase, and



Fig. 1: Circle of Risk Management

continues until after the facility is placed into service or risks are reduced to an acceptable level.

Numerous sources of risk exist on a complex project. It becomes easy to overlook or forget a significant source of risk that later threatens the project objectives. Using established methods and tools, qualitative risk analysis assesses the probability and the consequences of each identified risk to determine its overall importance. Risks to project cost and schedule involve two principal elements: uncertainties in quantities and unit costs for known elements and

unknown conditions and events that are not covered in the baseline cost and schedule elements. During the planning phase of a project, quantities and unit prices may have considerable uncertainty. These uncertainties can be estimated by asking the sources of the information to expand their estimates to lowest possible value, highest conceivable value and the most likely value for each cost, quantity, and schedule item.

These types of variability have traditionally been handled by the estimators making individual conclusions about what amount to put into a price estimate and then adding a contingency to the project total cost. The problem with the contingency approach is that different estimators use different means to decide how much contingency to add to each cost item and then another contingency gets added to the total bid cost. No one knows what the final project price really represents relative to all the uncertainties that were or were not considered in the individual price elements.

APPLICATION ILLUSTRATION

Explicit consideration of the best estimates of the uncertainties in each element of the project costs can be used to obtain a range of probable cost for the project. This range can then be used to decide how much risk to accept in preparing the final bid price. This is illustrated with an example. A large earthworks project is estimated by conventional means to cost \$495 million. The bid management team discusses uncertainties and risks and decides to add a 6% contingency to the base estimate for external risks making their total cost estimate \$525 million.

A risk assessment breaks this global estimate of risks into an estimate of uncertainty in cost and schedule for each component of the project and for each potential risk event. Table 1 gives a summarized risk registry for the primary unknowns. A detailed review by item of the base cost and schedule with the project estimators results in a range for base cost and schedule. Table 1 summarizes the estimates for lowest possible value, the highest conceivable value and the most likely value (called mode) for costs, schedule and likelihoods. The values come from the subjective assessments by the project team members most familiar with the project. A review with the project team indicates 5 events with significant potential impact to the project cost and schedule that were not covered in the base cost and schedule estimate. Estimates

are made for the range of potential cost and schedule impacts to the project and for the likelihood that each of these events may occur. Note that uncertainty in the likelihood estimate is also included. These data are used as input to a numerical simulation run in a spreadsheet that develops a probability distribution for each uncertain element and numerically integrates the individual event distributions into one overall distribution on cost and another on schedule. These risk costs are added to the base cost uncertainties to obtain the overall uncertainty for project cost. Such estimates are shown by the six curves in Figure 2.

Table 1: Simplified Risk Registry

Risk Event	ID	Consequence (ranges are lowest, mode and highest estimates)	Likelihood and Sources of Data
Base	Base	475/500/550 millions 46/48/54 months	100% review of base estimates
Earthwork issues	A	5/6/7.5 millions 3/4/6 months	12-16-22% from project manager
Delays in shoring delivery	B	7/8/9 millions 4/5/6 months	10/20/25% from suppliers
Unexpected site conditions	C	30/54/90 millions 4/6/8 months	7-10-15% from geotechnical consultants
Bad weather	D	1/1.5/2.5 millions 1/1.3/2 months	9-12-15% from weather records
Approval Delays	E	0.2/0.25/0.3 millions 3/4/6 months	25-30-35% past experience
Additional Testing and Monitoring	F	1/1.2/1.5 millions No schedule impact	Likelihood for A reduced to 4/5.3/7.3%; Likelihood for C reduced to 0.7/1.0/1.5%

The seventh curve, ID F, is actually an opportunity. An additional testing program to reduce uncertainty in soil properties and a performance monitoring program to give early warnings to invoke contingency measures costs money but reduces uncertainty which lowers risk. The reduced uncertainty lowers risk costs by much more than the cost of the additional work.

Accounting for risk costs from event uncertainties in the example increases the best estimate of the base cost from \$495M to \$507 million. There is a 10% chance that the base cost could exceed \$530M. The range of probable cost for the project with all uncertainties and identified risks accounted for is \$492 to 554M (C_{10} and C_{90} exceedance values). Prudent decision makers would consider this range of probable cost in preparing budgets for the project and bids for the construction. It is useful to note that an estimate using mean values for unit prices and quantities and adding a 6% contingency to account for uncertainty in costs and quantities, but not including the unknown risks, would yield a cost of \$525M. Figure 2 shows that there is a 15% chance that this cost will be exceeded if risk events A-E are not considered and a 33% chance if risk events A-E are included. Most contractors would be very

uncomfortable bidding a project with a price that had a 33% chance of being exceeded.

Figure 3 shows the risk curves for schedule. The best estimate of likely time to complete the job is 48 months. Adding in the effects of potential external events shows that the chance of completing the project in 48 months is about 10%. There is a 10% chance that the project will take more than 56.6 months to complete. This additional time has a significant impact on the cost of the project.

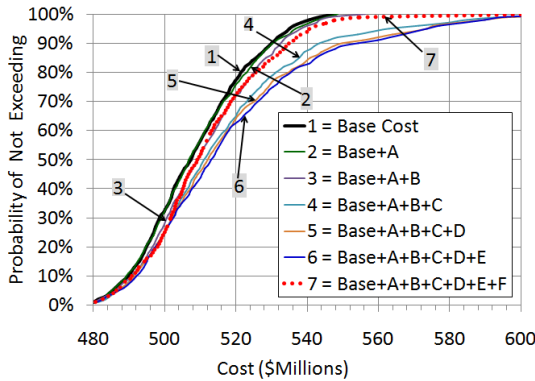


Fig. 2: Estimated Cost with Risk

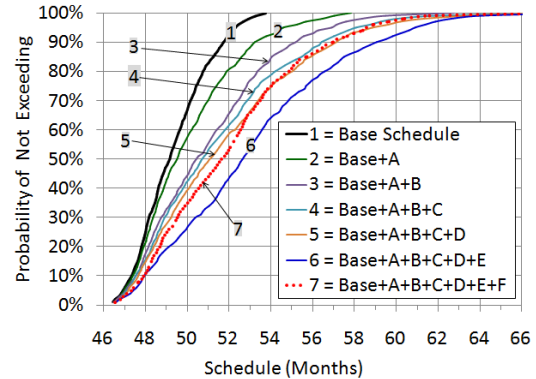


Fig. 3: Estimated Schedule with Risk

This example shows the effects of uncertainties on project costs and schedule estimates during the planning phase of a project. As the project progresses, new information alters the uncertainties. Pricing and quantities become more certain. As time passes, a risk event happens or doesn't happen which alters its probability to 0 or 1. Uncertainties in cost and schedule can also be reduced by collecting additional information that reduces uncertainty in risk events. Curve 7 shows the potential benefits of performing more testing on the earthen materials to reduce uncertainty in how they can be excavated and compacted, and of adding an instrumentation program to determine as early as possible how the work is performing and whether remedial actions may be required to prevent undesirable performance, such as a slope stability failure or a foundation failure, that increase cost or schedule.

Another useful outcome of the risk assessment is a ranking of the sources of risk by their relative impacts on estimated cost and schedule. Figures 4 and 5 show results for this example. The highest cost risk is caused by uncertainty in site conditions. Based on the cost and likelihood estimates of the team this uncertainty has an expected cost impact of \$6.5M on the project and a schedule delay of 0.6 months.

ID F in Table 1 illustrates opportunity. By performing further site investigations to lower geotechnical uncertainty and adding a performance instrumentation-monitoring system, there is an expected cost increase of \$1.2M but the value of the expected reduction in risk is \$7M for a net potential gain of almost \$6M and a schedule reduction of 1 month. The effect on the risk curves for cost and schedule are shown by the difference between curves 6 and 7 in Figures 2 and 3. For geotechnical engineers, results like these provide a great way to communicate the value of additional site investigations and performance monitoring programs to clients.

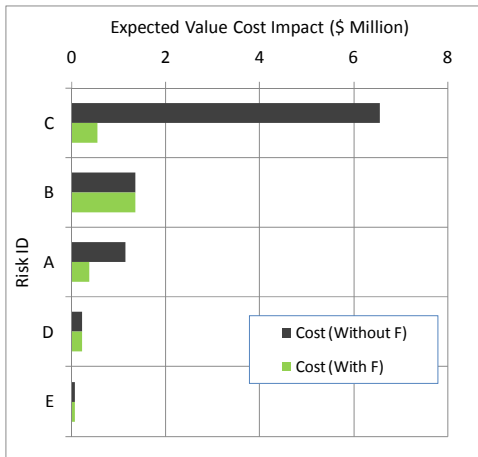


Fig. 4: Tornado Chart for Costs

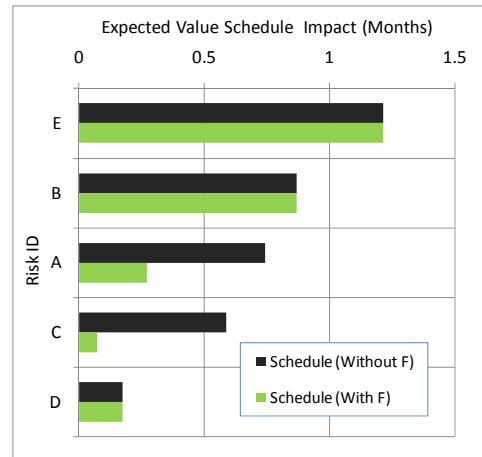


Fig. 5: Tornado Chart for Schedule

The Risk Management approach illustrated in this example occurs at the beginning of the project. It provides very useful information to help bid the project and develop strategies to manage the project to minimize risks during the execution. It provides a rational and consistent methodology to quantify all uncertainties in the project cost and schedule elements. To be most effective however, this risk assessment methodology should continue throughout the project with a monitoring and updating program to expose emerging risks and manage their consequences. This addition is what makes the Active Risk Management concept unique. The “F” event given in the example shows the potential benefit of continuing risk management through the project.

TEN STEP APPROACH TO ACTIVE RISK MANAGEMENT

The ARM™ approach to risk management involves close teamwork among the Owner, the Engineer, the Contractor (if contract has been awarded) and a team of subject matter experts. The Owner provides information on the project scope and objectives and supplies other resources necessary to conduct the risk assessment. The Engineer provides information on possible risk

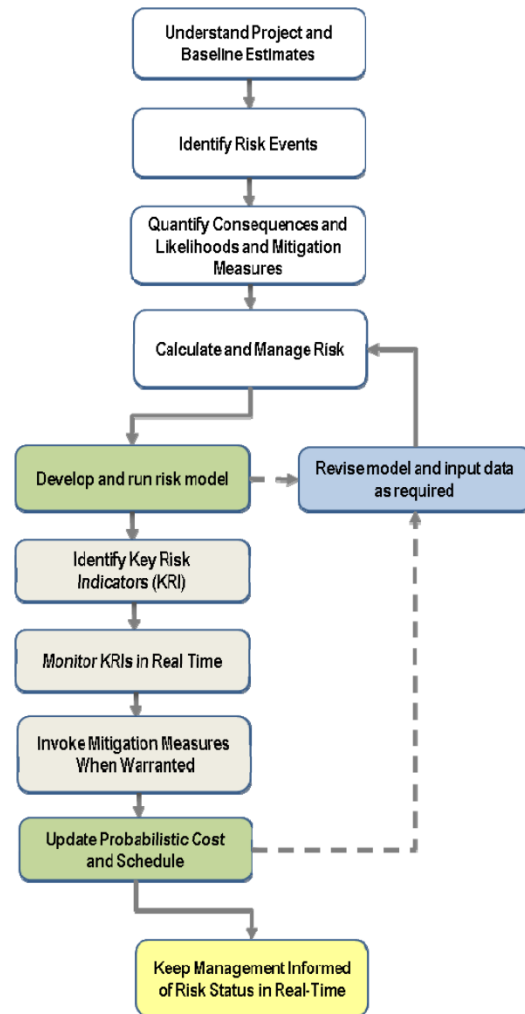


Fig. 6: Work Tasks for Active Risk Management Process

events, their likelihood of occurrence and their consequences. Perspective Contractors, or construction specialists, also provide information on possible risk events - especially those tied to construction means and methods, their likelihood of occurrence, and their consequences. The Risk Team facilitator provides the framework for a systematic examination of risk by the team; facilitates the definition of risk events, their likelihood of occurrence, and their consequences; tests the information for completeness and consistency with scientific requirements; develops and applies a mathematical model of risk; and interprets and reports the results to the project team. The Risk Assessment Team is comprised of professionals experienced in all aspects of planning, design, and construction of the facility. Independent consultants or subject matter experts whose expertise closely aligns with unique aspects of the project and who understand the essential elements of risk analysis may be added to the team.

