UNDERSTANDING THE FULL POTENTIAL OF AN INTEGRATED GEOSCIENCE STUDY

Alan G Young PE, M ASCE
Started Pioneering Journey in 1946

Helped develop technical practices in:

- Offshore engineering geology
- Site investigation methods
- Laboratory testing methods
- Analytical foundation design methods
McClelland’s First Offshore Paper

Foundation Investigations for Offshore Structures in the Gulf of Mexico (McClelland, 1952)

Paper described Quaternary Geology of the Continental Shelf in the Gulf of Mexico and the physical properties of the Recent and Pleistocene soil.

Building Blocks of an Integrated Geoscience Study still Applicable Today
Lessons Learned from Bram McClelland

1. Employ an interdisciplinary team of experts to understand the regional processes and geology structure.

2. Use high-resolution geophysical equipment to thoroughly investigate seafloor and stratigraphic features over an extensive seafloor region.

3. Conduct the geotechnical investigation with equipment capable of performing *in situ* testing accompanied with high quality undisturbed samples.
Lessons Learned (cont.)

4. Rely heavily on the *in situ* testing data to interpret the undrained strength profile and, in particular, to identify the disturbance effects of sampling on laboratory test data.

5. Rely on experimental testing and case studies to calibrate the empirical foundation design methods.

6. Develop an integrated geologic geotechnical model to assess risks and define constraints to site development.
Phases of an Integrated Study
Objectives of an Integrated Geoscience Study

Provide a clear picture and understanding of:

1. Seafloor conditions
2. Shallow subsurface stratigraphy
3. Variability of soil conditions
4. Potential geo-constraints (geohazards), and
5. Impact of all these factors upon selection and placement of seafloor supported infrastructure.
Defining the 4D Geo-Site Model (aka Ground Model)
4D Geo-Site Model

Ordinate for x, y, and z Coordinates

Sea-Level

Horizon

Fault

Note: Model allows construction of seismic section, fence diagrams, bathymetric maps, and isopach/soil province maps.

Seafloor

Youngest Sediments

$\begin{align*}
  t \text{ (time and age)} & \quad \text{increases with depth} \\
  z \text{ (depth)} & \quad \text{increasing depth}
\end{align*}

Oldest Sediments

Note: GIS database stores all geophysical, geotechnical, and geologic data.

Note: Model allows construction of seismic section, fence diagrams, bathymetric maps, and isopach/soil province maps.
Components of 4D Geo-Site Model

- Physiographic and Geomorphic Conditions
- Structural Framework
- Stratigraphic Framework and Definition
- Geotechnical Stratigraphy and
- Geochronologic Sequence.
Regional Desktop Study

• Conducted first to understand regional geologic conditions and plan the scope of the geophysical program.

• Provides a framework for collecting other forms of *in situ* data and sediment samples, understanding environmental processes, and for achieving an optimal engineering design.
3D Enhanced Seafloor Rendering
Shell Auger Development
(Doyle et al., 1996)
Large Scale Slope Failure and Slumping
Possible Recent Debris Flows at Seabed
Buried Debris Flows
Multi-phase Complex Channeling
Unconformity (Horsnell et al., 2009)

Large Fault at Seabed
Small Mud diapir
Possible Pressure Ridges
Ring Faults around Caldera
Fan-shaped Mud Flow Deposits
Shelf Edge Slumps and Faults at Seabed
Recent Debris Flow at Seabed

Predominantly CLAYSTONES with occasional SANDSTONES, DOLOMITES and LIMESTONES
Predominantly CLAYS with occasional Sand stringers and Debris Flows
Unconformity

(Horsnell et al., 2009)
Seismic Profile-Salt/Fault Interaction
Sigsbee Escarpment

Seafloor

Planar Normal Fault

Keystone Fault Family

Rollover Faults

Sigsbee Escarpment

Abyssal Plain

Salt Fault Family

Ramps and Flats in Salt Base Reflect Trust Geometry

Trust Fault Family

V.E. = 2.5x

(Young and Kasch, 2011)
## Site Favorability Assessment Criteria

(Young and Kasch, 2011)

<table>
<thead>
<tr>
<th>Geologic Process or Condition (Geo-Constraint)</th>
<th>Seafloor Lineaments (Pipelines, mooring lines, etc.)</th>
<th>Shallow Foundation (Mudmats, suction piles, etc)</th>
<th>Deep Foundation (Driven piles, conductors, etc.)</th>
<th>Geophysical Data Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steep Slope Gradients</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>Multi-Beam Bathymetry</td>
</tr>
<tr>
<td>Slope Reversal (Irregular Seafloor Topography)</td>
<td>High</td>
<td>High</td>
<td>none</td>
<td>Multi-Beam Bathymetry</td>
</tr>
<tr>
<td>Fault Displacement/Offsets</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Side Scan Sonar &amp; Sub-bottom Profiler</td>
</tr>
<tr>
<td>Shallow/Deep-Seated Slope Instability</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Side Scan Sonar &amp; Sub-bottom Profiler</td>
</tr>
<tr>
<td>Debris/ Turbidity Flows</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Side Scan Sonar &amp; Sub-bottom Profiler</td>
</tr>
<tr>
<td>Spatial Soil Variability</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Side Scan Sonar &amp; Sub-bottom Profiler</td>
</tr>
<tr>
<td>Currents and Erosion</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Multi-Beam Bathymetry, Side Scan Sonar &amp; Sub-bottom Profiler</td>
</tr>
<tr>
<td>Gas/Fluid Expulsion Shallow Water Flow</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>3D Seismic &amp; 2D High Resolution</td>
</tr>
</tbody>
</table>
Integrated Geoscience Study Characterizes the Range of Geologic/Geotechnical Site Conditions

