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Project Title

Improving Design and Construction of Transportation Infrastructure through Bedrock Characterization

University

University of Wyoming

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Research Needs

Tertiary bedrock formations are commonly encountered during the design and construction of transportation infrastructure in Wyoming. Examples include the White River, Wasatch, Fort Union, Green River, Wind River, and Arkaree Formations in their respective basins shown in Figure 1. The lithology of these formations consists of pooly consolidated claystone, siltstone, mudstone, sandstone, shale, and conglomerate. The engineering properties of these bedrocks are highly variable due to the geological processes to which they have been subjected including deposition, cementation, weathering and erosion. Furthermore, comprehensive experimental investigations on these bedrocks are rarely performed in the past due to the absence of advanced rock testing equipment, and hence their strength and deformation behaviors are not well understood. However, our transportation infrastructure, such as bridges, slopes and roadways, is either constructed on or associated with these bedrock formations in Wyoming.

Due to the commonly encountered yet poorly understood Tertiary Formation in Wyoming, it is indispensable to characterize the engineering properties of these bedrocks to improve the design and construction of our transportation infrastructure. Shear strength, elastic properties, failure parameters, stiffness, and bedrock quality description are some of the important properties required in many engineering applications. However, many of these properties are neither measured nor readily available from Wyoming Department of Transportation (WYDOT) database due to the absence of high-pressure load frame and servo-controlled system for routine rock testing. Not only the equipment is expensive, but also the operation of this high-pressure rock equipment is complex and should be conducted by trained personnel. Although correlations developed by researchers and published in literature (e.g., Bieniawski, 1978; Hoek and Brown, 1997) are applied to estimate some bedrock properties, these correlations were developed based on bedrocks that do not represent the formation conditions in Wyoming. Hence, the applicability of these correlations is questionable, typical rock mass strength and deformation properties recommended in AASHTO (2017) have yet been verified, and the reliability of these correlations has yet been quantified due to absence of measured properties of Wyoming bedrocks.

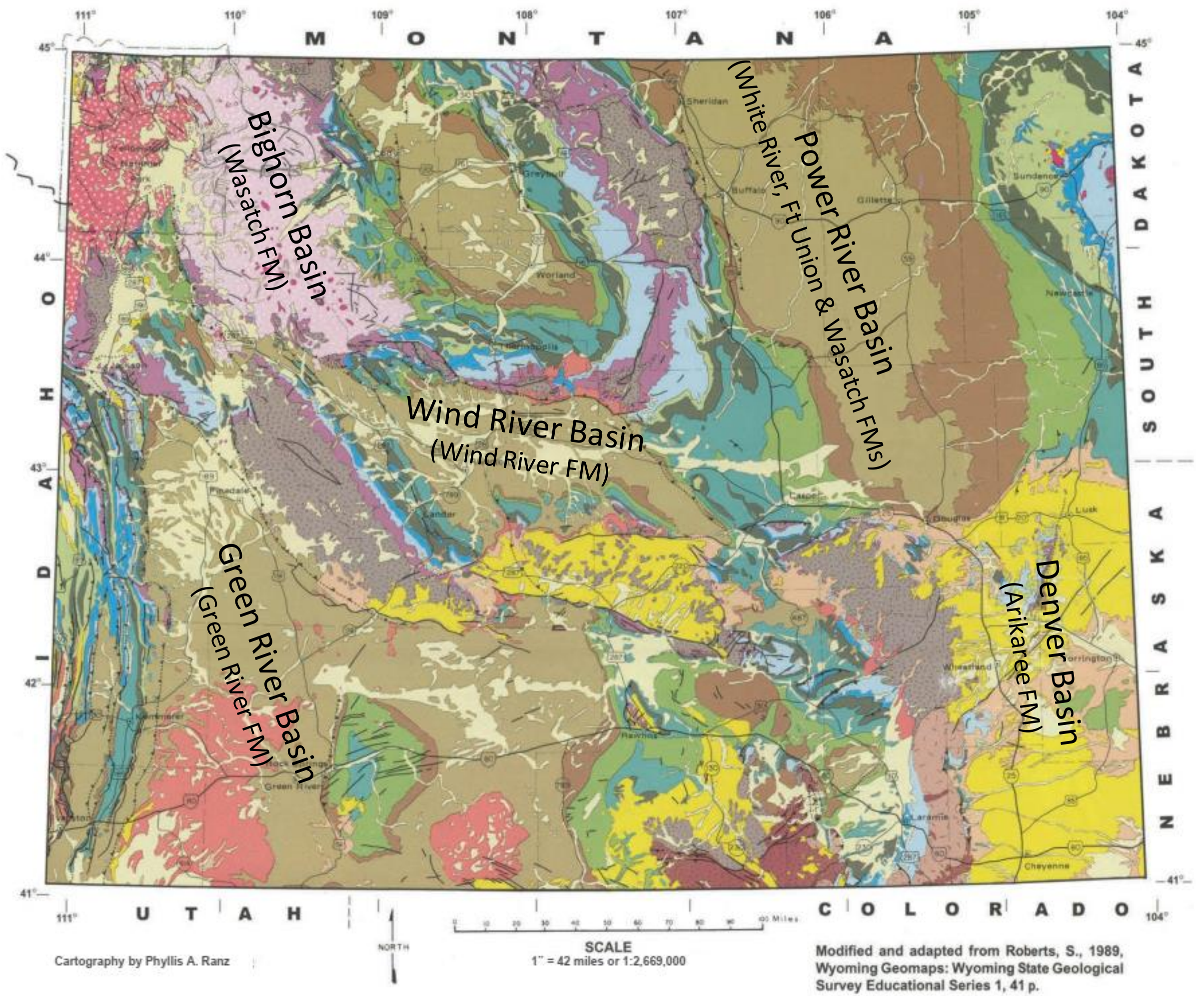
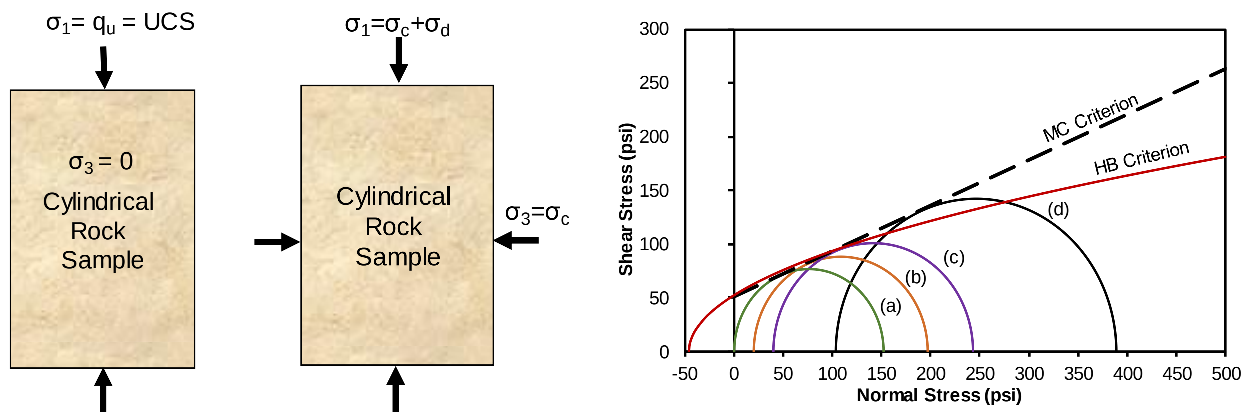