Figure 6 illustrates the sequence of tasks we use to complete an active risk assessment program. The process runs in a linear sequence in which the specific work in each task depends on the results of previous tasks. Each task is self evident.

CONCLUSIONS

Active Risk Management provides the project team with complete information on the risks they face in an understandable format – cost and schedule at risk. It identifies the uncertainties and potential events that create the most risk to the project and develops ways to minimize these uncertainties on final project cost and schedule. This not only helps team members to make informed decisions, but also to monitor the progress of risk management efforts over the duration of the project. Active Risk Management provides clients with a continual assessment of their risk profile and how it is changing as the project progresses. Active Risk Management identifies specific actions that can be used to alter events and reduce consequences; thereby preventing unexpected and costly events. Active Risk Management seeks to contain and control the many costs that result from unexpected and uncontrolled events. The result can be savings that are many times the cost of the risk management effort.

The author's experience shows that the project's best interests are served when key participants take a proactive approach to minimizing the occurrence of significant unexpected events and controlling the significant consequences of undesirable performance. Using Active Risk Management concepts on significant projects around the world has shown that this methodology is best applied by whoever has the most at risk in a project's successful outcome. Depending on the project and its risk profile, this may be the Owner, the General Contractor, the Construction Manager, the Insurer or the Financer.

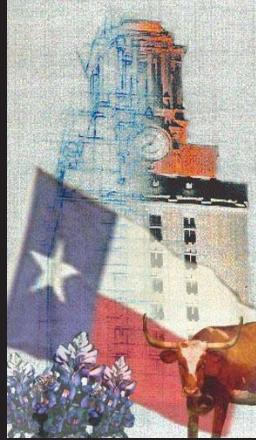
REFERENCES

- Marr, W.A. (2006) "Geotechnical Engineering and Judgment in the Information Age," Keynote lecture. *ASCE GSP GeoCongress-2006*, Atlanta, GA.
- Peck, R.B. (1969) "Advantages and Limitations of the Observational Method In Applied Soil Mechanics," *Geotechnique*, June, pp. 173-187.

Seismic Measurements and Geotechnical Engineering

The 2011 Karl Terzaghi Lecture
By Dr. Kenneth Stokoe

Seismic Measurements and Geotechnical Engineering



Prof. Kenneth H. Stokoe, II
Jennie C. and Milton T.
Graves Chair

Civil, Architectural and
Environmental Engrg. Dept.
University of Texas at Austin

47th Terzaghi Lecture
Texas A& M University
College Station, Texas
November 30, 2012

Focus

Characterizing the linear and nonlinear
stiffnesses of soil and rock in the field

Outline

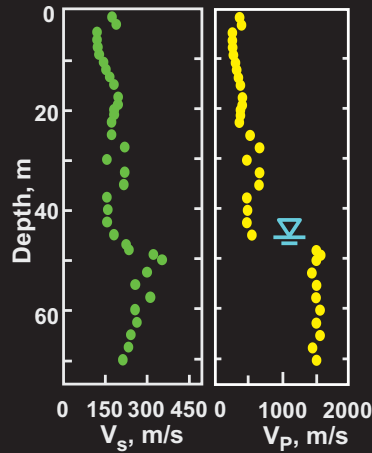
1. Present a Brief Background
2. Discuss State of Practice
3. Show Applications
4. Discuss Next-Generation Test
Methods and Future Directions
5. Concluding Remarks

1. Brief Background: **Seismic Measurements**

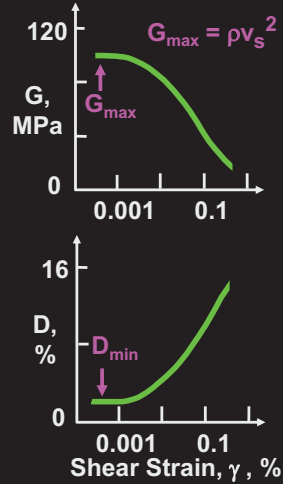
- Imaging with seismic (stress) waves
- Subset of geophysical measurements
- Emphasize field measurements
 - **traditional and advanced methods**
 - **perform at existing field conditions**
 - **link field conditions to lab tests**
- Laboratory testing
 - **permits parametric studies**
- Overview surface-wave measurements
 - **robust nonintrusive tests**

1a. Traditional Roles: Field and Laboratory Seismic (Stress Wave) Measurements

1. Soil Profile

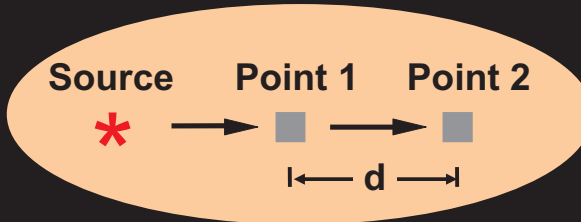


3. Lab: Linear and Nonlinear G and D



1b. Field: Seismic Measurements

Objective: **measure time, t, for a known stress wave to propagate a known distance, d ... then velocity = d/t**



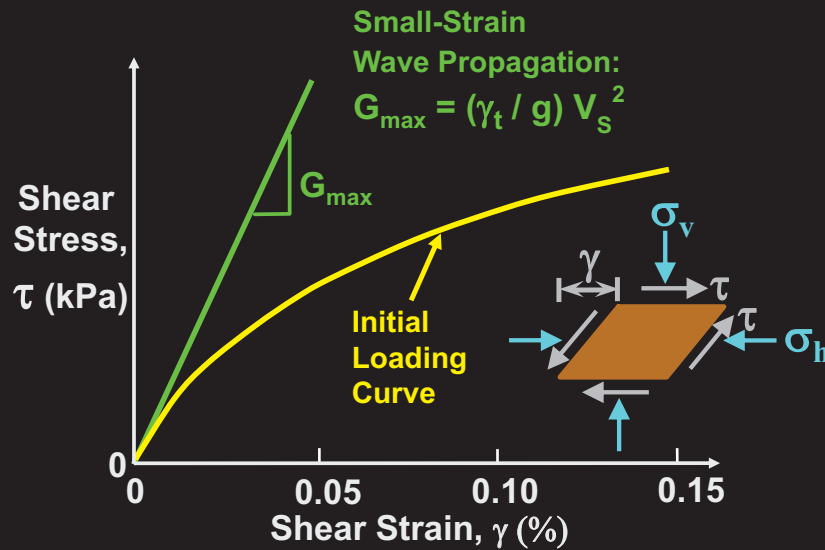
Key characteristic: **small-strain (linear) measurements**

Key points: (1) "good" seismic source, (2) receivers properly oriented, and (3) proper analysis procedure

Field Measurements with Compression (P) and Shear (S) Waves

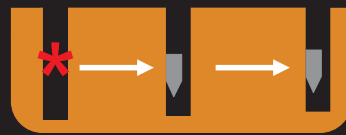
Wave Type	Particle Motion	Distortion	Wave Velocity	Small-Strain Modulus
P			V_p	$M_{max} = \frac{\gamma_t}{g} V_p^2$
S			V_s	$G_{max} = \frac{\gamma_t}{g} V_s^2$

Small-Strain Seismic Measurements

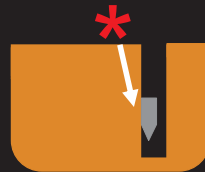


Traditional "Geotechnical" Field Seismic Methods (1970s)

1. Crosshole Test



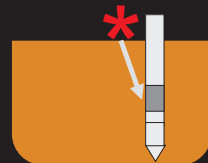
2. Downhole Test



Direct P and S Waves

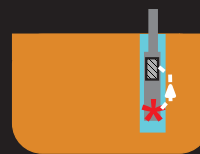
Advanced Field Methods (1980s & 90s)

1. Seismic Cone Penetrometer (SCPT)



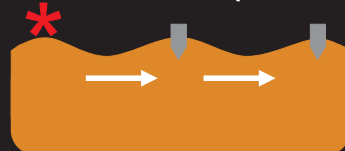
Direct S Waves

2. P-S Suspension Logger



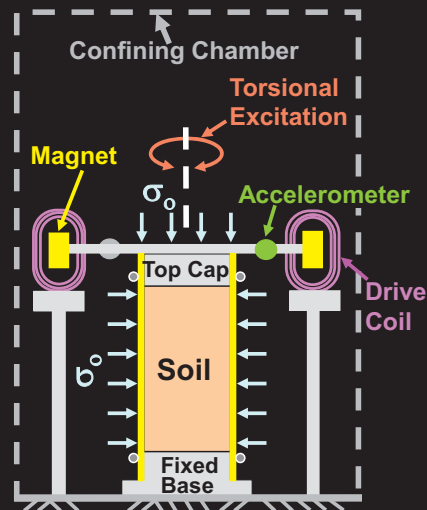
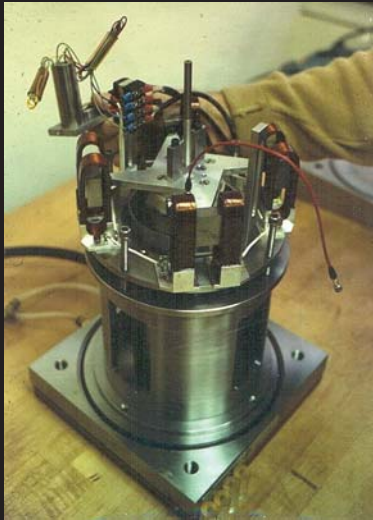
Direct P and S Waves