Study provides a reliable understanding of subsurface conditions important to achieve:

1. Realistic geohazard risk assessment
2. Reliable site selection of all facilities
3. Successful foundation design and installation
Critical Interactions of the Integrated Geoscience Team

• Integration is not a stand-alone task; rather, integration is a way of thinking and questioning adopted by all team members.

• Iterative process of analyzing the data sets to define the state of knowledge, uncertainty, consequences, and risks associated with the development of offshore facilities.

• Communication is especially important when more information is needed or when unfavorable conditions present obstacles.
Key Considerations of an Integrated Geoscience Study

- We must understand the natural processes that formed the soil deposits if we want to understand their inherent variability.

- Geology plays an essential and significant role and should guide all data acquisition activities.

- The credibility of the integrated assessment depends upon the resolution and quality of the geophysical and geotechnical data.
Importance of Stratigraphic Interpretation
Subsurface engineering is an art; soil mechanics is an engineering science. This distinction, often expressed but seldom fully appreciated, must be understood if we are to achieve progress and proficiency in both fields of endeavor.

Whether we realise it or not, every interpretation of the results of a test boring and every interpolation between two borings is an exercise in geology.
Role of Stratigraphy

• Stratigraphy defines the lateral and vertical relationship of various sediment units.

• Defines the temporal framework of the continuum of processes and features defined in space over time.

“Stratigraphy is the great unifying agency of geology that makes possible the synthesis of a unified geological science from its component parts.” – Weller 1947
Geophysical High-Resolution Data

a) High-Resolution 3D Data

b) Exploration 3D Data
Methods Used to Ground-Truth Stratigraphic Interpretation
Jumbo Piston Coring Operation

Courtesy of TDI-Brooks International
Photo of Split Jumbo Piston Core
PROD System
Seafloor Sampling and In Situ Testing

Courtesy of Mr. Alan Foley with the Benthic Group
Critical Sample Quality Factors

- Weather conditions that induce motion of the drill-string during drilling and sampling;
- Sampling procedure and size of sampling tube;
- Stress relief during sampling recovery;
- Sample extrusion procedure;
- Sample handling, packaging, transportation processes;
- Sample storage methods;
- Adherence to laboratory testing standards;
- Unusual geologic and physio-chemical properties of sediment; and
- Gas expansion.
Reliable versus Disturbed Data

Note: Red strength data are 10 percent less than Su line based on CPT.
“It is of vital importance that the quality of the samples is good from a geotechnical viewpoint, otherwise the results of laboratory tests on the samples will not be representative for the in situ conditions”.

Lunne (2012) – 4th James K Mitchell Lecture
Overview of TDI-Brooks CPT Stinger System

Data
Overlap
Area
JPC Short CPT Long CPT
Seafloor
Overlapping Data

18 m BML
CPT-cone (housing removed) at end of JPC barrel

JPC 20m
Dynamic (free fall) CPT Data
Static (2 cm/s) CPT Data

Overlapping Data
JPC Short CPT Long CPT
Seafloor
Data Overlap Area
18 m BML

Courtesy of TDI-Brooks International
“...in most parts of the world it is hardly possible to consider an offshore soil investigation without the use of the CPT, and the results are essential input in establishing the soil profile and soil parameters for foundation design.”
Advantages of Continuous Core and CPT Data Compared to Discontinuous Sampling

- Continuous core can be logged and compared to sub-bottom profiler data,
- Continuous CPT can be correlated with sub-bottom profiler data,
- Continuous core can be split and photographed to identify depositional changes,
- Effort and time for site investigations may be reduced, and
- Entire foundation design process is conducted with less uncertainty and fewer risks.
Extrapolation of Spatial Strength Properties
McClelland Paper - Types of Strength Profiles

UNDER-CONSOLIDATED
RAPID DEPOSITION

OVER-CONSOLIDATED
NORMALLY CONSOLIDATED

SLOW DEPOSITION

Depth, ft

0.63 kPa/m
Strength Profile

10 kPa

19 kPa

Depth, m

1.25 kPa/m
Strength Profile

1.25 kPa/m
Strength Profile

Preconsolidation Datum

Seafloor Depth, ft
Gulf of Mexico Continental Shelf Atlas

(Parker et al., 1979)
The effect of different loading mechanisms means...