Figure 1. Geological map of Wyoming highlighting some problematic Tertiary Formations in their respective basins (WSGS, 2019)

WYDOT currently adopts the American Association of State Highway and Transportation Officials (AASHTO) recommendations and applies local experiences in engineering design and construction, especially foundation systems in accordance with the AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications (2017). A site investigation is normally performed by the Geology Program to determine its subsurface profile and geomaterial properties. Standard Penetration Test (SPT) is the most commonly used in-situ field test in Wyoming. At the same location for SPT test, a drivepoint penetration test is performed by driving a 2-inch diameter drivepoint into the ground using a 140-lb hammer at a drop height of 30 inches. Hammer blow counts to penetrate the drivepoint 12 inches into the ground are recorded. The main purpose of the drivepoint penetration test is to determine the depth of an adequate bearing layer, such as unweathered bedrock for a deep foundation design and construction. When a bedrock layer is encountered, rock coring will be performed to determine the Rock Quality Designation (*RQD*) and Geological Strength Index (*GSI*) (Hoek et al., 2013).

Selected intact rock samples from the rock core will be tested at the Geology Laboratory for the uniaxial compressive (UC) strength ($\sigma_1 = q_u$ or *UCS*) by neglecting the confinement (i.e., $\sigma_3=0$) as illustrated in Figure 2(a). The q_u value is normally plotted as a Mohr's circle (a) in Figure 2(c) as illustrated using the recently completed test results on siltstone for the Lodgepole Creek bridge project in Pine Bluffs, WY. Figure 2(c) shows that the nonlinear Hoek and Brown (HB) and the linear Mohr-Coulomb (MC) failure envelopes of the siltstone could not be fully described based on the UC strength test alone but with the additional triaxial compressive test results plotted as Mohr's circles (b), (c) and (d). Triaxial test is performed by applying a confining pressure (σ_c) on a rock sample followed by an axial deviator stress (σ_d) to failure as illustrated in Figure 2(b). Furthermore, other engineering properties (e.g., Young's modulus (E), Poisson ratio (ν) and tensile strength) can be determined from the triaxial test as summarized in Table 1 based on three siltstone samples T1, T2 and T3.