3. Surface Wave (SASW) Test



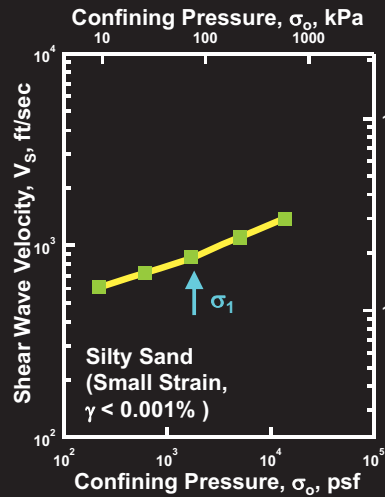
Measure Rayleigh (R) Waves

1c. Laboratory: Combined Resonant Column and Torsional Shear (RCTS) Device

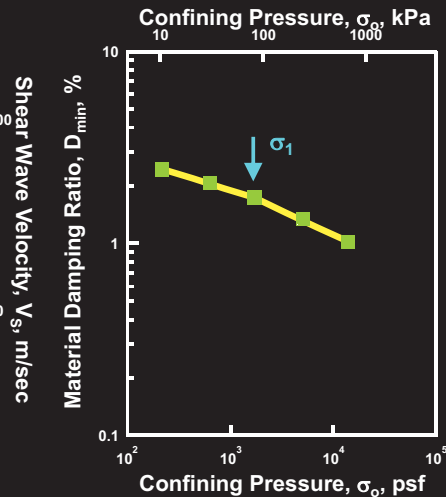


Laboratory Parametric Studies

a. $\log V_s - \log \sigma_0$

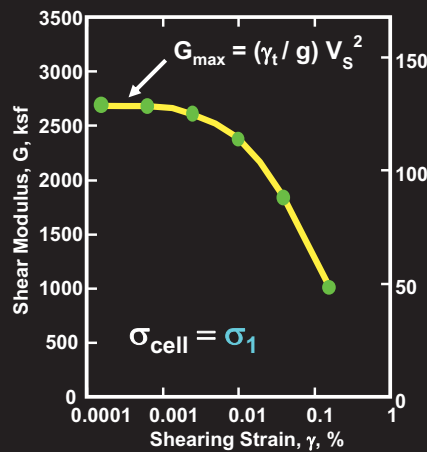


b. $\log D_{min} - \log \sigma_0$

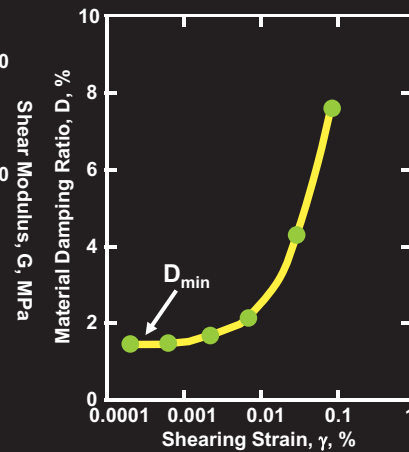


Laboratory Parametric Studies

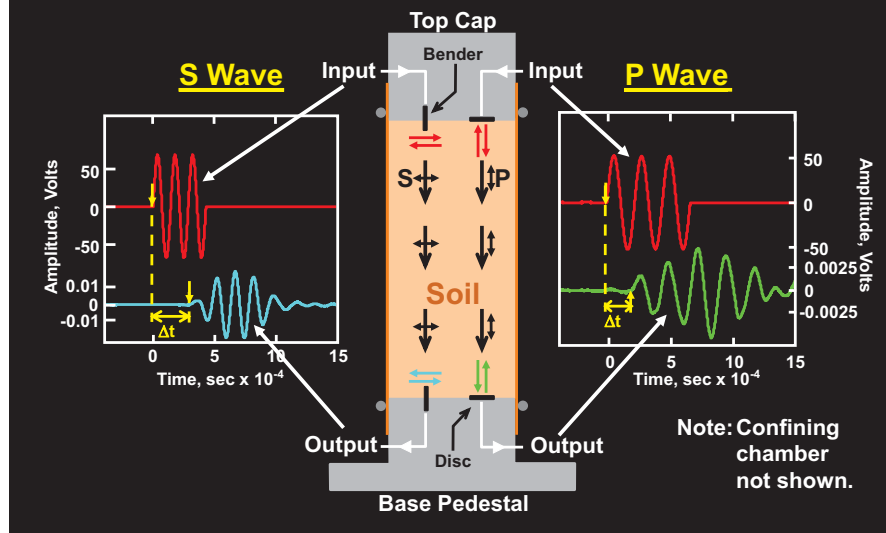
a. $G - \log \gamma$



b. $D - \log \gamma$

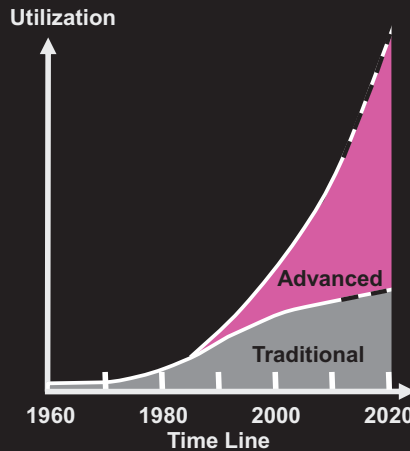


Small-Strain V_p and V_s Measurements: Piezoelectric Transducers

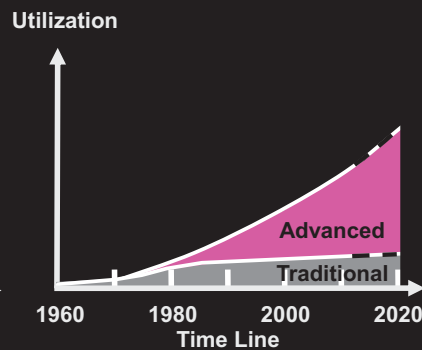


Integration of Seismic Measurements into Geotechnical Engineering

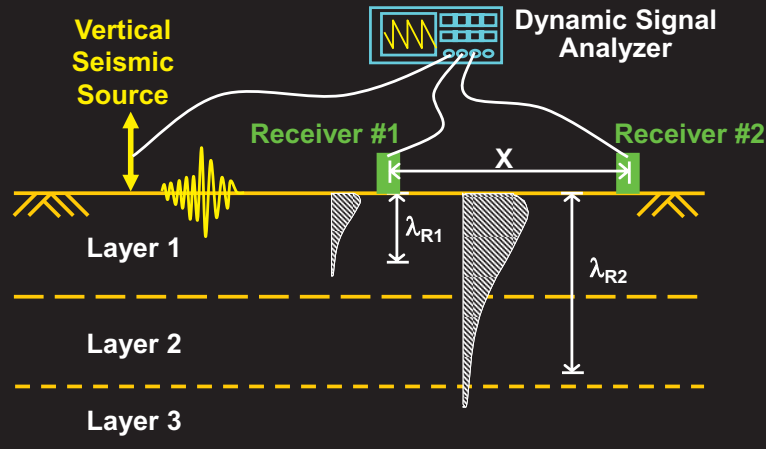
a. Field Testing



b. Laboratory Testing

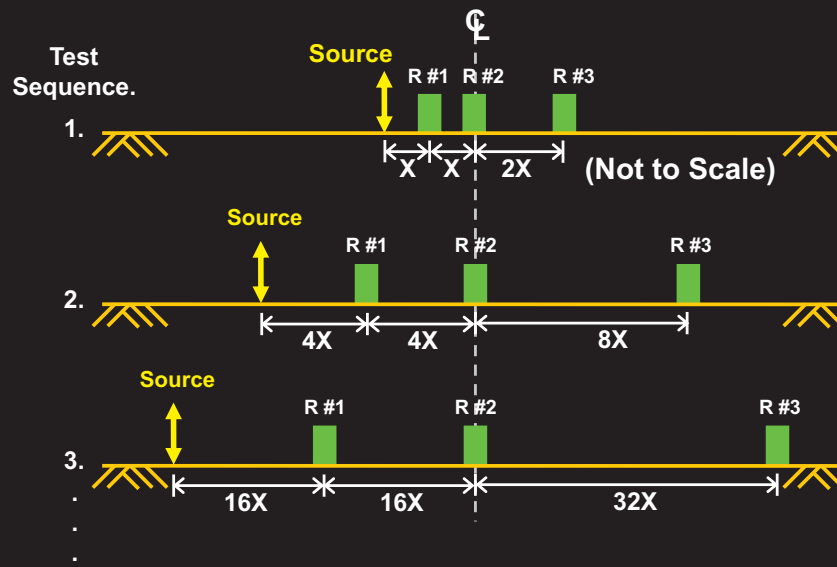


1d. Overview of SASW*: Generalized Field Arrangement and Sampling

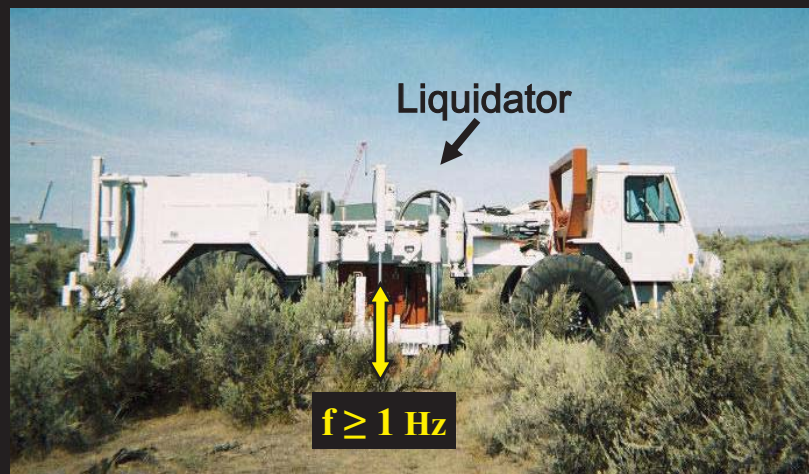


* SASW = Spectral Analysis of Surface Waves

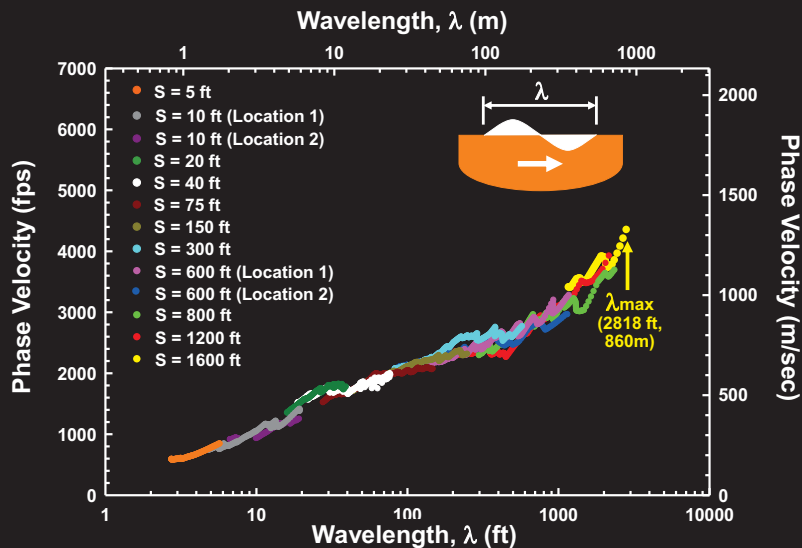
Multiple Source-Receiver Positions



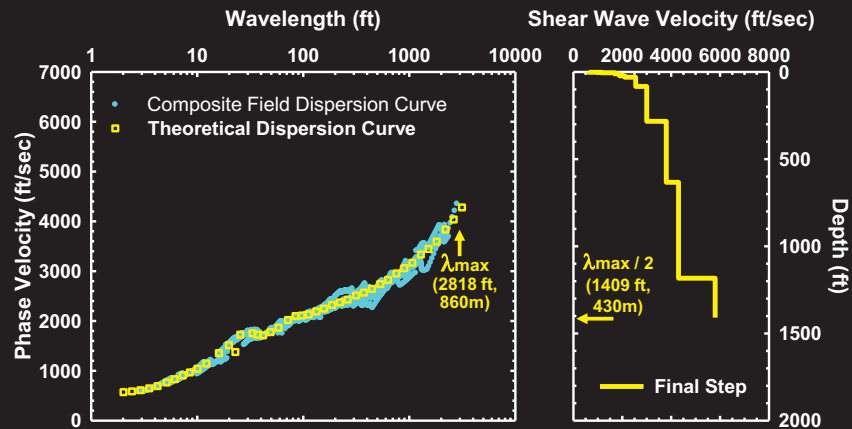
Liquidator Used as SASW Source



Composite Field Dispersion Curve Generated from All Receiver Spacings



Best-Match Theoretical Dispersion Curve (Final Step in Forward Modeling)



2. State of Practice: Field Seismic Testing

Seismic method or combination of methods depends upon:

- critical level of facilities
- geologic profile
 - materials (soft soil, alluvium, etc)
 - spatial variability
 - depth of critical layer(s)
- overall profiling depth
- area of investigation
- sampling volume

Field Seismic Testing

Depth of Profiling (d)

- shallow, $d < 250$ ft (75 m)
- intermediate, $250 \text{ ft} \leq d \leq 750$ ft
- deep, $d > 750$ ft (225 m)