“Consequently, there cannot be a unique undrained shear strength of a soil, and different values will be observed in different tests.”
Geology Defines Spatial Variability

Baecher and Christian (2003) indicate that measured soil properties are often treated as if they are independent samplings of a random variable. Offshore soils are frequently deposited in a uniform physical process over time, so their spatial variability is often not random. The uncertainty is frequently in the model or error in soil measurements and not in the soil deposit.
Interpretation of Undrained Shear Strength

- Traditional practice relies upon laboratory strength data instead of CPT data,
- Large scatter in laboratory data due to soil anisotropy, strain rate, stress history, and different loading mechanisms,
- CPT data is more consistent and representative measure of depositional nature of marine sediments and avoids other effects, and
- CPT is a great tool for obtaining continuous rapid and reliable soil profile.
\[ q_{net} = N_{kt} S_u \]
SHANSEP Method
Stress History and Normalized Soil Engineering Parameters

\[ S_u = \sigma'_v \left( \frac{s_{udSS}}{\sigma'_{vc}} \right)_{nc} OCR^m \]
SPW Method

c_u/c_{vc} = 0.294 \left( \sigma'_{vc} \right)^{-0.113}
R^2 = 0.65

(Quiros et al., 2000)
Comparison of CPT Data from Different PCPT Systems

(Caruthers et al., 2014)
Laboratory and In Situ Strength Data for Two Investigations
Data Comparison–Undrained Shear Strength

![Graph showing data comparison for undrained shear strength](image-url)
Mad Dog SPAR Mooring Spread with 11 Suction Piles

Cluster 1
Cluster 2
Cluster 3

GC782

4.8 km

CPT Borings
All the anchors were successfully installed to their target depths with appropriate sampling or extrapolation of data.

1 boring and CPT at each anchor location

Anchor locations projected onto AUV SBP
Uniform Soil Stratigraphy between Pile Clusters 1 and 3
Comparison of 7 Mad Dog Soundings
Radiocarbon Analysis for Atlantis
Reference Core CSS-1
Objectives of Age Dating

- Provides understanding of spatial and temporal distribution of sediment stratigraphic units,
- Correlates sediment properties and lithologies to regionally persistent seismic reflectors, and
- Constrains past geological events (timing and frequency).
A boring must be taken at the most heavily loaded anchor location and at anchor points approximately 120° and 240° around the anchor pattern from the boring, and as necessary to establish a suitable soil profile.
Panel of Geotechnical Engineer Experts

- Regulations are prescriptive in nature and do not take into consideration the site geology and the influence of site variability upon the required scope of the geotechnical investigation.

- Regulations should allow experienced engineers and geologists to serve their critical role in planning the scope of the site investigation.
Proper Reference Datum
Su = 13.1 kPa
Su = 16.0 to 21.0 kPa
(22 to 60% greater)

Su = 27.5 kPa
Su = 30.2 to 35.1 kPa
(10 to 28% greater)

CPT-6 and -9 will be same for all CPT's
adjusted to marker horizon

Current
Seafloor

Erosion

Depth Below Seafloor, m

Depth Referenced to Seafloor at CPT-6, m

Su, kPa

Marker Horizon
Benefits of Integrated Geoscience Approach

- Existing data is used to maximum extent possible
- Provides information for design at an early stage
- Limits amounts of additional geophysical/geotechnical data
- Decreases field acquisition time, thereby reducing field costs
Change Our Way of Thinking

- Geotechnical engineers often concentrate on defining engineering properties for a single site using widely scattered laboratory test data.

- Marine geologists focus on mapping “geohazards” and identifying seafloor constraints.

- When we change our way of collectively studying the seafloor; then an integrated study will reduce uncertainty in the overall design process.
“If you change the way you look at things, the things you look at change.”
Anonymous

“We must integrate the science of geology and geotechnics to master the art of seafloor engineering.”
Young
Conclusions:

- Employ an interdisciplinary team of experts who understand the regional processes and geology structure.
- Use high-resolution geophysical data to develop 4D Geo-Site Model and reduce the scope of the geotechnical investigation.
- Perform age dating to constrain the timing of different depositional systems, establish sedimentation rates, and determine the timing and frequency of past geologic events.
- Conduct more CPT testing and less sampling and testing on samples in a soil boring.
Conclusions (cont.)

- Consider using $N_{kt}$ of 17.5 to correlate with Quiros/SHANSEP DSS data to interpret $Su$ in normally consolidated clays.

- The CPT, SHANSEP, and Quiros data should be used to select the design strength profile instead of relying upon widely scattered laboratory test data.

- Confirm regulations are not too prescriptive and allow experienced engineers and geologists to plan the scope of the site investigations.
Dedication and Acknowledgements

The paper is dedicated to Bram McClelland and Melinda Young – two special people that strongly influenced my life since 1971.

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