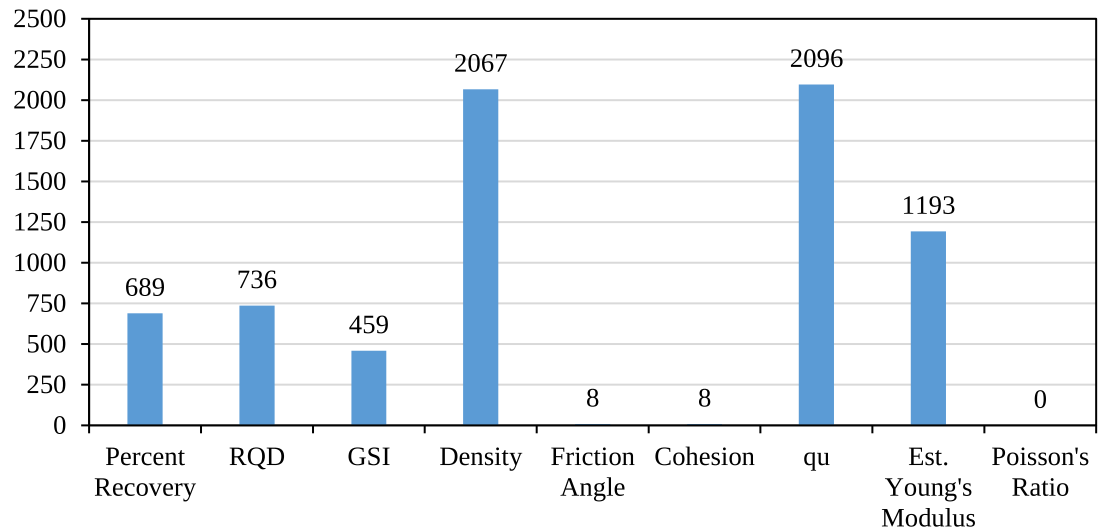
(a) Uniaxial Test (b) Triaxial Test (c) Rock Test Results

Figure 2. (a) Stress state at uniaxial compressive test, (b) stress state at triaxial compressive test, and (c) a combination of uniaxial and triaxial test results including two failure envelopes.

Table 1. Summary of properties of siltstone for the Lodgepole Creek bridge project

Description/Property	**T1**	**T2**	**T3**
Sample Depth (ft)	71.1	73.7	75.6
Sample Diameter x Length (in)	1.836 x 4.281	1.794 x 4.216	1.781 x 4.250
Confining Stress (psi)	104	20	40
Peak Axial Stress (psi)	389	197	243
Young's Modulus, E_i (psi)	138	149	233
Poisson's Ratio, ν	0.41	0.45	0.31
Cohesion-MC (psi)	51		
Friction Angle (degree)	23		
HB's m_i coefficient	3.3		
Cohesion-HB (psi)	53		
Tensile Strength (psi)	46		

Since 2000, the Geology Program has developed an electronic database known as "*Bedrock Properties Database*" to compile the project and bedrock test information. The database consists 2100 project and rock test records, and 523 records were identified as Tertiary Formations. Of the 2100 records, the available engineering properties recorded in the database are summarized Figure 3. About 30% of the total records have the rock quality description in terms of percent recovery, *RQD* or *GSI*. Almost all records have measured bedrock density and q_u values. However, it is important to highlight that the vital shear strength properties (friction angles and cohesion) and elastic properties (Young's modulus and Poisson's ratio) were rarely measured but estimated. Furthermore, other important properties (e.g., HB parameters) of bedrocks vital for designs are not available and are often estimated using correlations found in literature developed based on rocks that do not represent the rock formations in Wyoming. Hence, it has been an urgent need to truly understand the Wyoming bedrock behaviors and characterize their properties to improve the design and construction of the transportation infrastructure so as a greater economic benefit can be realized. Furthermore, performance uncertainties of this transportation infrastructure during construction can be minimized.



Note: Young's modulus was estimated using correlations from literature.

Figure 3. Summary of engineering properties recorded in the *Bedrock Properties Database* developed by WYDOT Geology Program.

Research Objectives

The overall goal of the proposed research project is to understand the strength and deformation behaviors of Wyoming bedrocks in order to improve the design and construction of transportation infrastructure. Recognizing the design and construction challenges due to the lack of measured engineering properties of bedrock representing the Wyoming formations, the research project is proposed to accomplish the following objectives:

1) To characterize the strength and deformation properties of bedrocks;
2) To develop locally calibrated relationships for bedrock properties in terms of index parameters, rock quality, and q_u;
3) To expand the WYDOT database of rock properties; and
4) To improve the understanding between Wyoming geology and bedrock behaviors.

Research Methods

The research program was established based on the aforementioned research objectives. The research objectives will be achieved by completing six major tasks.