Shallow Seismic Investigations

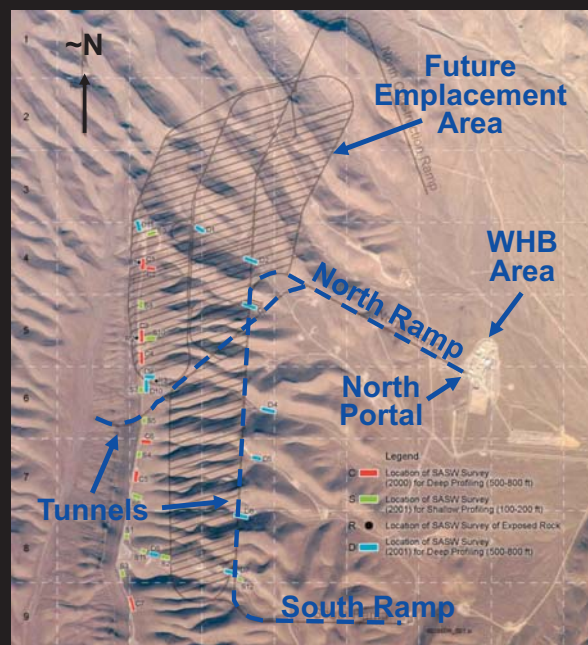
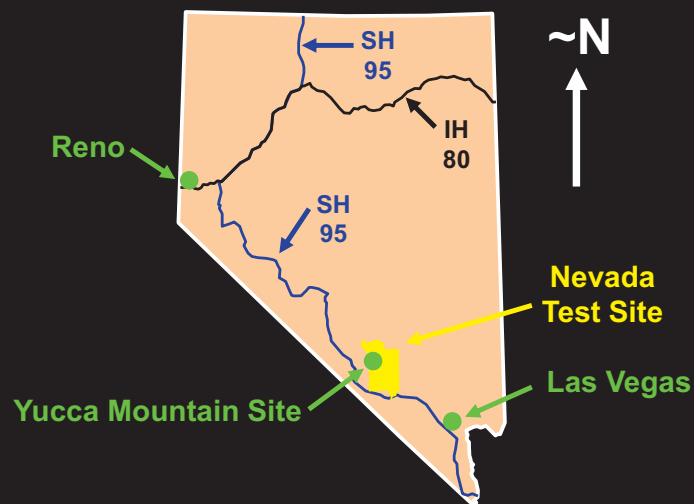
- state of practice ranges (very good \rightarrow poor)
- many seismic methods used
- number of practitioners is growing

Comparison of Field Seismic Methods: Shallow ($d < 75$ m) Field Investigations

1. Waste Handling Building (WHB) Area at Yucca Mountain, Nevada

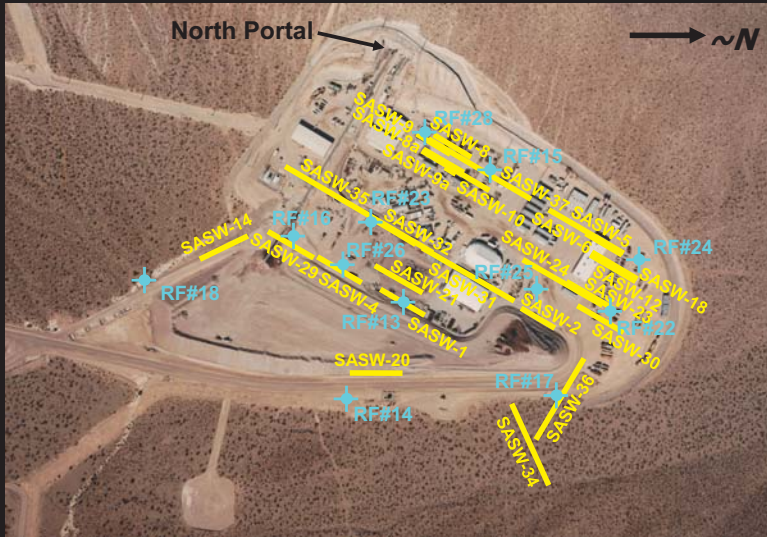
- three seismic methods (blind comparisons)
- plan dimensions of area: 300 m by 400 m
- alluvium over faulted tuffs
- compare statistical analysis of profiles

General Location of Yucca Mountain Site, Nevada

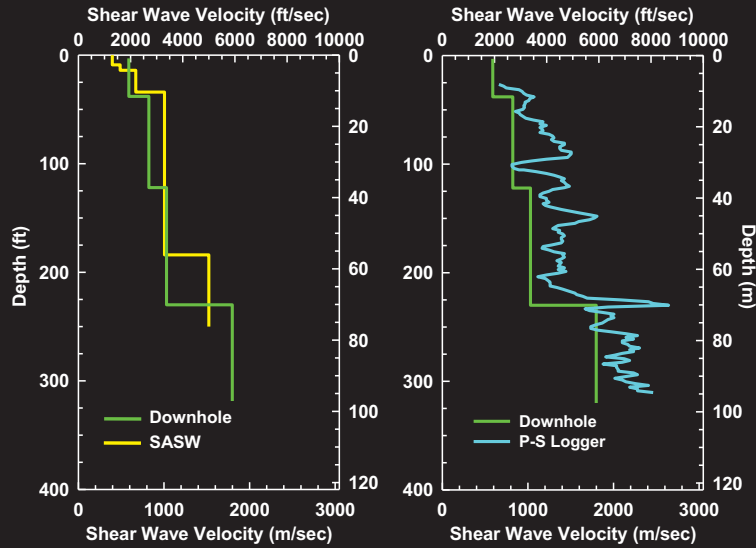


Seismic Testing at Yucca Mountain Site

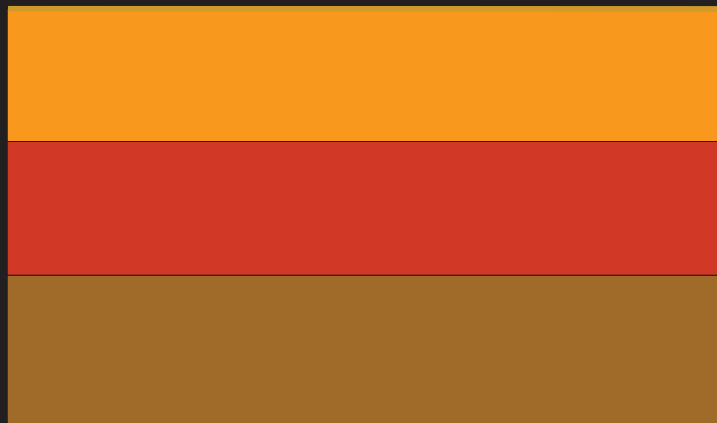
Locations of 12 Common (Boreholes) Sites and Nearby SASW Test Arrays at WHB Area



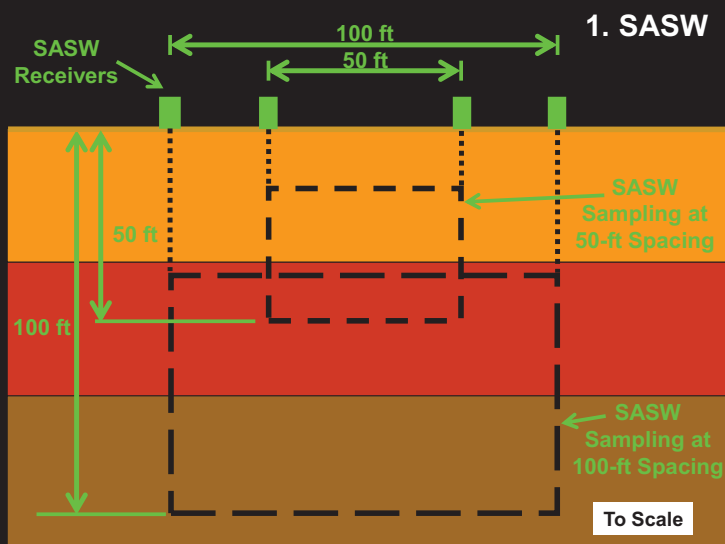
Comparison of Downhole, P-S Logger and SASW V_s Profiles at RF #15 in WHB Area



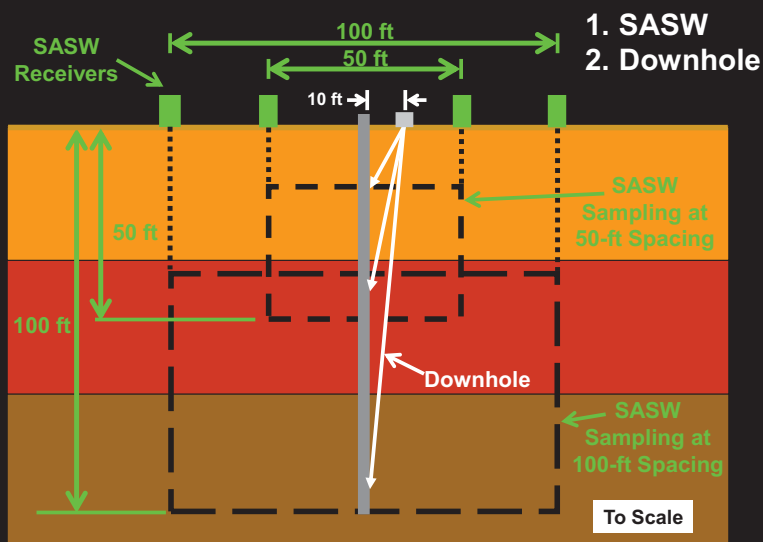
Different Seismic Methods Sample Different Amounts of Material



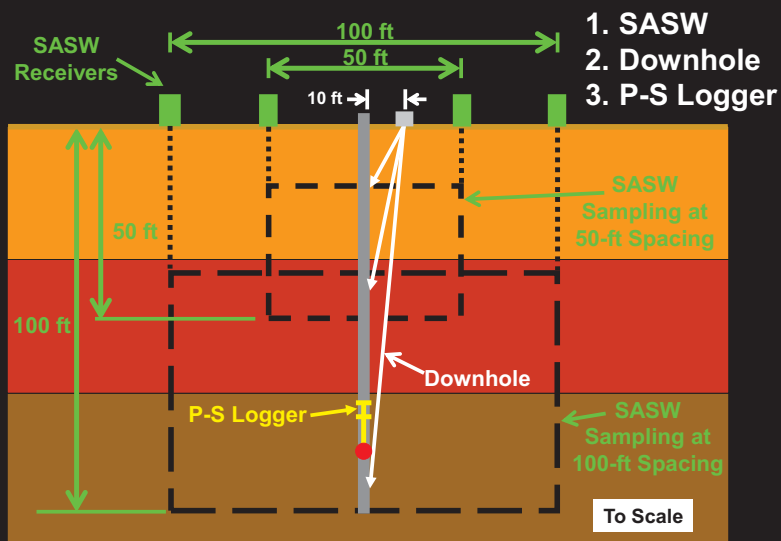
Different Seismic Methods Sample Different Amounts of Material



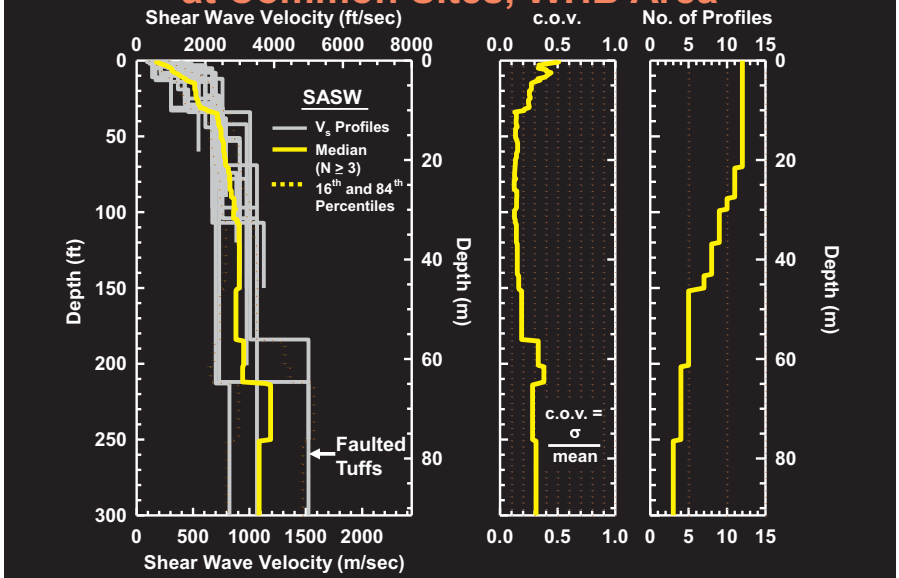
Different Seismic Methods Sample Different Amounts of Material



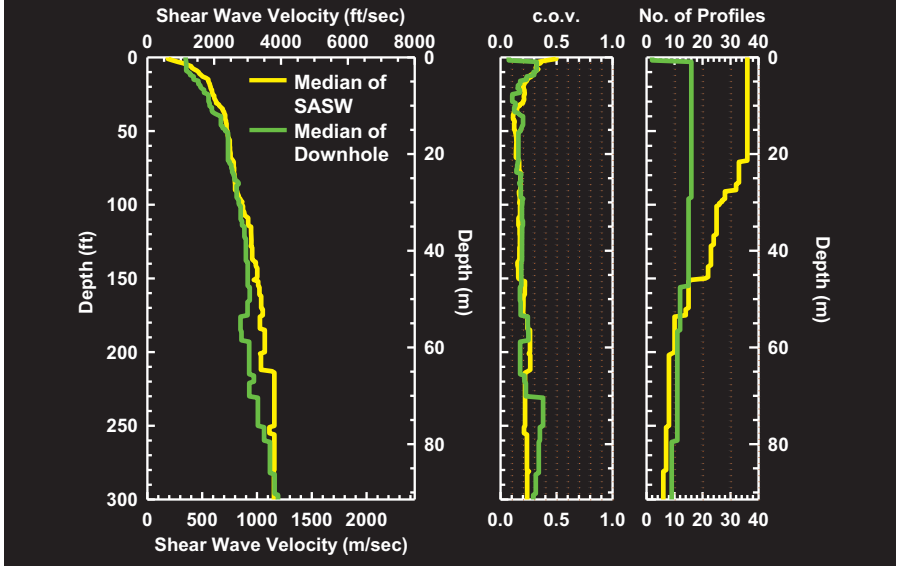
Different Seismic Methods Sample Different Amounts of Material



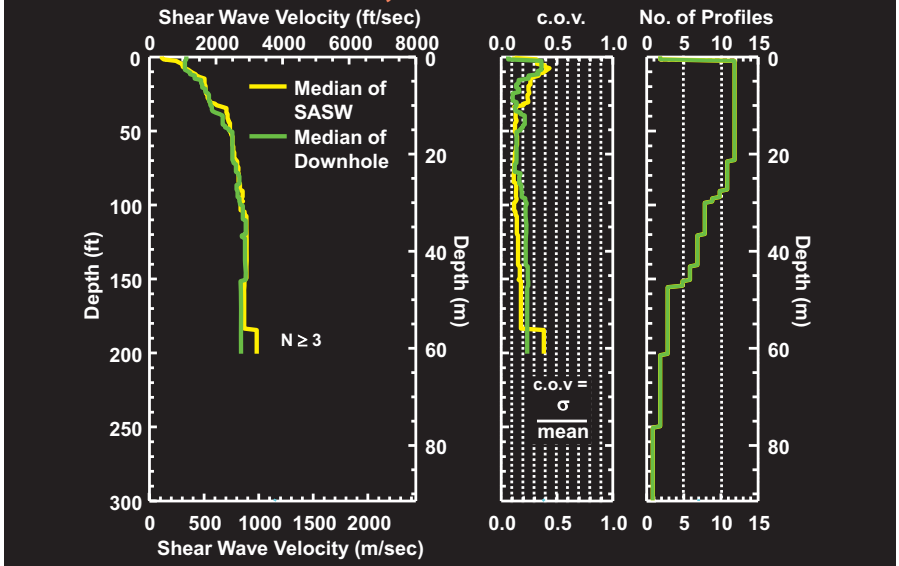
Statistical Analysis of 12 V_s Profiles at Common Sites, WHB Area



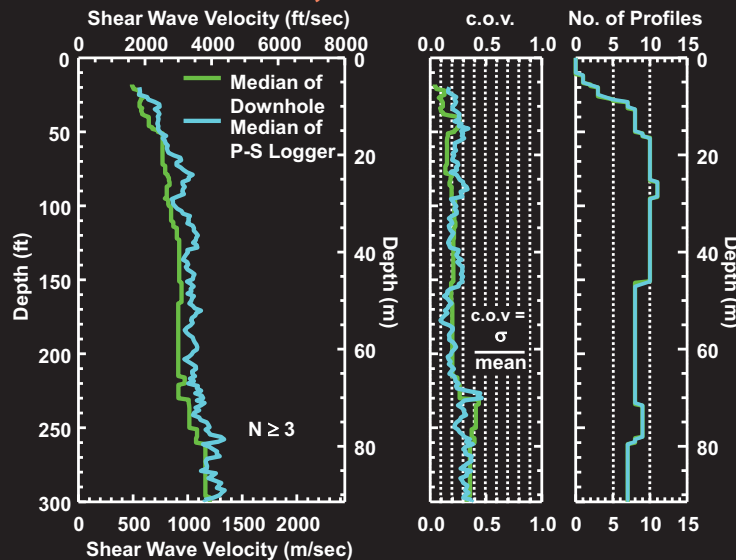
“Apples-to-Oranges” Comparison WHB Area, Yucca Mountain



“Red-Apples-to-Red-Apples” Comparison WHB Area, Yucca Mountain



“Red-Apples-to-Red-Apples” Comparison WHB Area, Yucca Mountain



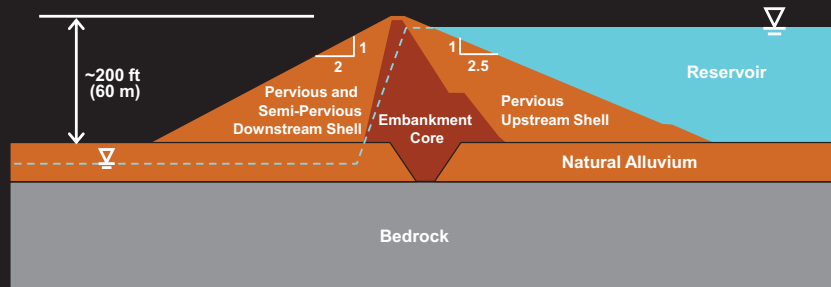
Parts 1 and 2: Conclusions

1. Many seismic methods are available; accurate results if properly performed by knowledgeable practitioners.
2. Good agreement is found between median V_s profiles for common-site-and-depth comparisons (“red apples to red apples”).
3. Differences between median V_s profiles are mainly due to sampling volumes and geology.
4. For exploration areas with common parent material (covering small to large areas), c.o.v.s:
 - range from 0.10 to 0.20, with 0.15 representing a reasonable average value, and
 - increase near the surface (top 3 to 6m).

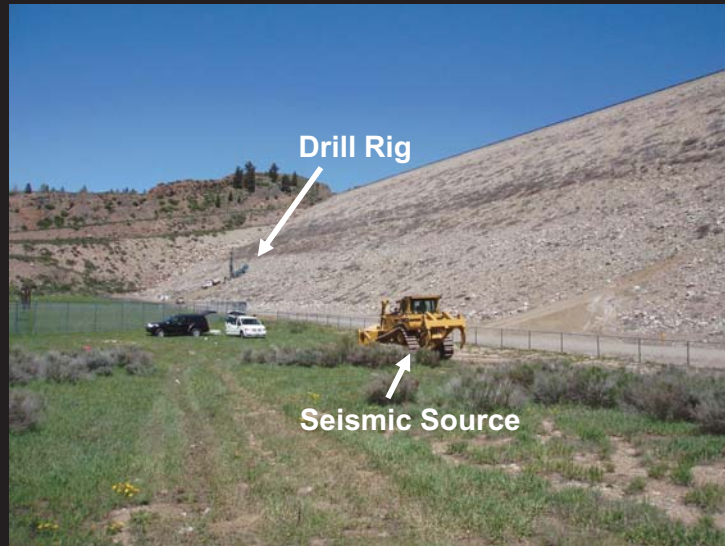
3. Applications: Traditional and Advanced Field Seismic Methods

- Site Characterization
 - layering, variability, soft zones, etc.
- Evaluate Stiffness Properties
 - static and dynamic analyses
 - material type, “quality”, cementation, etc.
- Monitoring Processes
 - compaction, consolidation, grouting, etc.
- Liquefaction Evaluations
- Form Link Between Field and Lab
- Integrity Testing of Foundations

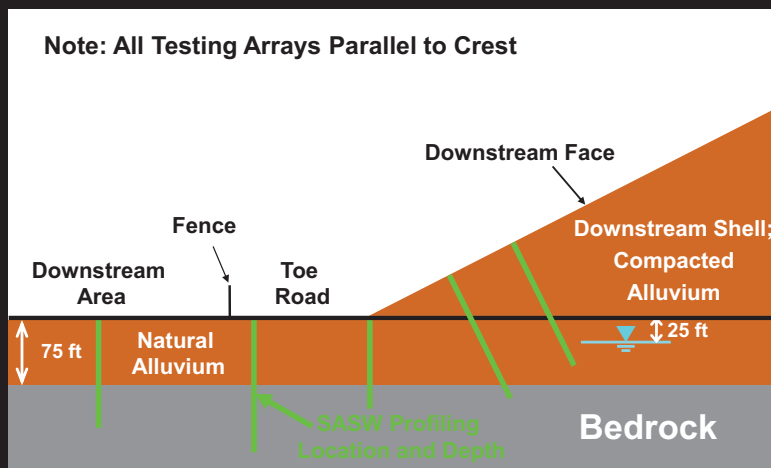
3a. Embankment Dam Investigation: "Quality" of Alluvium in and beneath Dam



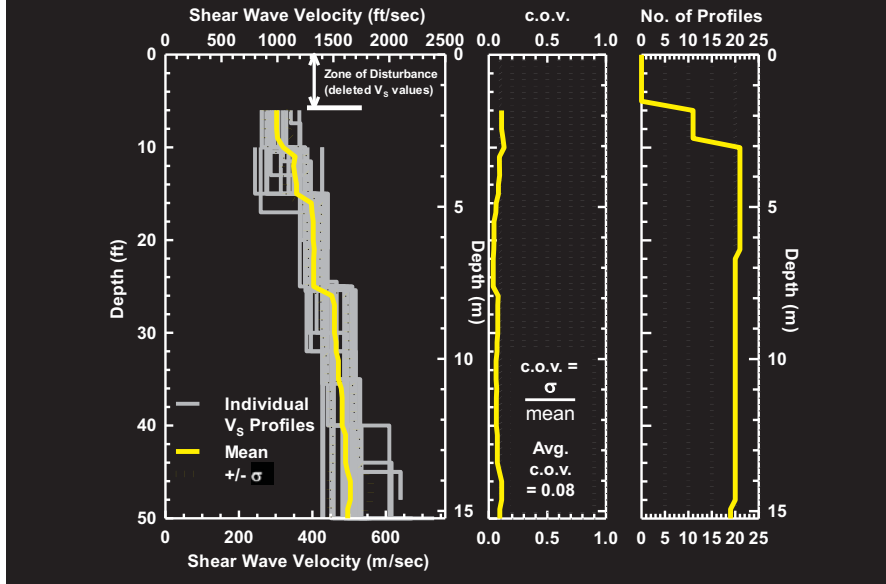
Dam Site



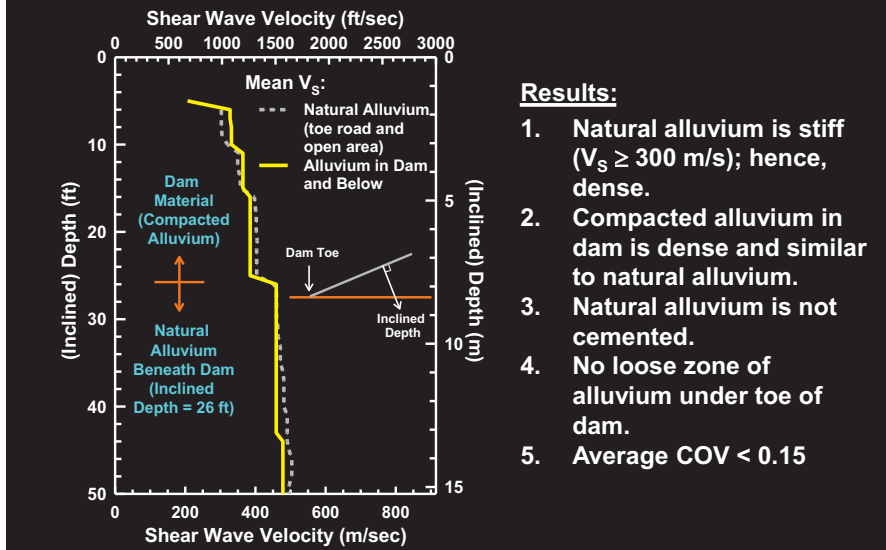
SASW Test Locations - Downstream Face and Downstream Area