Task 1: Literature Review

This task will focus on conducting a literature review pertinent to rock mechanics and bedrock properties. This task will provide the necessary references for completing the subsequent tasks. The literature review will include the following activities:

1) Conduct a literature search for documents, books, papers, reports, catalogs, manuals, notes, and presentation slides pertinent to bedrock quality and properties related to civil engineering applications;
2) Document and review the current state of knowledge and the current state of practice relating to bedrock classification, description, testing and properties;
3) Study current specifications and guidelines adopted by various DOTs, AASHTO, and other agencies; and
4) Identify gaps in the body of knowledge.

Task 2: Assessment of WYDOT Electronic Database and Rock Inventory

The current WYDOT *Bedrock Properties Database* will be reviewed and analyzed to identify usable records for subsequent studies. Usable records are those that contain rock quality description, q_u value, and geology description. This assessment will be conducted to determine the relationship between project information, bedrock geology, bedrock quality, and strength and deformation properties. After identifying the usable records by their project information and working along with the WYDOT Geology Program, relevant rock cores will be identified and usable rock samples will be collected from the WYDOT Geology storage for laboratory testing at the University of Wyoming (UW) described in Task 4.

Task 3: Geotechnical Investigation and Rock Sampling

Besides testing rock samples from the WYDOT inventory described in Task 2, new rock samples will be obtained from geotechnical investigation on upcoming highway projects in Wyoming (e.g., see Table 2 for some upcoming bridge projects). The geotechnical investigation will be performed by the Geology Program using their current drill rigs. Standard rock cores with a diameter of about 1.91-in. (NQ-size) will be collected, and the rock quality will be described with *RQD* and *GSI*. Depending on the *RQD*, a standard 5-ft "core-run" segment is preferred for each bedrock formation. Geotechnical reports and subsurface profiles will be assessed to determine the underlying bedrock characteristics. The stratigraphy, geologic formation, and discontinuity of rocks will be described. A minimum three rock samples with a diameter to depth ratio of 1:2 will be obtained from each bedrock layer for laboratory testing described in Task 4. These characteristics will be used in Task 5 for data analysis and correlation studies.

Table 2. Summary of some anticipated WYDOT bridge projects in fiscal year 2020

Design Project No.	Route	Feature	Bridge Description
I254160	Casper Marginal	Walsh Drive	190 ft Long, Three Span Bridge
B123014	Rock Springs St.	UPRR Overpass	390 ft Long, Four Span Bridge
I802220	Rock Springs St.	I80 Interchange	250 ft Long, Three Span Bridge
CN19036	Uinta County Road	Sulphur Creek	65 ft Long, Tri-Deck Beam Bridge
B123014	Rock Springs St.	Bitter Creek	122 ft Long Box Girder Bridge

Task 4: Laboratory Rock Testing

Laboratory rock tests will be performed by the PI's research team to determine the rock properties. Intact rock samples collected in Tasks 2 and 3 will be used for strength and deformation tests. Uniaxial and triaxial compressive tests will be performed by the research team at the UW in accordance with the ASTM D7012 (2014) using the servo-controlled testing system (GCTS RTR-1500) currently placed at the UW's Engineering Building as shown in Figure 4(a). This testing system has a maximum compressive load of 337 kips, tension load of 184 kips, and confining pressure of 20 ksi; capable of testing most rocks. The triaxial equipment has been upgraded with temperature control and ultrasonic measurement capability. Each rock sample will be cut and trimmed to produce high quality thin slices without disturbing the structure of the sample, to ensure both end faces are perpendicular to the length, and to have the length at least twice of the diameter. Prior to testing, each rock sample will be jacketed with a heat shrinkable flexible polyolefin tubing shown in Figure 4(b) and instrumented with three Linear Variable Differential Transformers (LVDTs) shown in Figure 4(c) to measure two axial strains and a radial strain. Each triaxial test will be conducted at a room temperature of about 23°C for two continuous stages. In first stage, the sample will be subjected to three cycles of loading and unloading of target confining pressure (σ_c) at a rate of 0.72 ksi/min, and the target σ_c will be eventually kept constant in the second stage. In the second stage, deviator pressure (σ_d) will be applied on the sample with a strain control at a rate of about 0.2%/min until the sample fails or reaches 5% axial strain. Radial (ε_r) and axial (ε_a) strains and externally applied pressures will be measured in all stages. For each bedrock formation at each project site, a minimum two triaxial tests will be conducted separately at two different σ_c values that cover the in-situ confining pressure. Based on the rock inventory and new rock samples collected from upcoming projects, it is expected that at least 100 triaxial tests will be conducted in this task to cover a wide range of bedrock formations in Wyoming.