Statistical Analysis of Natural Alluvium



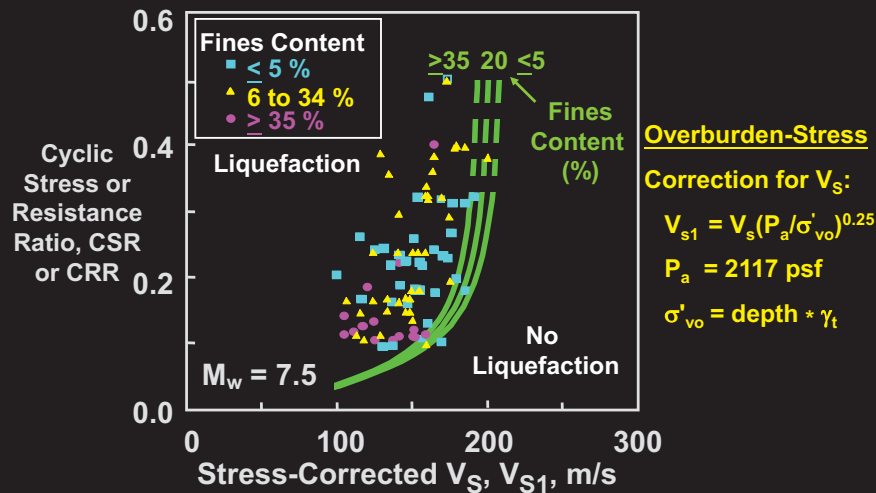
Comparison of Mean V_s Profiles - Natural Alluvium and Compacted Alluvium in Downstream Shell



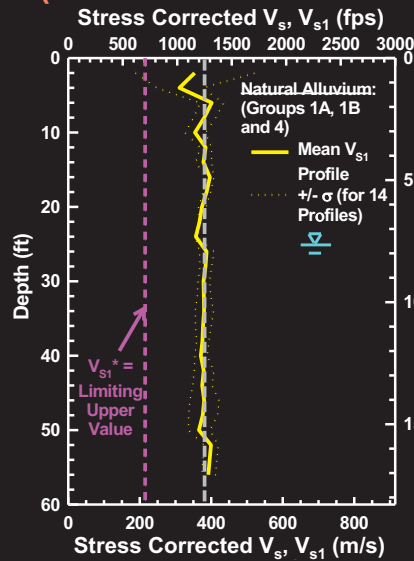
Results:

1. Natural alluvium is stiff ($V_s \geq 300$ m/s); hence, dense.
2. Compacted alluvium in dam is dense and similar to natural alluvium.
3. Natural alluvium is not cemented.
4. No loose zone of alluvium under toe of dam.
5. Average COV < 0.15

Liquefaction Resistance from V_s (Andrus and Stokoe, 2000)



Overburden - Stress Corrected V_{s1} Profile (Natural Alluvium - Downstream Area)



Overburden-Stress

Correction for V_s :

$$V_{s1} = V_s (P_a / \sigma'_{vo})^{0.32}$$

$$P_a = 2117 \text{ psf}$$

$$\sigma'_{vo} = \text{depth} * \gamma_t$$

Average V_{s1}

Assumed $\gamma_t \sim 130 \text{ pcf}$

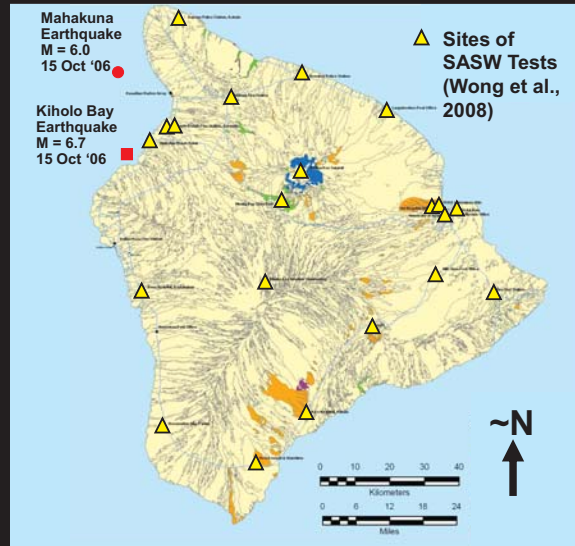
Avg. $V_{s1} = 1250 \text{ fps}$

(380 m/s)

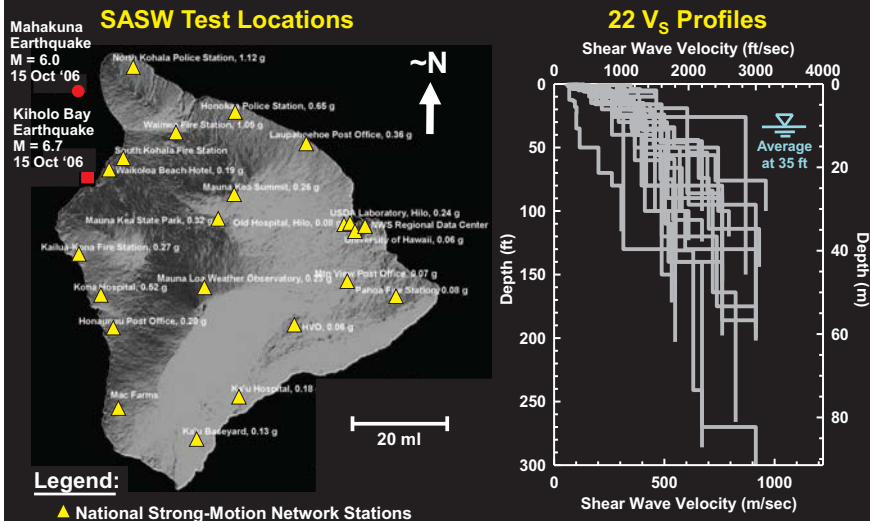
Note:

1. V_{s1}^* equals limiting value for triggering of liquefaction in sand with fines < 5%, $M_w = 7.5$, and level ground conditions (Youd, Idriss et al., 2001)

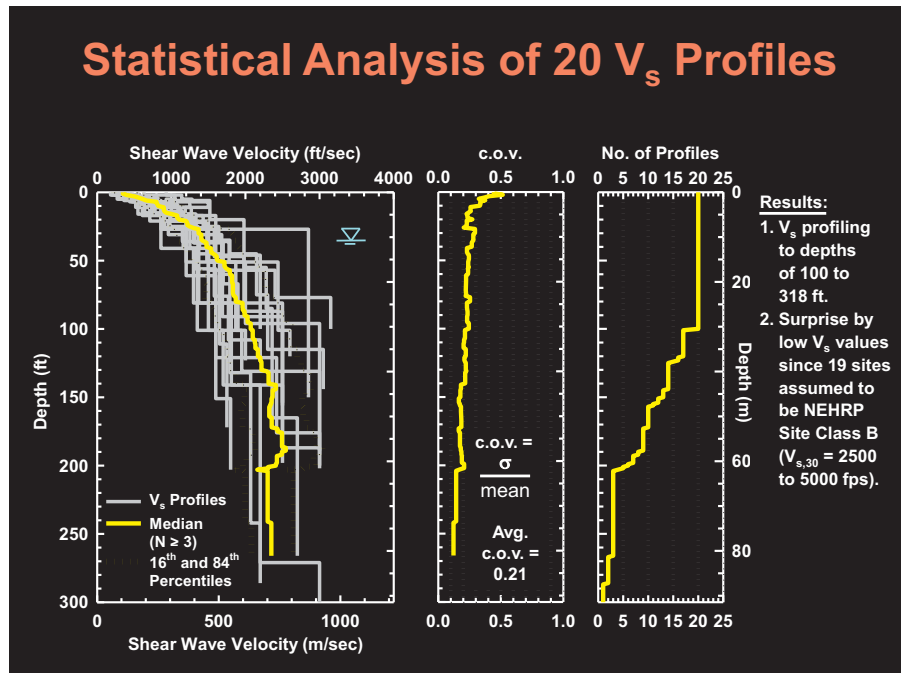
3b. V_s Profiling on Big Island, Hawaii: Map of Geologic Units and SASW Test Locations



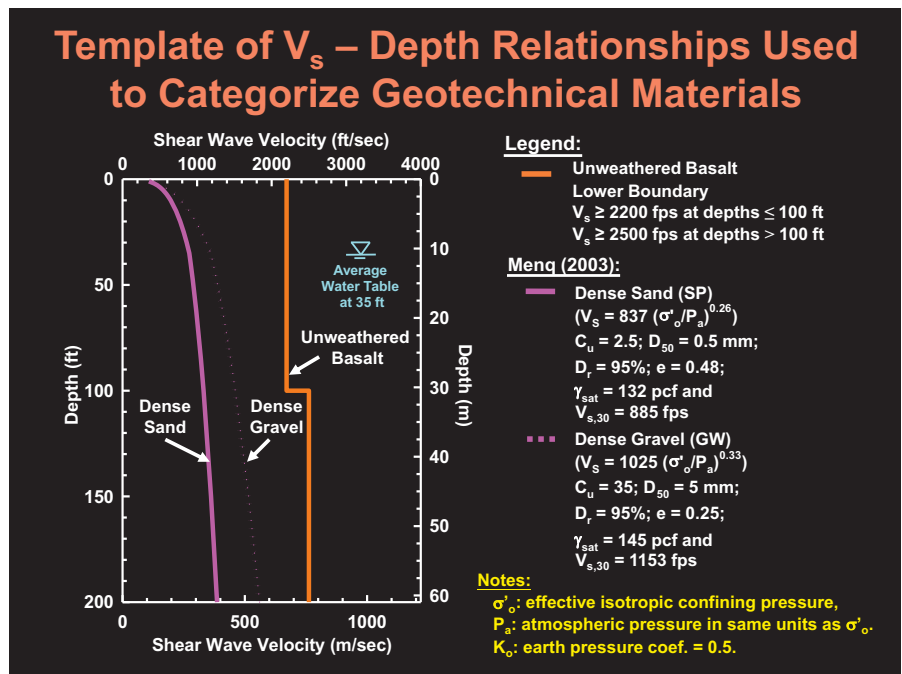
Test Locations and V_s Profiles



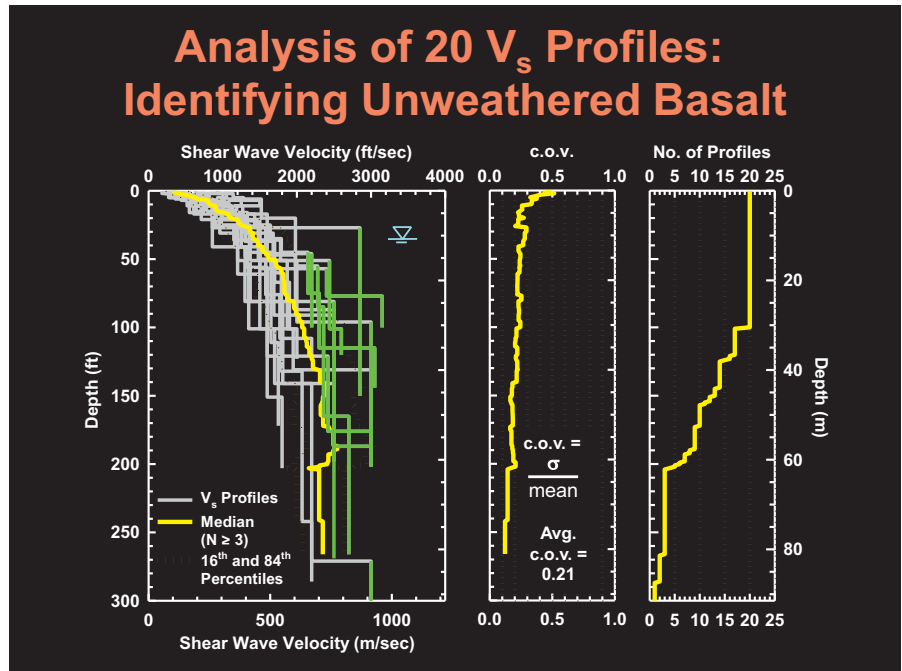
Statistical Analysis of 20 V_s Profiles



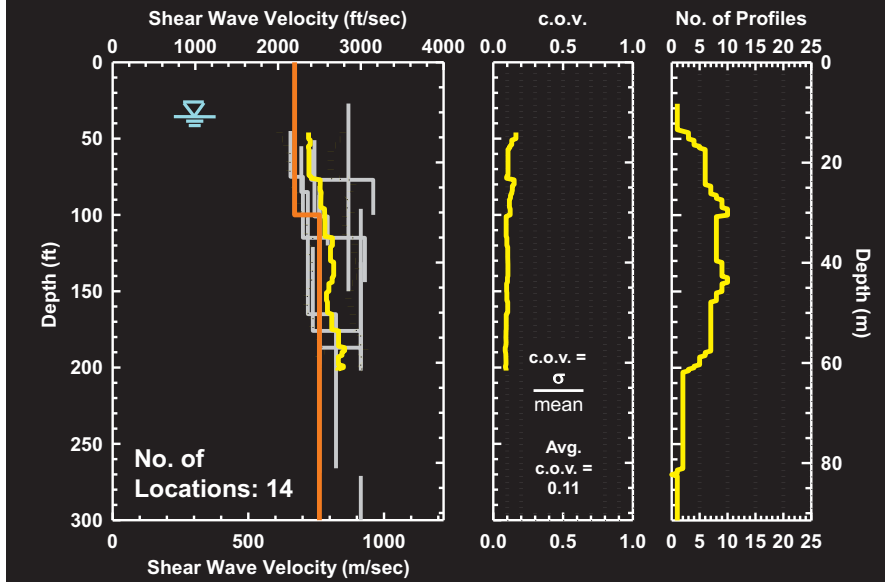
Template of V_s – Depth Relationships Used to Categorize Geotechnical Materials



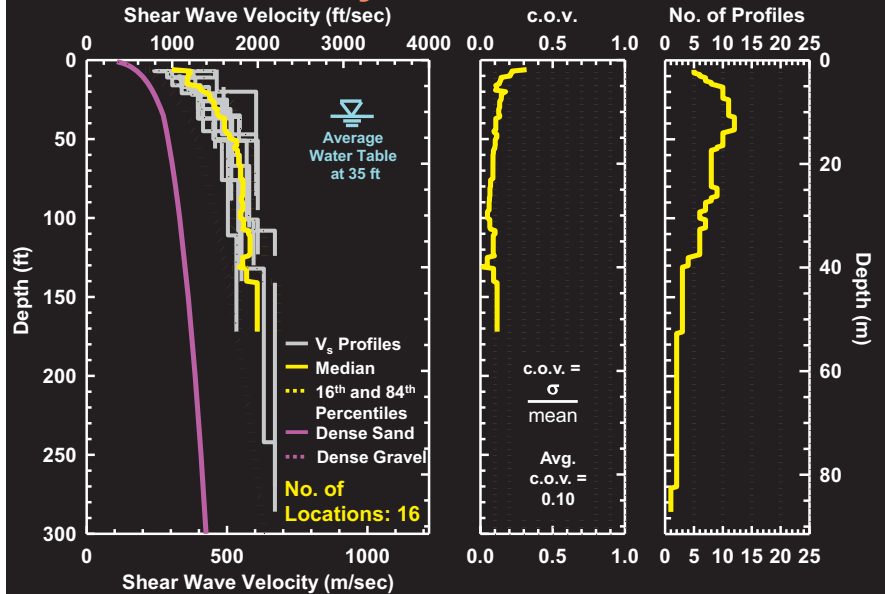
Analysis of 20 V_s Profiles: Identifying Unweathered Basalt



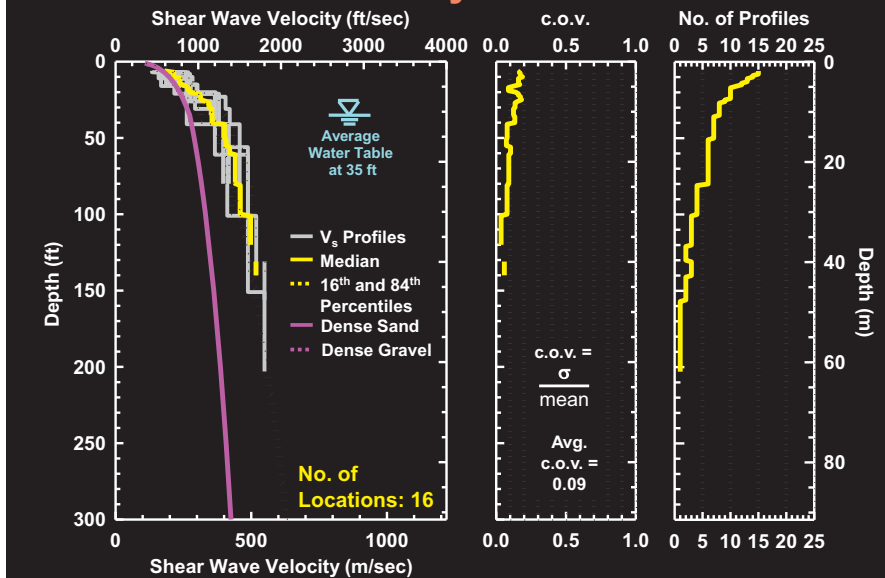
Statistical Analysis of Unweathered Basalt



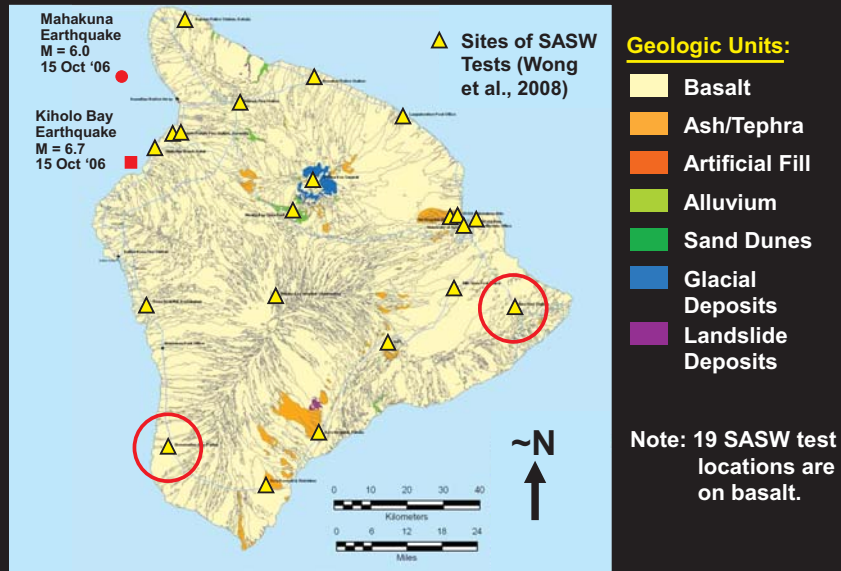
Statistical Analysis of Weathered Basalt



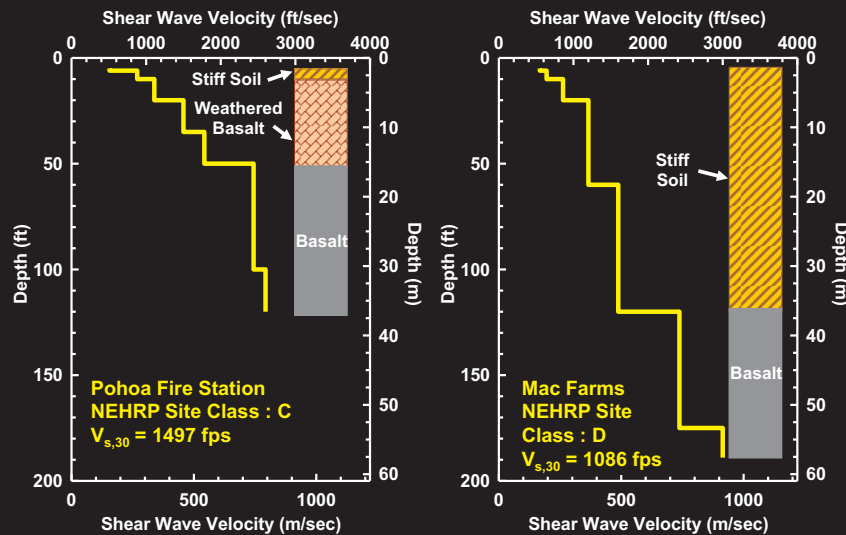
Statistical Analysis of Stiff Soil



Map of Geologic Units and SASW Test Locations



Example Interpreted Geotechnical Profiles



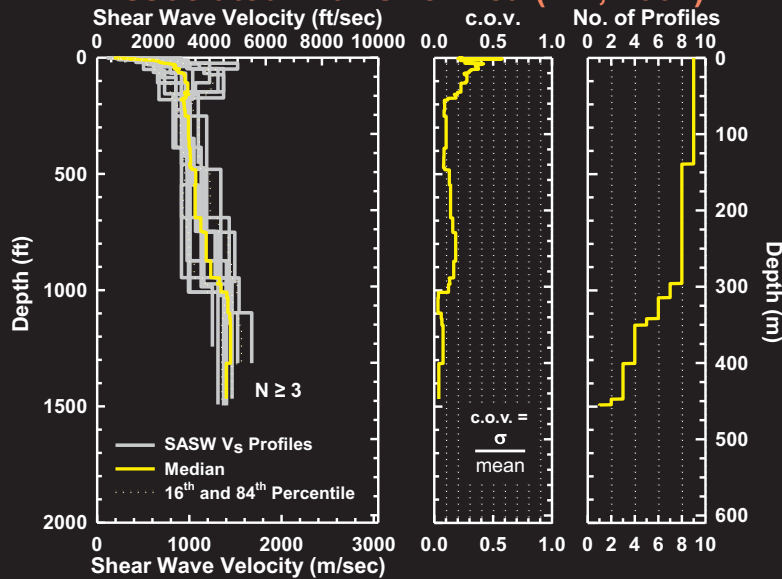
3c. Advanced Seismic Testing: Deep ($d > 225$ m) Field Investigations

1. Yucca Mountain, Nevada
 - SASW method
 - Plan dimensions of area: 3 km x 10 km
 - Profiling to 450 m
2. Hanford, Washington
 - Downhole method with T-Rex
 - 3 boreholes within about 700 m
 - Profiling to 420 m

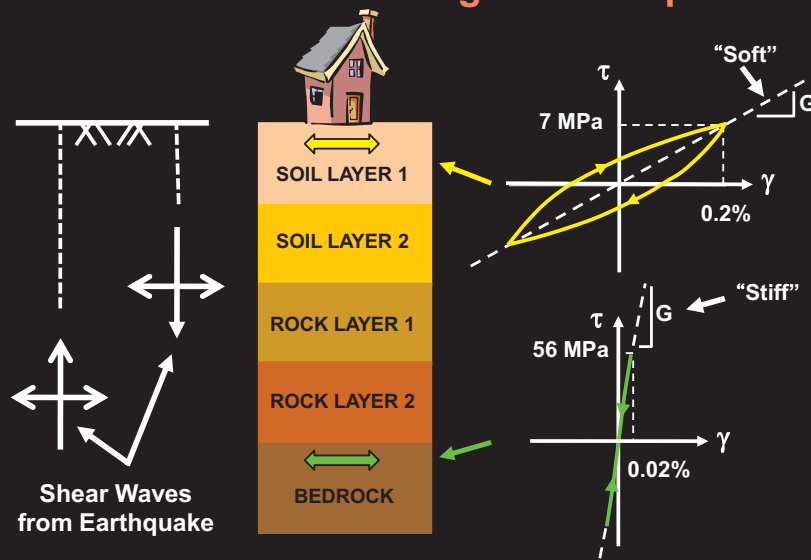
Recording Surface Waves up to 1000 m Long at Yucca Mountain