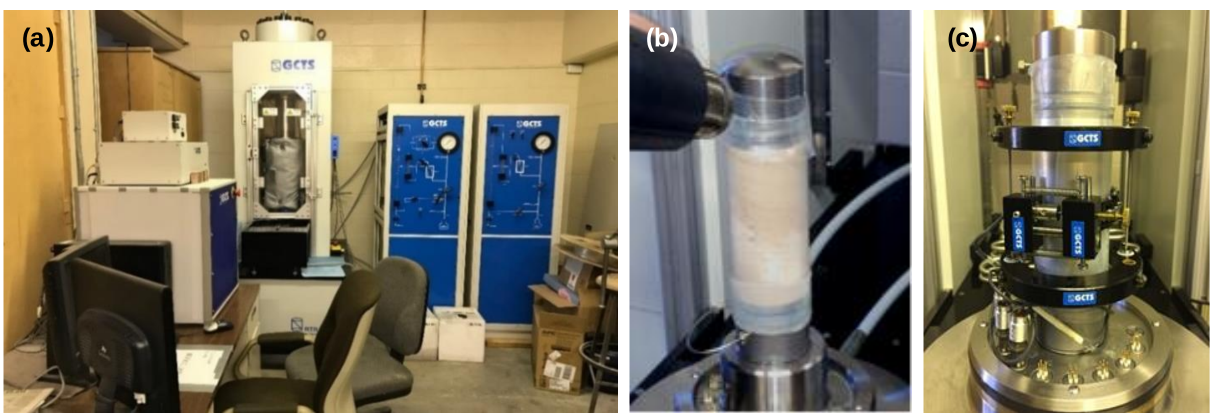


Figure 4. (a) Servo-controlled rock testing system, (b) a rock sample jacketed with a heat shrinkable flexible polyolefin tubing, and (c) rock sample instrumented with LVDTs.

Task 5: Data Analysis and Correlation Development

The triaxial rock test will yield important elastic properties, such as Young's modulus (E_i) and Poisson's ratio (ν). An example of the triaxial test result of the siltstone sample T3 for the Lodgepole Creek project is shown in Figure 5(a). The slope of the linear axial stress-strain line is the Young's modulus, and the ratio of the corresponding radial to axial strains is the Poisson's ratio. These elastic moduli can be determined and plotted as a function of axial strain as shown in Figure 5(b). The failure behavior (e.g., brittle or ductile) will be determined to understand the deformation behavior of the bedrock. Combining the results from two to three triaxial tests and a uniaxial test, Hoek-Brown parameters and Mohr-Coulomb shear strength parameters can be determined from Mohr's circles and failure envelopes as plotted in Figure 2(c) for the Lodgepole Creek project as an example to illustrate the data analysis process.

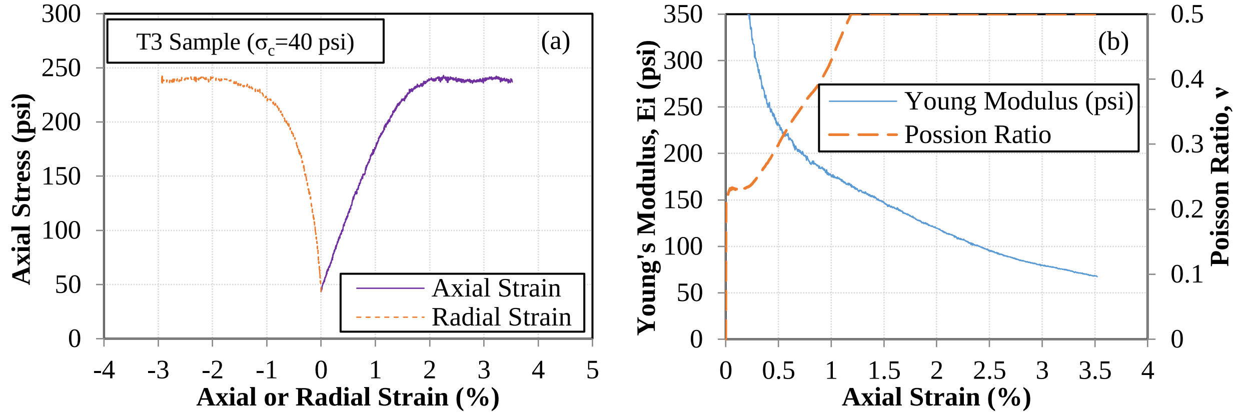


Figure 5. Triaxial test results of the siltstone sample T3 for the Lodgepole Creek project showing (a) the stress-strain measurements, and (b) elastic properties as a function of axial strain.

Since laboratory tests will be performed on intact rock samples, the aforementioned measured properties and parameters will be applied to relate its rock mass strength characteristics based on the rock quality information. For example, the HB parameter m_i can be better quantified for Wyoming bedrocks from the test results instead of assuming a constant for a general rock type (Marinos and Hoek, 2000). Hence, the empirical HB parameter m_b for rock mass using Equation (1), where D is a disturbance factor (Hoek et al., 2002), can be better estimated. Furthermore, measured E_i value can be used to better estimate Young's modulus of rock mass (E_m) given by Equation (2) (Yang 2006). Using the measured E_i and q_u values, the Wyoming bedrocks can be classified for engineering purposes in terms of their strength (Deere and Miller, 1966) while avoiding subjectivity due to the background and experience of the person making the classification.

$$m_b = m_i e^{\left(\frac{GSI-100}{28-14D}\right)} \tag{1}$$

$$E_m = \frac{E_i}{100} e^{\left(\frac{GSI}{21.7}\right)} \tag{2}$$

The measured rock properties along with rock quality description will be compiled for each Wyoming bedrock formation and lithology. A catalog of bedrock properties will be established to facilitate design process. The properties will be presented in a range described with statistical parameters.

The measured test results will be used to develop possible correlations for elastic moduli, HB parameters and MC strength parameters based on commonly measured q_u, RQD and GSI values for Wyoming bedrock formations. This correlation study will be conducted using multiple regression models to account for the joint effects of the possible predictors on a bedrock parameter. Correlation assessment criteria: adjusted R-square, Akaike's information criteria

(AIC), Schwarz' Bayesian criteria (BIC), and Mallows' criterion (C_p) (Kutner et al., 2005) will be applied to evaluate the proposed correlations.

Besides the HB and MC failure criteria, other nonlinear failure criteria and their parameters, such as the generalized power-law criterion proposed by the PI's research team (Hua 2018), will be possibly calibrated using the measured properties to better describe the shear strength behavior.

<u>Task 6: Outcomes Recommendations and Reporting</u>
Upon completion of Tasks 1 through 5, research outcomes will be determined and recommendations will be established to facilitate the design and construction of transportation infrastructure in Wyoming. The anticipated research outcomes and recommendations are summarized as follows:

1) The test results will be compiled and presented to the WYDOT Geology Program in order to expand the *Bedrock Properties Database*.
2) A catalog of bedrock properties and parameters will be developed to facilitate design process and engineering analysis.
3) Correlations will be established to relate important yet uncommonly measured bedrock strength and deformation properties based on q_u and rock quality description.
4) Linear and nonlinear failure criteria will be calibrated for Wyoming bedrocks.
5) The failure behavior of bedrocks will be better understood, and factors, such rock geology, contributing to the failure process will be determined.

The research outcomes and recommendations will provide WYDOT the necessary background for future studies to further improve the design and construction of transportation infrastructure, such as bridge foundations, roadways and highway slopes. It is envisioned that the recommendations will satisfy the study objectives and bring benefits to WYDOT and relevant stakeholders.

Expected Outcomes

Since bedrock is one of the fundamental construction materials, it is expecting that bedrock characterization through the proposed laboratory testing program will yield the following outcomes and benefits: 1) improve the design and construction of drilled shafts socketed into bedrock, 2) facilitate the evaluation and mitigation development for landslides primarily due to rock slide and rock topple, 3) increase the design reliability of spread footing on bedrock, 4) increase the acceptance rate of pile performance driven into soft bedrock, 5) improve the assessment of the rippability of bedrock cuts for roadway construction, 6) complement the current pooled fund study TPF 5-391 by the principal investigator (PI), and 7) provide the technical background for future assessment of suitable bedrock sources for base aggregates.

1) *Geomaterial*: The natural variability of bedrocks creates a high uncertainty in the subsurface condition for engineering design and construction. Knowledge on the bedrock is limited to *RQD* and q_u values in the current practice. Measured strength and elastic properties are not readily available for engineering analysis and design. For example, softer bedrock is not well defined for driven pile design in the AASHTO LRFD Bridge Design Specifications (2017). Due to the natural variability of soft rock, uncertainties in deep foundation design are exacerbated, leading to many construction challenges (Mokwa and Brooks 2008). The proposed research will populate the measured rock properties to

advance the development of a geomaterial classification system (Adhikari et al., 2019) and reduce the uncertainties associated with engineering design and construction. Improving design efficiency will minimize the discrepancy between design outcome and construction performance.

2) *Driven Pile*: The AASHTO (2017) recommend that piles driven in soft rocks shall be designed in the same manner as soil while piles driven in hard rocks shall be governed by the structural limit. Since static analysis methods for soft rocks are not readily available for pile resistance estimation, pile resistances are usually under-predicted (Ng and Sullivan 2017). Congruent to the design challenges, total pile resistance in soft rock is typically determined using dynamic analysis methods during construction. Large discrepancies between estimated and measured pile resistances were identified (Ng et al. 2015). It is not unusual that these piles do not satisfy the LRFD strength limit state at the end of driving (EOD) and occasionally at the beginning of last restrike (BOR). This could incur additional construction duration and operational cost. The high uncertainty in pile performance could incur difficulty in the construction management since foundation construction is the critical path of a bridge project. Bedrock properties generated from the proposed research will be applied to calibrate static analysis methods and improve pile resistance estimation in soft rock so that a cost saving in pile design and construction can be realized. This research outcome will complement the current pooled fund study TPF 5-391 led by the PI focusing on the development of LRFD procedure for driven piles in soft rock.