Statistical Analysis of Softer V_s Profiles Associated with One Area (Lin, 2007)

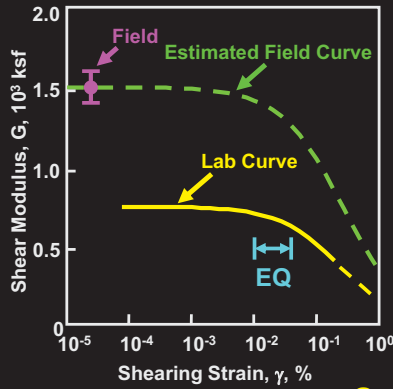


3d. Link Between Field and Lab: Predicting Ground Motions During an Earthquake



Estimating the Field G – log γ Relationship

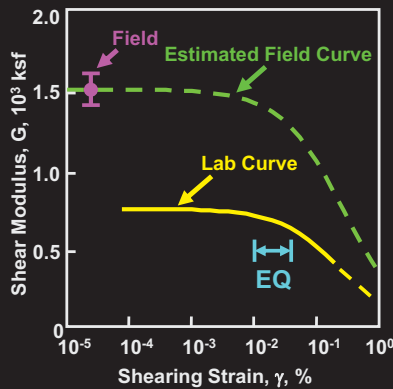
Typical Soil



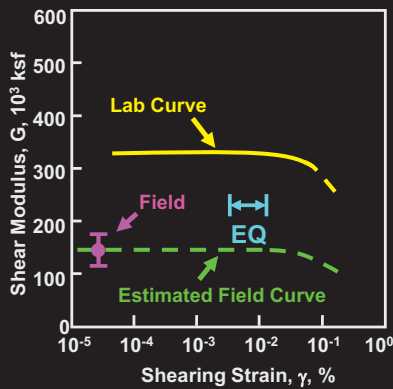
Note: $G_{\gamma \text{ field}} = \left(\frac{G_{\text{max field}}}{G_{\text{max lab}}} \right) G_{\gamma \text{ lab}}$

Estimating the Field G – log γ Relationship

Typical Soil



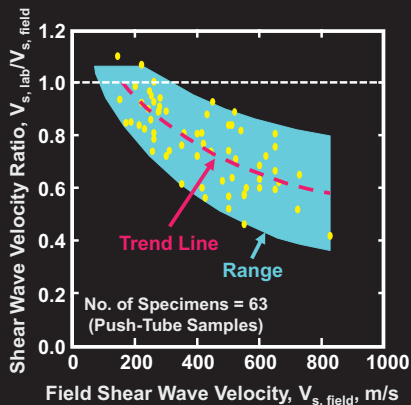
Typical Rock



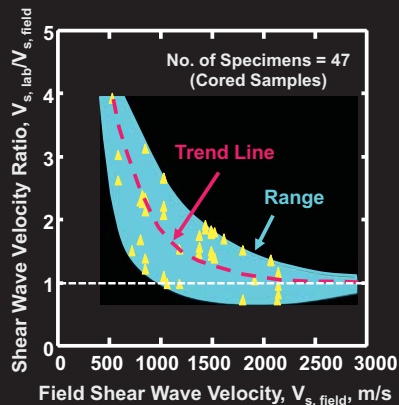
Note: $G_{\gamma \text{ field}} = \left(\frac{G_{\text{max field}}}{G_{\text{max lab}}} \right) G_{\gamma \text{ lab}}$

Relationship Between Field and Laboratory V_s Values

Typical Soil



Typical Rock

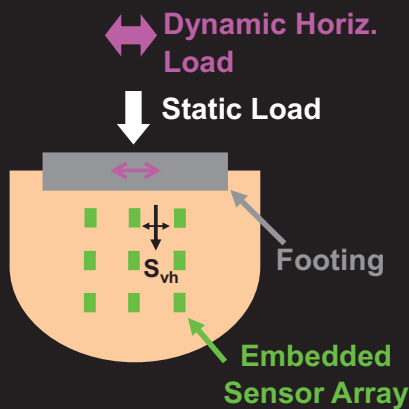


4. Next Generation Test Methods: Parametric Studies in the Field

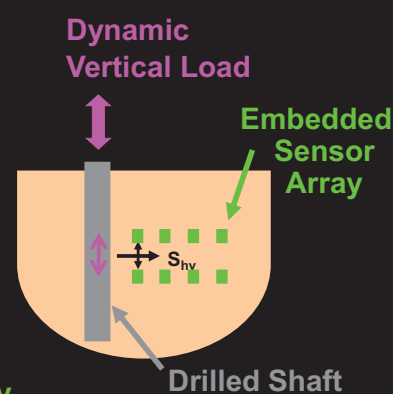
- Vary Stress State
 - $\log V_s - \log \sigma'_o$ and $\log V_p - \log \sigma'_o$
- Vary Strain Amplitude
 - $G - \log \gamma$ and $G/G_{max} - \log \gamma$
- Vary Strain Amplitude and N
 - $\Delta u - \log \gamma$ at given numbers of cycles (liquefaction testing)

4a. Next Generation Testing: Nonlinear Shear Modulus Measurements

Surface Footing
(Park, 2010)



Deep Foundation
(Kurtulus, 2006)

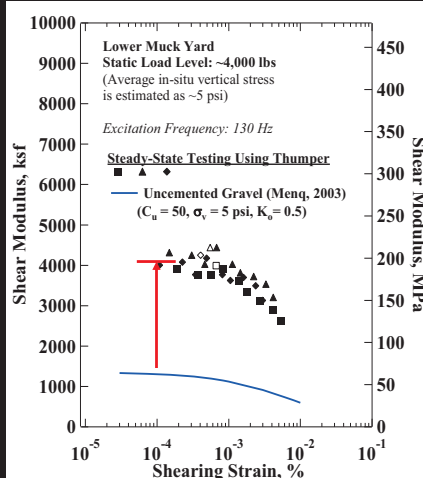


Linear and Nonlinear Steady-State Dynamic Tests: Yucca Mountain (Park, 2010)

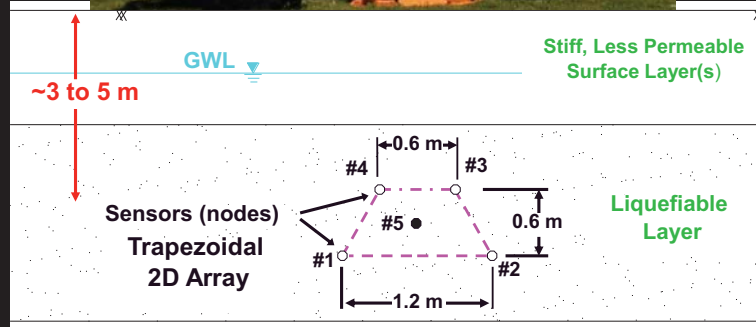
(a) Test –Set-up



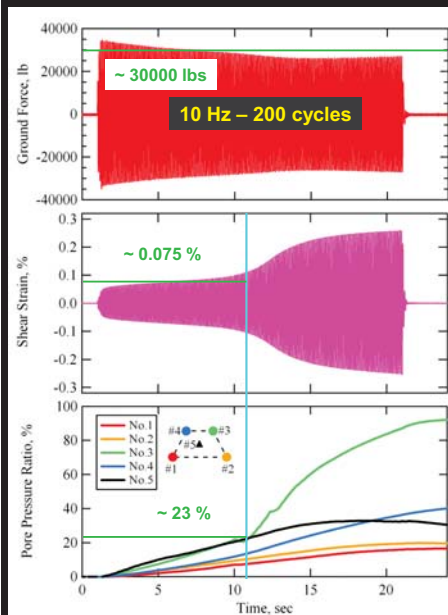
(b) $G - \log \gamma$



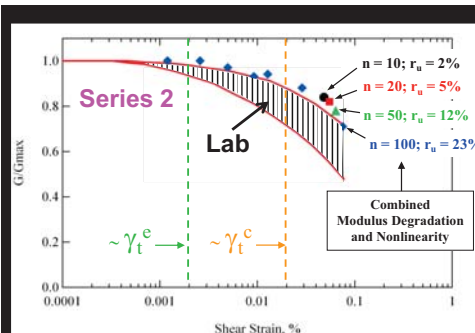
4b. Next Generation Testing: In-Situ Liquefaction Measurements (Cox, 2006)



Highest Amplitude

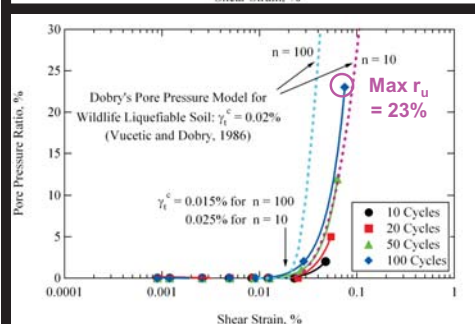


- Nonlinear shear strain time history
- Major nonlinear development coincides with sharp pressure increase at node #3
- Pore pressure ratios and shear moduli resulting from more than 100 cycles of loading are not included in the results

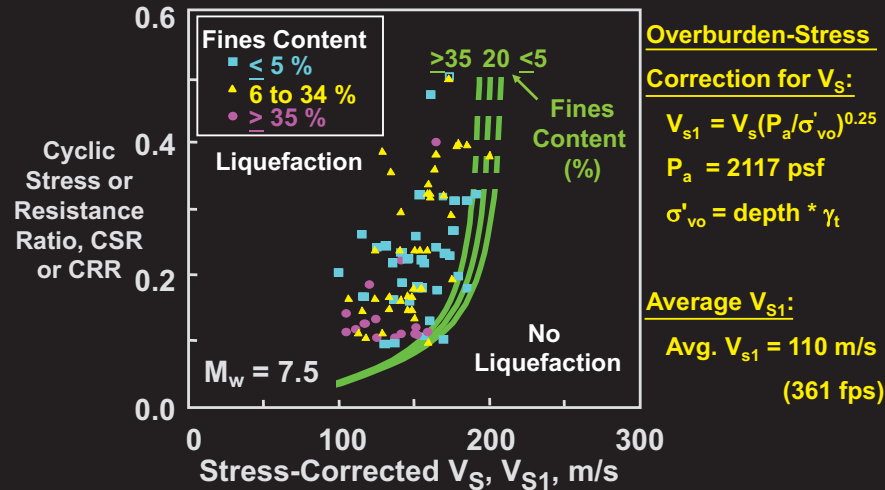


Results for Site C

- **Dobry's Pore Pressure Model** (Vucetic and Dobry, 1986)
 - Developed from cyclic laboratory tests on liquefiable soils from the Wildlife Site
 - Assumed cyclic threshold shear strain of 0.02%



Liquefaction Resistance from V_s (Andrus and Stokoe, 2000)



4. Next-Generation Test Methods and Future Directions (continued)

- Field Measurements
 - develop full-waveform analyses
 - develop techniques to identify soil types
 - perform suites of geophysical tests
 - combine R and Love wave measurements
 - investigate $M - \log \varepsilon$, $D - \log \gamma$, etc.
- Laboratory Measurements
 - develop capabilities to measure at $\gamma > 1\%$
 - develop nonlinear models of test specimens
 - develop capabilities to measure V_p , M , and D_p
 - improve automation
- Education

Concluding Remarks

- Seismic (stress wave) measurements play an important role in geotechnical engineering.
- This role will continue to grow in solving static and dynamic problems.
- The growth will involve four areas:
 1. education, 2. integration, 3. automation, and 4. innovation.

THANK YOU



Spencer J. Buchanan '26 Chair in Civil Engineering

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My matching gift company will contribute:	\$	Year 1	Year 2	Year 3	Year 4
Name of company:		\$	\$	\$	\$
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