3) *Drilled Shaft*: For drilled shafts socketed into fractured bedrock, the unit end bearing (q_p) can be estimated using Equation (3) in terms of HB parameters m_b, s and a (AASHTO 2017). The parameters were estimated using empirical correlations developed based on general bedrocks that may not necessarily represent the Wyoming bedrock conditions. The accumulated uncertainties will reduce the accuracy of q_p estimation as well as the reliability of drilled shaft design and construction in Wyoming. Hence, the measured properties of intact rock samples (E_i, m_i, v) obtained from the proposed testing program along with q_u and *GSI* recorded in the *Bedrock Properties Database* will be used to calibrate the HB parameters and improve q_p estimation. It is hoping that the improvement will reduce the bedrock socket depth and overall construction cost of drilled shafts.

$$q_p = A + q_u\left[m_b\left(\frac{A}{q_u}\right) + s\right]^a; \text{ where } A = \sigma'_{vb} + q_u\left[m_b\left(\frac{\sigma'_{vb}}{q_u}\right) + s\right]^a \qquad (3)$$

4) *Landslide*: Landslide evaluation of rock slopes relies on the shear strength properties of the bedrock. Due to the absence of rock equipment for routine testing, measured friction angle and cohesion were rarely available as illustrated in Figure 3, and estimated values are normally used in design to evaluate the rock slope stability and develop mitigation strategies for rock slope stabilization. The measured shear strength properties of commonly encountered bedrocks in Wyoming will improve the safety of a rock slope and help WYDOT to develop a more cost-effective rock slope stabilization method.

5) *Spread Footing*: Similar to drilled shaft design, the design of spread footing on shallow bedrock requires the determination of HB parameters (Carter and Kulhawy 1988) or the

shear strength properties (Goodman 1989). However, these properties are rarely available nor measured. This limitation could create higher risk in using the relatively less expensive spread footing system on bridges unless the strength and deformation properties of the bedrock are characterized. Alternatively, a more expensive plate load test can be conducted to determine its nominal bearing resistance during construction.

6) *Bedrock Rippability*: Road construction involves the excavation of bedrock. Bedrock is normally loosen using steel shank rippers attached to the rear of bulldozers. The rippability of rock depends on its geology and engineering properties. Historically, WYDOT conducted seismic investigations in locations where the drill rigs could not gain access. More recently, seismic lines are run at sites where borrow drill holes have been conducted in an effort to correlate drilling characteristics and seismic velocities to the rippability of the rock. The comparison to the drilling has been made more difficult recently by the increased torque and horsepower generated by larger drills used by WYDOT. A cost analysis performed on three past projects (Flying V Slide, Rosie's Ridge Section and Sybille Creek Station) indicates that additional claims of at least $90,000 were estimated on projects with the issue of rock rippability. Particularly for the Flying V Slide project, the additional cost increased by as high as 41.5% or $354,240. The measured bedrock properties from this proposed research will provide the technical background for future study to improve the rock rippability evaluation and excavation effort prediction, which will improve the preparation of both construction schedule and cost estimation, facilitate the selection of proper ripping equipment, and maximize rock cut production.

7) *Base Aggregate*: Base aggregate is one of the important construction materials for flexible and rigid pavements. WYDOT is implementing the Mechanistic-Empirical Pavement Design Guide (MEPDG) through the characterization of base materials. Laboratory-measured properties and resilient modulus of these local base materials have been recently quantified (Ng et al., 2019). The effects of moisture content, percent fines content, stresses, and gradation on base resilient modulus have been examined. However, it is little known how different Wyoming bedrock formations as the parent material and source of base aggregates affect their resilient moduli. A study conducted for Virginia DOT concluded that limestone aggregates have a higher resilient modulus than that of granite aggregates (Hossain and Lane 2015). The bedrock characterization proposed in this research will provide the technical background for future assessment of suitable bedrock sources for base aggregates in terms of their degradation behavior, particle breakage, and mechanical properties.

The proposed research project will have several direct benefits to WYDOT, civil engineering consultants and contractors, and other relevant stakeholders. These anticipated benefits to design and construction of transportation infrastructure on bedrocks are described as follows:

<u>Benefits to Design:</u>

1) A catalog of representative bedrock engineering properties will be developed to facilitate design process.
2) Locally calibrated correlations will be recommended to improve the estimation of bedrock properties.

3) Wyoming bedrock conditions and geology will be incorporated into the determination of more representative engineering properties.
4) Accumulated uncertainties from existing empirical correlations for bedrock properties will be reduced during the design process to improve design reliability.
5) Not only strength but also deformation analysis will be enabled in order to evaluate the serviceability of our transportation infrastructure.
6) The WYDOT *Bedrock Properties Database* will be populated with important and measured properties to improve design efficiency and accuracy.
7) The estimation of rock mass strength and deformation properties will be improved.
8) Engineering design can be optimized to reduce overall cost.

<u>Benefits to Construction:</u>

1) The discrepancy between estimated and measured performance in terms of strength and deformation of highway infrastructure will be minimized.
2) Acceptance rate of our highway infrastructure will be increased.
3) Uncertainties associated with the performance of our highway infrastructure will be reduced.
4) A more cost-effective rock slope stabilization method can be developed.
5) The constructability of our drilled shafts can be improved through a better understanding of the bedrock behavior.
6) Unnecessary conflicts between contractors and WYDOT can be avoided.
7) Overall construction will be improved due to lower construction bids, avoiding construction delays, minimizing additional operational costs, and reducing the possibility of additional claims.

Relevance to Strategic Goals

The project outcomes will address the primary strategic goal of *State of Good Repair*. Since roadways, bridges and slopes are critical elements of our highway infrastructure, it is essential to properly design, construct, and maintain this transportation infrastructure on bedrock to maximize their productivity and performance as well as to minimize their full life cycle costs. In addition, the research outcomes will indirectly reduce unnecessary construction materials, increase construction productivity, and lead to the efficient use of non-renewable natural resources. The secondary strategic goal is related to *Safety*. Bedrock characterization through the proposed testing program will reduce the uncertainties associated with strength and deformation behaviors and the risk in design and construction. Hence, the safety of our transportation infrastructure described by the LRFD philosophy can be ensured, and a target safety margin can be achieved.

Educational Benefits

A PhD student majoring in civil engineering will be hired in July 2020 to assist principal investigators to complete this project. The bedrock mechanics will be introduced in the following civil engineering courses: CE4610 (Foundation Engineering) and CE4620 (Soil/Rock Engineering). A new graduate course on rock mechanics will be developed using the experimental data and outcomes generated from this proposed research.

Technology Transfer

To update the progress of the research project, short quarterly reports will be submitted to WYDOT Research and Geology Programs and the MPC. Also, a yearly interim report will be submitted to WYDOT and MPC at the end of 2020 and 2021 to report the research progress. Integrating all the outcomes obtained from previous tasks as well as comments given by WYDOT and MPC representatives, a draft final report will be prepared. A final report, containing all aspects of the proposed research, will be prepared and submitted to the WYDOT and MPC. A technical presentation on the completed project will be given to the WYDOT Research Advisory Committee (RAC) upon request. To further disseminate the research outcomes, journal/conference papers will be published, and technical presentations will be given at regional and/or national conferences.

Technology transfer will be performed in close coordination with WYDOT, especially the Geology Program, throughout the entire project. The final report will provide recommendations to expand the *Bedrock Properties Database* with measured bedrock properties. Research activities and outcomes will be summarized in the final report. They will be disseminated through peer-reviewed publications and technical presentations at state conferences, such as the annual Wyoming Engineering Society meeting, and national conferences, such as the Transportation Research Board annual meeting in Washington, D.C.

Work Plan

The work plan consists of six tasks, and they are explicitly described under the Research Method section. This section lists the six proposed tasks and their respective timeline. The total duration for the proposed research is 24 months, tentatively beginning July 2020 through June 2022.

<u>Task 1: Literature review (Month 1 to Month 12)</u>
Literature review will be conducted pertinent to rock mechanics and bedrock properties

<u>Task 2: Assessment of Database and Rock Inventory (Month 1 to Month 6)</u>
Rock Properties Database will be reviewed to determine the relationship between project information, bedrock geology, bedrock quality, and strength and deformation properties.

<u>Task 3: Geotechnical Investigation and Rock Sampling (Month 1 to Month 12)</u>
Geotechnical investigation including borehole drilling rock sampling will be conducted on upcoming projects to collect additional rock samples for laboratory rock testing in Task 4.

<u>Task 4: Laboratory Rock Testing (Month 4 to 18)</u>
Laboratory uniaxial and triaxial rock tests will be performed to determine the mechanical properties of rocks covering a wide range of bedrock formations in Wyoming.

<u>Task 5: Data Analysis and Correlation Development (Month 13 to Month 24)</u>
Laboratory measurements along with geological and in-situ rock information will be analyzed to quantify elastic properties, rock mass strength parameters, and nonlinear failure criteria and their parameters. A catalog of bedrock properties and correlations for elastic properties will be developed.

Task 6: Outcomes Recommendations and Reporting (Month 22 to 24)
Research outcomes will be determined, and recommendations will be established in the final report.

Project Cost

Total Project Costs:	$125,000
MPC Funds Requested:	$ 50,000
Matching Funds:	$ 75,000
Source of Matching Funds:	Wyoming Department of Transportation

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